Shallow Carbon Sequestration Demonstration Project

DE-NT0006642

Final Scientific/Technical Report

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ABSTRACT

The potential for carbon sequestration at relatively shallow depths was investigated at four power plant sites in Missouri. Exploratory boreholes were cored through the Davis Shale confining layer into the St. Francois aquifer (Lamotte Sandstone and Bonneterre Formation). Precambrian basement contact ranged from 654.4 meters at the John Twitty Energy Center in Southwest Missouri to over 1100 meters near the Sioux Power Plant in St. Charles County. Investigations at the John Twitty Energy Center included 3D seismic reflection surveys, downhole geophysical logging and pressure testing, and laboratory analysis of rock core and water samples. Plans to perform injectivity tests at the John Twitty Energy Center, using food grade CO_2, had to be abandoned when the isolated aquifer was found to have very low dissolved solids content. Investigations at the Sioux Plant and Thomas Hill Energy Center in Randolph County found suitably saline conditions in the St. Francois. A fourth borehole in Platte County was discontinued before reaching the aquifer. Laboratory analyses of rock core and water samples indicate that the St. Charles and Randolph County sites could have storage potentials worthy of further study. The report suggests additional Missouri areas for further investigation as well.

ACKNOWLEDGEMENT

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EXECUTIVE SUMMARY

The Shallow Carbon Sequestration Demonstration Project is a research project led by City Utilities of Springfield, Missouri (CU) under a Cooperative Agreement (DE-NT0006642) with the U.S. Department of Energy (DOE). The project's goal was to assess the feasibility of onsite carbon sequestration at Missouri power plant sites. Research Teams involved in the project included CU, the Missouri Department of Natural Resources (MDNR), Missouri State University (MSU), and Missouri University of Science & Technology (Missouri S&T). Matching funds for the project were provided jointly by a consortium of Missouri utility companies which included CU, Ameren Missouri (Ameren), Associated Electric Cooperative, Inc. (AECI), The Empire District Electric Company (Empire District), and Kansas City Power & Light (KCP&L). These utility companies collectively operate sixteen coal-fired power plants in Missouri and provide 90% of the electric power used by Missouri's farms, families and businesses.

Although relatively few existing boreholes penetrated the full sequence of sedimentary strata underlying Missouri, available data suggested that the St. Francois Aquifer (Lamotte Sandstone and Bonneterre Formation) could serve as a suitable reservoir for injection and storage of carbon dioxide (CO2) captured from power plant emission streams, and that the St. Francois Confining Unit (Davis and Derby-Doerun Formations) could serve as a suitable confining layer. The Lamotte Sandstone is the basal sedimentary unit in the state and lies directly above Precambrian basement rock. The St. Francois Confining Unit and St. Francois Aquifer are often referred to functionally in this report as the confining unit and target formation, respectively.

The project, as originally scoped, involved site characterization and an injection demonstration using food-grade CO_2 at CU's John Twitty Energy Center (JTEC) in Springfield. A 3D seismic reflection survey was performed at the site in an attempt to locate exploratory boreholes/monitoring wells and the injection well in areas where the Lamotte Sandstone was found to be thickest. Exploratory Borehole #1 was drilled at JTEC, and continuous rock core obtained from the confining layer and the prospective reservoir. The St. Francois confining unit was encountered at a depth of 459.3 m (1,507 feet) and the St. Francois Aquifer was encountered at a depth of 518.5 (1,701 feet). Precambrian basement rock was encountered at a depth of 654.4 m (2,147 feet). Once the Lamotte Sandstone could be isolated and representative formation water samples obtained, however, it was found that the concentration of Total Dissolved Solids (TDS) was around 150 mg/L, which was well below the 10,000 mg/L threshold requiring classification of the aquifer as an Underground Source of Drinking Water (USDW). This classification precluded an injection test or any subsequent carbon sequestration at this site, and led to CU working with DOE to re-scope the project.

The project was re-scoped to provide a state-wide assessment of the feasibility of carbon sequestration at Missouri power plant sites. The revised scope provided for completion of three additional exploratory boreholes at other power plant sites. Exploratory Borehole #2 was sited at AECI's Thomas Hill Energy Center (THEC) in north-central Missouri, Exploratory Borehole #3 was sited at KCP&L's Iatan Generating Station (IGS) in western Missouri, and Borehole #4 was sited at Ameren's Sioux Power Plant (SPP) in eastern Missouri. Each of the four power plant sites occupied a different geological setting and, collectively, would provide useful data for assessment of the feasibility of carbon sequestration in Missouri.

Exploratory Borehole #2 at THEC was drilled to a total depth of 785.5 m (2,577) feet. The St. Francois Confining Unit was found to have suitable thickness (88.4 m) and suitable permeability (from less than one microdarcy to 3 millidarcies) to serve as a confining layer for carbon sequestration. The St. Francois Aquifer was found to have suitable depth (636.1 m), suitable thickness (138 m), suitable porosity (10.8%) and suitable permeability (5.7 millidarcies to 307 millidarcies) to serve as a CO_2 storage reservoir. Reservoir

calculations indicate an injection rate of 60 m^3 per day for an 800 m x 800 m reservoir with 5-spot water withdrawal may provide a storage capacity of 1.27 x 10^6 metric tons of CO_2 over a period of 15.8 years. AECI owns approximately 14,000 hectares at THEC, which means a number of injection well fields could be installed and operated at the site.

Exploratory Borehole #3 at IGS was advanced to a depth of depth of 637.0 m, but caving within the borehole made interpretation of strata impractical. Drilling at IGS was terminated before reaching the St. Francois Confining Unit, and the borehole was subsequently abandoned. Since no research was conducted at this site, no assessment could be made regarding the feasibility of carbon sequestration.

Exploratory Borehole #4 at SPP was advanced to a depth of 1,105 m, at which point drilling was terminated due to the physical limitations of the coring rig. The St. Francois Confining Unit was found to have suitable thickness (87.2 m) and suitable permeability (2.9 microdarcies to 15 microdarcies) to serve as a confining layer for carbon sequestration. The St. Francois Aquifer was found to have suitable depth (893.7 m), suitable thickness (greater than 211.3 m), suitable porosity (6% to over 21%) and suitable permeability (.02 millidarcy to 99 millidarcies) to serve as a CO_2 storage reservoir. Reservoir calculations indicate an injection rate of 60 m^3 per day for an 800 m x 800 m reservoir with 5-spot water withdrawal may provide a storage capacity of 5.53 x 10^5 metric tons of CO_2 over a period of 15.8 years.

The research indicates that the northern half of Missouri is generally favorable for carbon sequestration. The St. Francois Confining Unit was found to be very consistent across the state, and exhibited very low permeability. The St. Francois Aquifer was found to be more variable, but exhibited suitable depth, thickness and reservoir properties in the northern half of the state. THEC appears to be a good candidate for development as a regional carbon sequestration site, and warrants more detailed site characterization. SPP appears to hold the greatest promise for supercritical injection of CO_2, and also warrants additional site characterization. Research at IGS was inconclusive, and additional site characterization would be required to assess the IGS site and the Forest City Basin, in general. A transitional zone between the Western Interior Plains Aquifer and the Ozark Plateaus/St. Francois Aquifers along the western border of the state may also provide a suitable hydrogeologic setting for carbon sequestration. This area was beyond the scope of the Shallow Carbon Sequestration Demonstration Project, but may warrant investigation.

The Shallow Carbon Sequestration Demonstration Project added significantly to our overall understanding of Missouri structural geology, stratigraphy and hydrology, and provided a valid assessment of the feasibility of carbon sequestration at Missouri power plant sites within the constraints of the limited project budget. This research will fill an important gap in the national DOE carbon sequestration database, and may form the basis for further research in Missouri.

CHAPTER I - BACKGROUND

A. CARBON SEQUESTRATION

With the growing concern for greenhouse gas emissions and the prospect of governmental regulation, electric utilities across the nation must find ways to reduce carbon emissions safely, effectively and economically. The Shallow Carbon Sequestration Demonstration Project is an important step toward Missouri utilities addressing that need, and the project serves as a model for state-led assessment of carbon sequestration feasibility.

The research project was led by City Utilities of Springfield (CU) under a Cooperative Agreement (DE-NT0006642) with the U.S. Department of Energy (DOE). The project's goal was to assess the feasibility of onsite carbon sequestration at Missouri power plant sites. Onsite sequestration avoids the time, expense, and risk involved in construction and operation of pipelines and compression stations necessary to transfer carbon dioxide from individual power plants to large, regional carbon sequestration sites.

B. WHY MISSOURI?

Coal has been the lifeblood of Missouri industry since the early 1800s. Prior to the Clean Air Amendments of 1990, coal mined in Missouri, Kansas, Oklahoma and Illinois provided much of the fuel for Missouri's power plants and industries. Following enactment of the amendments, many power plants elected to switch to low-sulfur coal, primarily from the Powder River Basin in Wyoming. Today, the five largest electric utilities in Missouri, all of which are involved in this project, operate sixteen coal- fired power plants and provide 90% of the electrical power used by Missouri's farms, families and businesses (Figure 1.1)

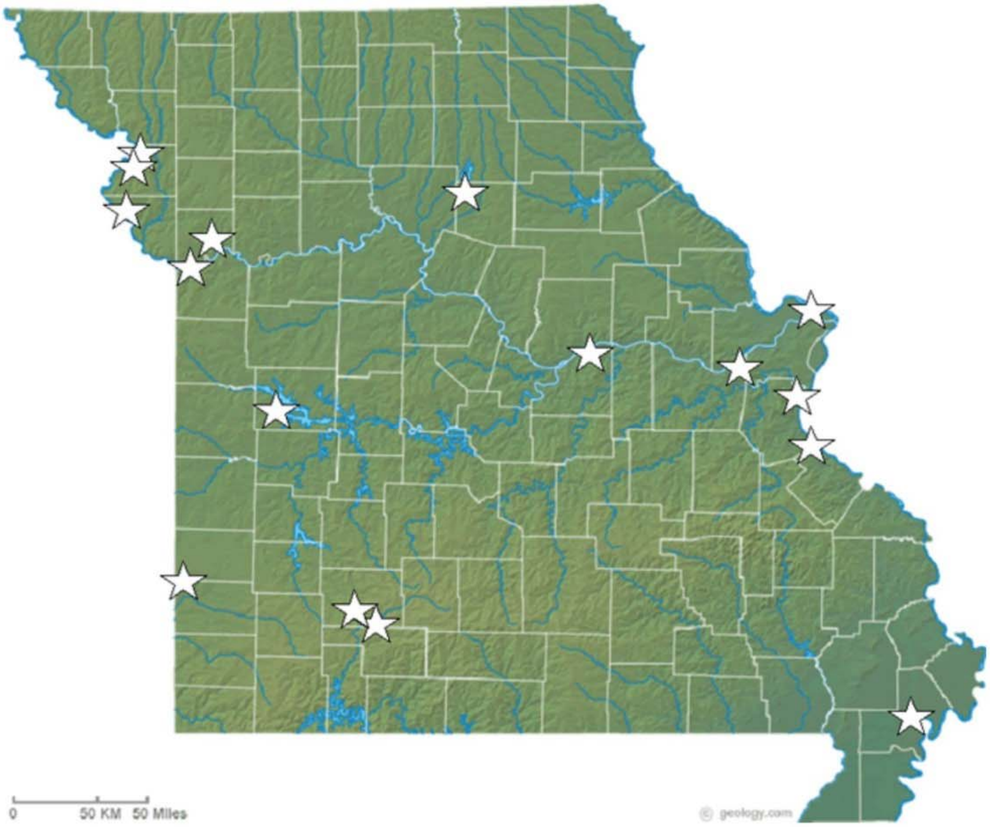
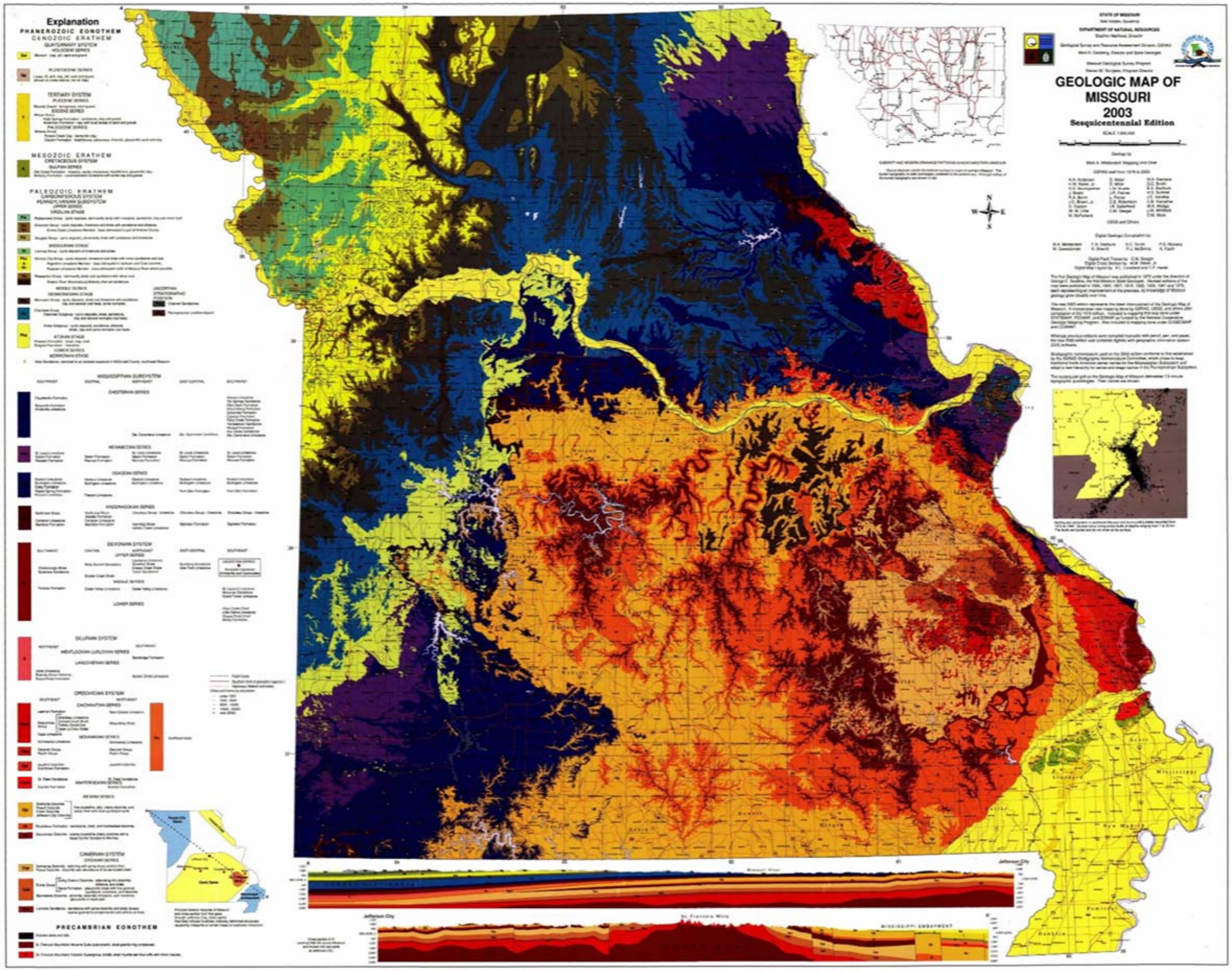


FIGURE 1.1 - MEMBER UTILITIES COAL-FIRED POWER PLANT LOCATIONS

Although Missouri lacks the deep geological basins found in other regions of the nation, the state is underlain by the type of geology that appeared suitable for geological storage of carbon dioxide, and warranted detailed study to assess the feasibility of onsite carbon sequestration. Missouri geology is dominated by the St. Francois uplift, a broad tectonic dome which exposes Precambrian basement rock at its center in southeastern Missouri. Sedimentary strata, Cambrian through Pennsylvanian age, slopes away from the dome in all directions, generally deepening away from the dome. Figure 1.2 provides descriptions of the stratigraphic units and depicts the predominant tectonic features in the state: the St. Francois uplift (Ozark Dome), Forest City Basin, Lincoln Fold, and Mississippi Embayment. Figure 1.3 details the locations of major anticlines, synclines and faults, and depicts the general configuration of sedimentary strata in the state.

FIGURE 1.2 – GEOLOGIC MAP OF MISSOURI



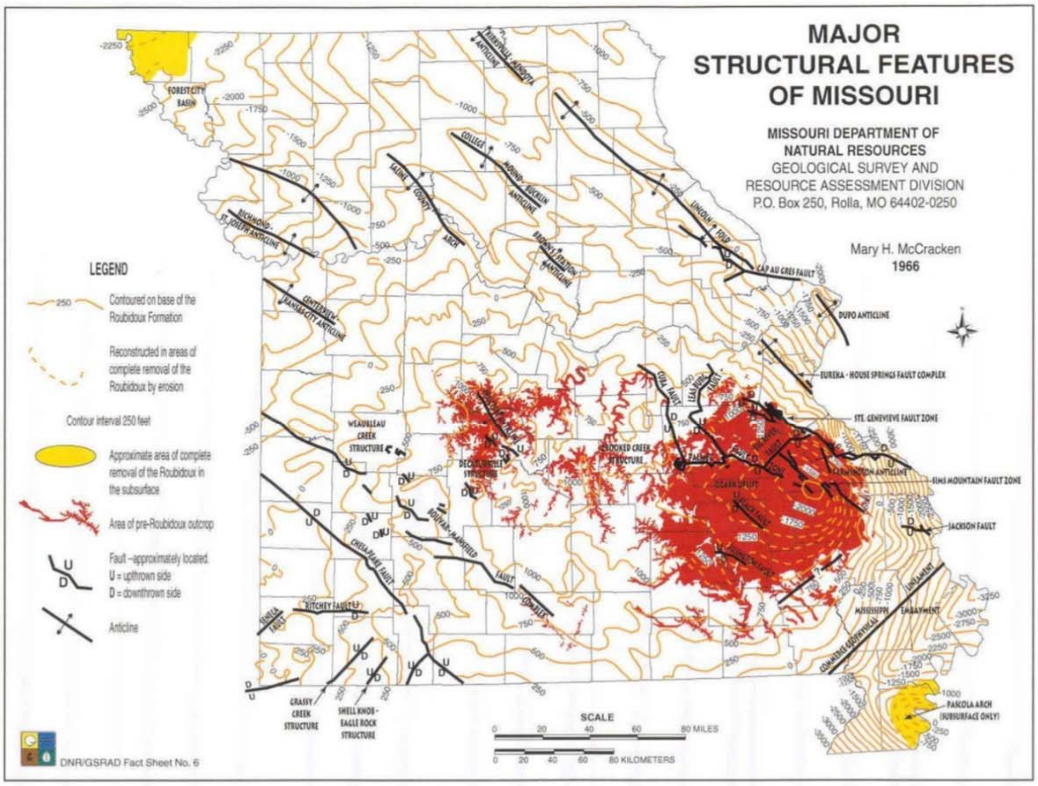


FIGURE 1.3 - MAJOR STRUCTURAL FEATURES OF MISSOURI

Missouri is generally underlain by three separate aquifer systems: the shallow Springfield Plateau Aquifer, which occurs primarily in southwestern Missouri, the Ozark Aquifer, which underlies much of the state, and the deeper St. Francois Aquifer which also underlies much of the state. Figure 1.4 depicts the outcrop areas of the respective aquifer systems. A cross section of the aquifer systems is provided in Figure 1.5, which illustrates how the respective aquifers deepen away from the St. Francois uplift.

The aquifer systems are separated by confining units. The Ozark confining unit is comprised primarily of the Northview Formation and Compton Limestone, and separates the Springfield Plateau Aquifer from the underlying Ozark Aquifer. The St. Francois confining unit is comprised of the Davis and Derby-Doerun Formations and separates the Ozark Aquifer from the underlying St. Francois Aquifer. The shallow Springfield Plateau Aquifer is utilized for water supply in some areas of the state, but is compromised in other areas by poor water quality. The Ozark Aquifer is a prolific water producer and the major groundwater source for a large portion of the state. Wells that penetrate the full thickness of the aquifer can produce more than 1,000 gallon per minute. The deeper St. Francois Aquifer, which is not generally utilized for water supply, which tends to be saline, and which is overlain by a competent confining unit, is the target reservoir for carbon sequestration in Missouri.

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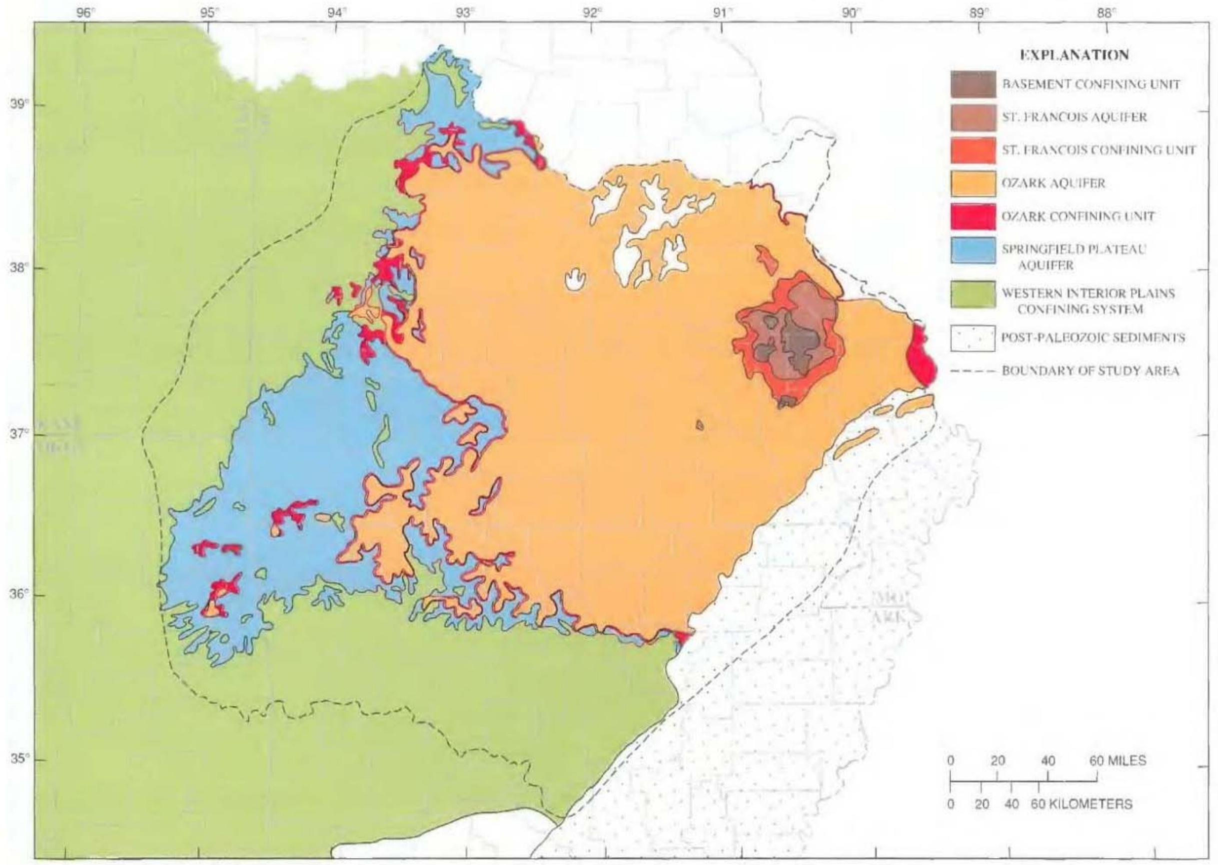

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Missouri Aquifers and Confining Units

Shallow Carbon Sequestration
Demonstration Project

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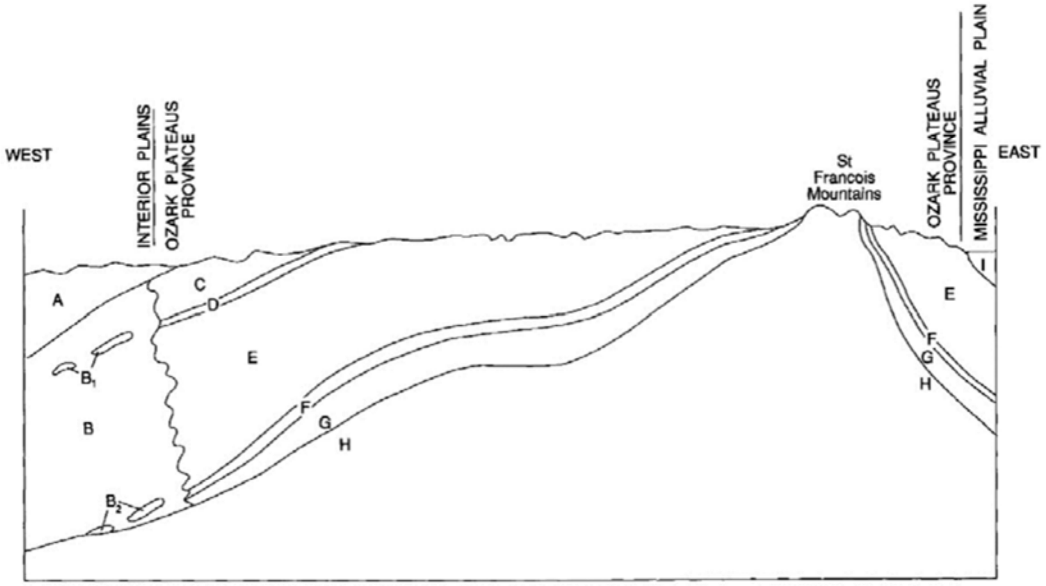
Figure 1.4



EXPLANATION

A	WESTERN INTERIOR PLAINS CONFINING SYSTEM
B	WESTERN INTERIOR PLAINS AQUIFER SYSTEM
B_1	STRATIGRAPHICALLY EQUIVALENT TO OZARK CONFINING UNIT
B_2	STRATIGRAPHICALLY EQUIVALENT TO ST. FRANCOIS CONFINING UNIT
	OZARK PLATEAUS AQUIFER SYSTEM
C	SPRINGFIELD PLATEAU AQUIFER
D	OZARK CONFINING UNIT
E	OZARK AQUIFER
F	ST. FRANCOIS CONFINING UNIT
G	ST. FRANCOIS AQUIFER
H	BASEMENT CONFINING UNIT
I	POST- PALEOZOIC SEDIMENTS

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Cross Section Depicting Missouri Aquifers and Confining Units

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Figure 1.5

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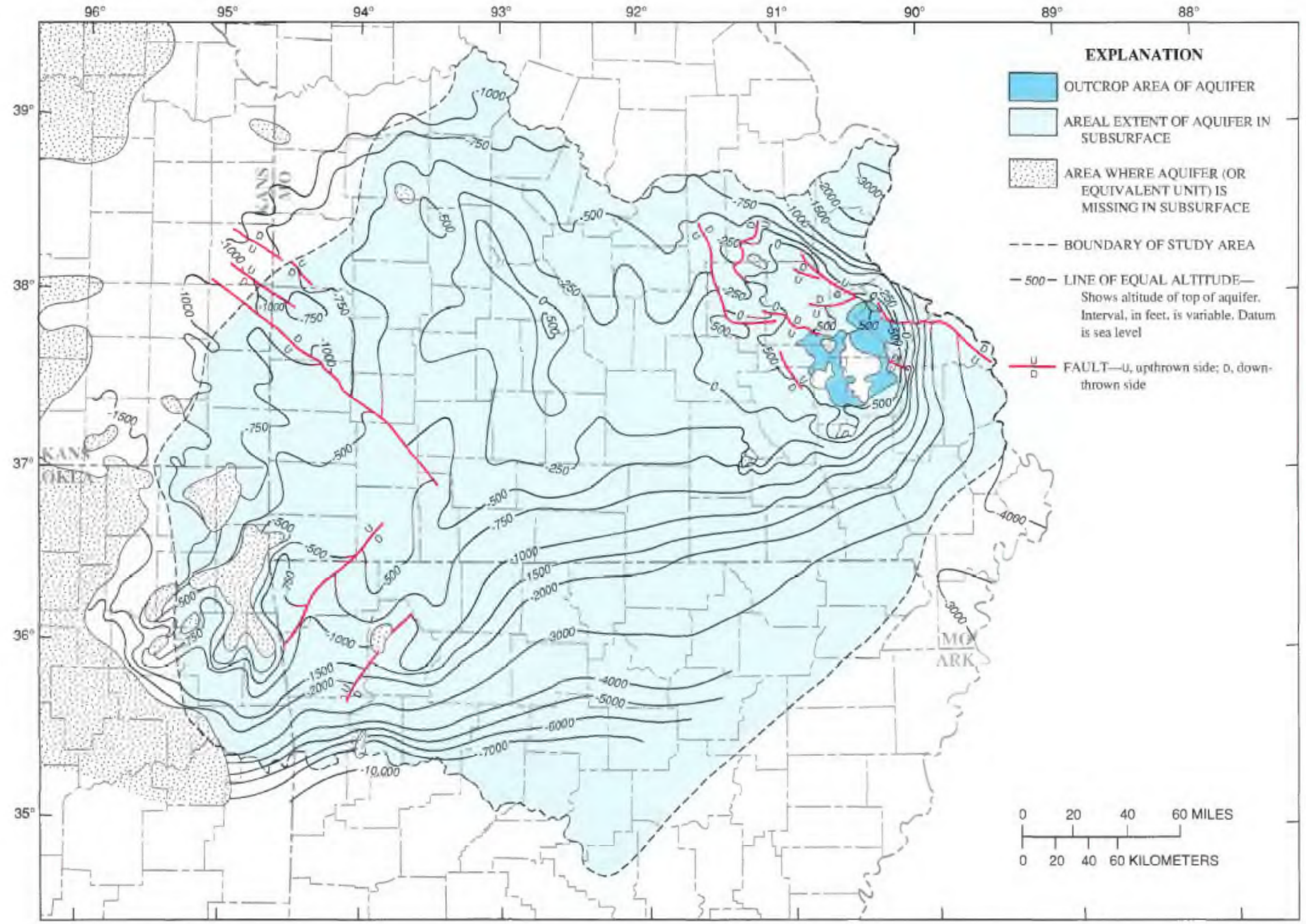
The St. Francois Aquifer is comprised of the basal Lamotte Sandstone and the Bonneterre Formation. Although relatively few boreholes had been drilled through the Lamotte Sandstone, available data suggested the Lamotte might be a suitable candidate for carbon sequestration. The structure contour map provided in Figure 1.6 shows the top of the aquifer slopes steeply to the east and more gently to the west from the St. Francois Mountains. Based on the depth of the aquifer beneath the ground surface, some areas of the state would require CO_2 injection in the gas phase, while other areas of the state would accommodate supercritical injection of CO_2. The isopach map provided in Figure 1.7 shows the thickness of the St. Francois to range from under 100 feet in western Missouri to more than 700 feet in eastern Missouri. The Total Dissolved Solids map provided in Figure 1.8 shows concentrations in the St. Francois Aquifer above 10,000 mg/L; below which the aquifer is classified as an Underground Source of Drinking Water (USDW) and above which carbon sequestration may be considered. Assuming adequate porosity and permeability, these characteristics appear suitable to support power plant scale carbon sequestration in several areas of the state.



Structure Contour Map of the Top of the St. Francois Aquifer

Shallow Carbon Sequestration Demonstration Project

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Figure 1.6

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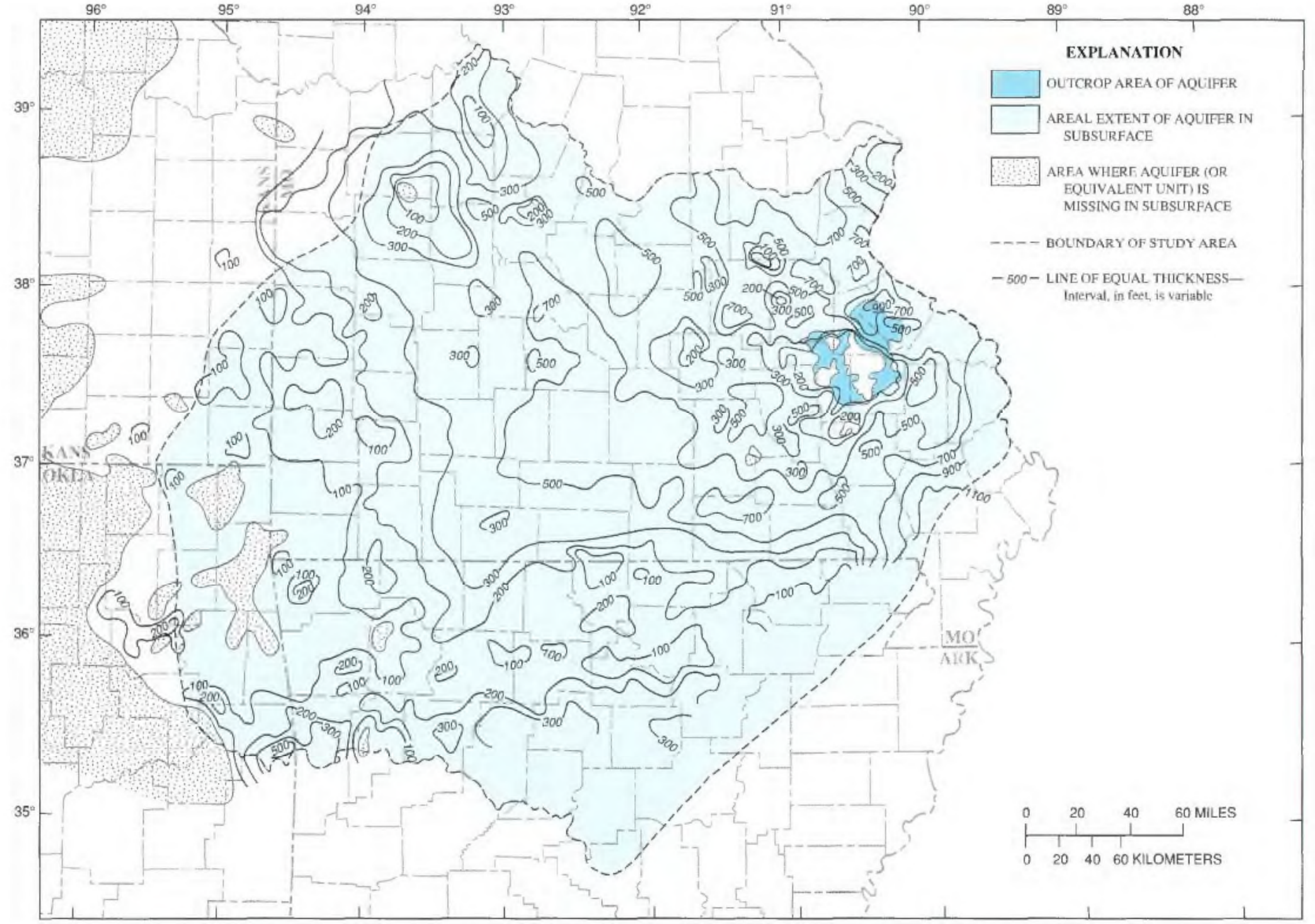

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Isopach Map Depicting the Thickness of the St. Francois Aquifer

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Figure 1.7

TOTAL DISSOLVED SOLIDS CONCENTRATIONS OF GROUNDWATER FROM THE ST. FRANCOIS AQUIFER (CAMBRIAN SYSTEM) IN MISSOURI

Geology and Digital Compilation
by
Jeffrey Crews, Thomas Mesko
and Scott Kaden

2010

OFM-10-605-GS

MISSOURI DEPARTMENT OF NATURAL RESOURCES
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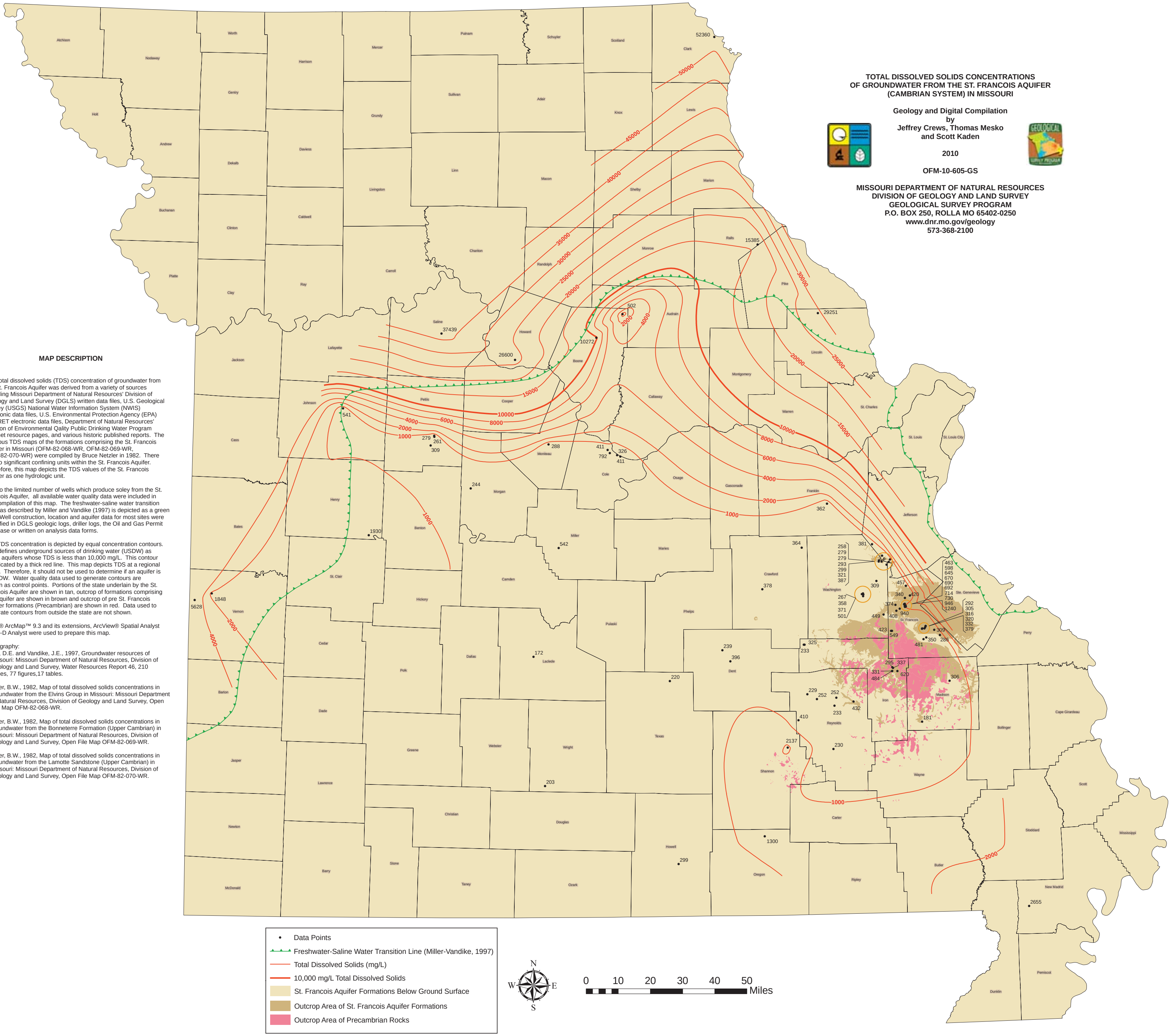


MAP DESCRIPTION

The total dissolved solids (TDS) concentration of groundwater from the St. Francois Aquifer was derived from a variety of sources including Missouri Department of Natural Resources' Division of Geology and Land Survey (DGLS) written data files, U.S. Geological Survey (USGS) National Water Information System (NWIS) electronic data files, U.S. Environmental Protection Agency (EPA) STORET electronic data files, Department of Natural Resources' Division of Environmental Qality Public Drinking Water Program Internet resource pages, and various historic published reports. The previous TDS maps of the formations comprising the St. Francois Aquifer in Missouri (OFM-82-068-WR, OFM-82-069-WR, OFM-82-070-WR) were compiled by Bruce Netzler in 1982. There are no significant confining units within the St. Francois Aquifer. Therefore, this map depicts the TDS values of the St. Francois Aquifer as one hydrologic unit.

Due to the limited number of wells which produce soley from the St. Francois Aquifer, all available water quality data were included in the compilation of this map. The freshwater-saline water transition zone as described by Miller and Vandike (1997) is depicted as a green line. Well construction, location and aquifer data for most sites were identified in DGLS geologic logs, driller logs, the Oil and Gas Permit database or written on analysis data forms.

The TDS concentration is depicted by equal concentration contours. EPA defines underground sources of drinking water (USDW) as those aquifers whose TDS is less than 10,000 mg/L. This contour is indicated by a thick red line. This map depicts TDS at a regional scale. Therefore, it should not be used to determine if an aquifer is a USDW. Water quality data used to generate contours are shown as control points. Portions of the state underlain by the St. Francois Aquifer are shown in tan, outcrop of formations comprising this aquifer are shown in brown and outcrop of pre St. Francois Aquifer formations (Precambrian) are shown in red. Data used to generate contours from outside the state are not shown.

ESRI® ArcMap™ 9.3 and its extensions, ArcView® Spatial Analyst and 3-D Analyst were used to prepare this map.

Bibliography:

Miller, D.E. and Vandike, J.E., 1997, Groundwater resources of Missouri: Missouri Department of Natural Resources, Division of Geology and Land Survey, Water Resources Report 46, 210 pages, 77 figures,17 tables.

Netzler, B.W., 1982, Map of total dissolved solids concentrations in groundwater from the Elvins Group in Missouri: Missouri Department of Natural Resources, Division of Geology and Land Survey, Open File Map OFM-82-068-WR.

Netzler, B.W., 1982, Map of total dissolved solids concentrations in groundwater from the Bonneterre Formation (Upper Cambrian) in Missouri: Missouri Department of Natural Resources, Division of Geology and Land Survey, Open File Map OFM-82-069-WR.

Netzler, B.W., 1982, Map of total dissolved solids concentrations in groundwater from the Lamotte Sandstone (Upper Cambrian) in Missouri: Missouri Department of Natural Resources, Division of Geology and Land Survey, Open File Map OFM-82-070-WR.

C. PROJECT PLANNING

After tracking the formation and progress of the DOE Regional Partnerships for some time, CU recognized the need for independent assessment of carbon sequestration within the State of Missouri. CU contacted other electric producers within the state and assembled a consortium of utility companies (stakeholders) who shared an interest in the feasibility of carbon sequestration. CU also met with the Missouri Department of Natural Resources and two of the leading universities in the state, Missouri State University and Missouri University of Science & Technology, to solicit their interest in the project. From the contacts, the basic project structure emerged with Ameren Missouri, Associated Electric Cooperative, Inc., CU, The Empire District Electric Company, and Kansas City Power & Light forming the Funding Members and CU, Missouri Department of Natural Resources, Missouri State University, and Missouri University of Science & Technology forming the Research Teams. The responsibilities and obligations of the respective organizations were subsequently memorialized in a Memorandum of Understanding. City Utilities executed a Cooperative Agreement with the Department of Energy – National Energy Technology Laboratory, and developed a Statement of Project Objectives and Project Management Plan which detailed the scope and intent of the project. A Project Management Team was assembled which included a core group of City Utilities employees and technical consultants.

D. FUNDING MEMBERS

The five electric utilities listed above collectively provided the matching funds required by the Cooperative Agreement. The project investments were secured through a Memorandum of Understanding. Brief descriptions of each funding member are provided in the following paragraphs.

City Utilities is a community-owned utility with a service area that covers 320 square miles which serves approximately 110,000 customers in the City of Springfield, Greene County, and part of northern Christian County.

Ameren Missouri is an investor-owned utility headquartered in St. Louis, Missouri which serves more than 900,000 customers in north-central, northeastern and southeastern Missouri. Ameren Missouri was incorporated in 1995.

Associated Electric Cooperative, Inc. (AECI) is an electricity co-op that supplies 51 local electric cooperatives in Missouri, Iowa and Oklahoma. Those cooperatives serve about 875,000 customers in primarily rural areas. AECI was formed by six generation and transmission cooperatives in 1961 and is led by a member-directed board and management.

The Empire District Electric Company (Empire District) began generating power in 1909. The utility now serves more than 167,000 customers in southwestern Missouri, the southeast corner of Kansas, the northwest corner of Arkansas and northeastern Oklahoma.

Kansas City Power & Light (KCP&L), headquartered in Kansas City, Missouri, is an investor-owned utility that serves more than 800,000 customers in 47 northwest Missouri counties and eastern Kansas Counties. The company was created in 1882 by four friends who believed electricity was more than a novelty and over the years under several acquisitions, restructuring and name changes, it became KCP&L. In 2008, Great Plains Energy, Inc. purchased KCP&L which today is comprised of Kansas City Light & Power and KCP&L Greater Missouri Operations, Inc.

E. RESEARCH TEAM

Research for the Shallow Carbon Sequestration Demonstration Project was divided among four Missouri organizations: CU, Missouri Department of Natural Resources (MDNR), Missouri State University (MSU), and Missouri University of Science & Technology (Missouri S&T). The CU Research Team was primarily responsible for field work involving drilling, coring, geophysical logging, pressure testing, and borehole closure. The MDNR Research Team was primarily responsible for logging of cuttings and core, determination of formation contacts, management of rock core, and preparation of geological descriptions and reports. The MSU Research Team was primarily responsible for core analysis to determine the petrology and mineralogy of each drilling site, and hydrologic testing to determine the hydrologic regimes at each site. The Missouri S&T Research Team was primarily responsible for reservoir analysis, fate & transport of CO_2, and determination of geomechanical rock properties.

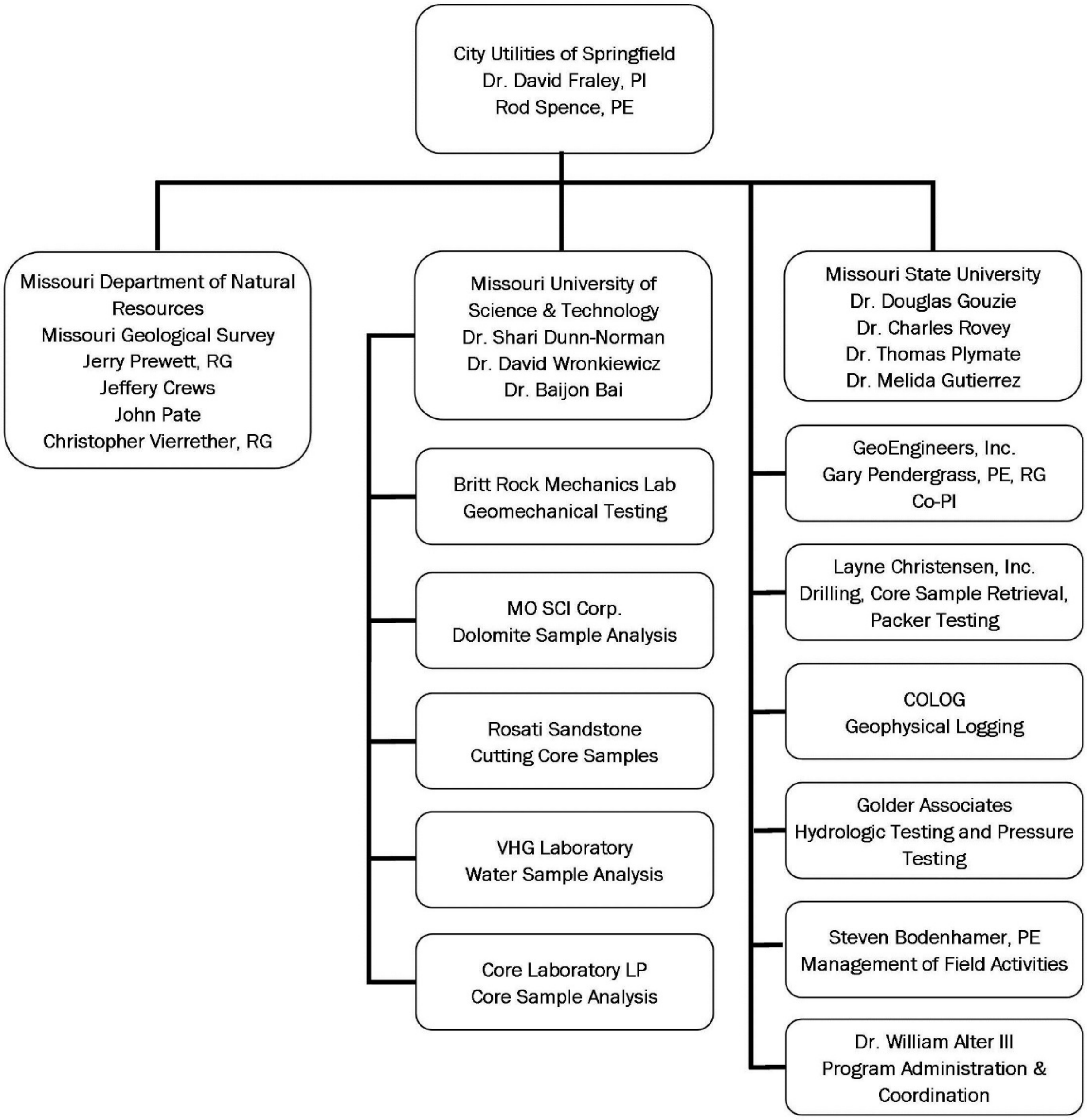
Table 1.1 is an Organizational Chart for this project. David M. Fraley, PhD, Director of Environmental Affairs with City Utilities, served as Principal Investigator. Gary Pendergrass, PE, RG, of GeoEngineers, Inc. (formerly Manager of Environmental Compliance with CU) served as Co-Principal Investigator. Dr. Fraley has extensive experience in environmental regulation and environmental chemistry and Mr. Pendergrass has extensive experience in Missouri geology and hydrology and project management. Other key members of the City Utilities Research Team included Rod Spence, PE, who has extensive experience in construction management and contract administration, Steven Bodenhamer, PE, who has extensive experience in drilling technology and project management, and William Alter III, PhD, who has extensive experience in administration of federal grants and federal regulations.

The MDNR Research Team was led by Jerry Prewett, RG, Deputy Director of the Missouri Geological Survey (MGS) and Assistant State Geologist. The MGS, a division of MDNR, was renamed from the former Division of Geology and Land Survey during this project. Mr. Prewett's expertise includes groundwater protection and resource assessment and evaluation. Mr. Prewett was assisted by Christopher Vierrether, RG and Chief of the Energy Resources Unit, Mr. Jeffrey Crews, and Mr. John Pate. Mr. Vierrether is experienced in geological mapping of stratigraphic units and structural features. Mr. Crews is experienced in subsurface geology, aquifer water quality, and aquifer characteristics. Mr. Pate is experienced in evaluating contamination from leaking above-ground or underground storage tanks and logging of exploratory boreholes.

The MSU Research Team was led by Douglas Gouzie, PhD, RG, who is an Associate Professor of Geology with extensive experience in groundwater investigation and environmental remediation. Other members of the Missouri State University research team include Thomas Plymate, PhD, Chair of the Geology, Geography and Planning Department, who has extensive experience in petrology, optical mineralogy, and X-ray mineralogy; Charles Rovey, PhD, who is an Associate Professor of Geology with extensive experience in the hydrostratigraphy of the Ozark and St. Francois aquifer systems of Missouri; and Melida Gutierrez, PhD, who is a Professor of Geology with extensive experience in geohydrology and geochemical modeling.

The Missouri S&T Research Team was led by Shari Dunn-Norman, PhD, who is an Associate Professor and Head of Petroleum Engineering with extensive experience in well construction, CO_2 injection design, and hydraulic fracturing. Other members of the Missouri S&T Research Team include David Wronkiewicz, PhD, who is an Associate Professor with extensive experience in sedimentary geochemistry, contaminant metal mobility, and carbon sequestration and Baojun Bai, PhD, who is an Associate Professor with extensive expertise in enhanced oil recovery, conformance control, carbon sequestration, and unconventional oil & gas development.

Table 1.1: Organizational Chart for the Shallow Carbon Sequestration Demonstration Project



More detailed information on the expertise of the scientists and engineers shown in Table 1.1 is provided in Appendix 1.A at the end of this chapter. This project also provided training opportunities for undergraduate and graduate students at the two universities. Appendix 1.B lists the students involved in this project. As a result of the work undertaken by the researchers and students at the two universities, several presentations at professional meetings and publications were developed during the project. These appear in Appendix 1.C.

F. PROJECT FUNDING

Total funding for this project was $5,837,936. The U.S Department of Energy awarded a Cooperative Agreement (DE-NT0006642) to CU. The budget period began on October 1, 2008. The initial federal government share of the award was $2,362,349. In accordance with DOE requirements, a 20% non-federal cost share amount of $590,587 was provided through a Memorandum of Understanding among the utilities described in Section D above. Several modifications to the original Cooperative Agreement were issued including an increase in the federal government share to $4,670,349 and an increase in the non-federal cost-share to $1,167,587. The end date for the project was September 30, 2013. Table 1.2 list the original award and the subsequent modifications.

Table 1.2 Funding for the Shallow Carbon Sequestration Demonstration Project

Award/Mod #	Effective Date	Project Period	Federal Funds Obligated	Non-federal Cost Share	Modifications
DE-NT0006642		10/01/2008 - 9/30/2010	$2,363,349	$590,587	
001	4/24/2009	10/01/2008 - 12/31/2010	$2,352,349	$1,167,587	Delete NEPA Requirements, Revise Completion Date, Replace SF-269 with SF-425
002	9/3/2010	12/30/2010 - 12/31/2012	$4,670,349	$1,167,587	Incorporate Revised SOPO
003	6/1/2011	10/01/2008 - 12/31/2012	$4,670,349	$1,167,587	Extend Budget Period 1, Change Principal Investigator from Gary Pendegrass to David Fraley
004	9/22/2011	10/01/2008 - 9/30/2013	$4,670,349	$1,167,587	Incorporate a Revised Budget and SOPO, Update T&C, Authorize continuation into Budget Period 2 and a no-cost extension
005	1/12/2012	10/01/2008 - 9/30/2013	$4,670,349	$1,167,587	Replace NEPA Requirements with categorical exclusion (CX) for drilling at Randolph City and Platt City, MO
006	3/23/2012	10/01/2008 - 9/30/2013	$4,670,439	$1,167,587	Replace SOPO, Replace NEPA Requirements with categorical exclusion (CX) for drilling at Randolph City, Platt City and Luecke Quarry, MO
007	4/6/2012	10/01/2008 - 9/30/2013	$4,670,439	$1,167,587	Replace NEPA Requirements with categorical exclusion for drilling at Randolph County, Platt County, and Luecke Quarry, MO.

G. PROJECT MANAGEMENT

The following discussion summarizes the activities completed that relate to overall management of the project.

Task 1.a. Coordinate with the DOE Project Officer to Modify and Finalize the PMP and Manage the Research Team

The Shallow Carbon Sequestration Demonstration Project (SCSDP) was originally intended to focus on determining the technical feasibility of sequestering carbon at the John Twitty Energy Center site in Springfield, MO. As will be described below in Chapter II, this site was found to not be suitable for carbon sequestration.

With the concurrence of the DOE Project Officer, the project was revised to enable an investigation and assessment of geologic and hydrologic conditions at three additional sites in Missouri that could be appropriate for carbon sequestration. The selection of these sites was accomplished in coordination with the Utility partners and was based on the following factors:

- Assessment of available geological information,
- Total Dissolved Solids data available for nearby areas, and
- Locations on or proximity to one of the Utility partners' power generating stations.

The revised scope was designed to characterize the various geological settings in Missouri and to serve as a state-wide assessment of the feasibility of carbon sequestration.

The revised tasks for the project for this approach appear in Table 1.3, which also contains a listing of the Research Team organizations that had lead responsibility for the various tasks. To more fully understand the permeability of both the confining layer and target formation, the latter was added to the work undertaken under Task 4.a.

Coordination among the Research Team organizations was essential to the success of this project. Regular teleconferences were held with the lead persons for each organization. To ensure that the Research Team and Utility partners were up to date on progress and challenges, periodic meetings were held. In addition, the Quarterly Progress Reports were made available to the Research Team and Utility partners.

Task 1.b. Prepare and Submit NEPA Questionnaires to DOE for the four Missouri power plant sites.

Federally funded projects are subject to environmental impact evaluation under the National Environmental Policy Act (NEPA). In August 2008 City Utilities prepared and submitted a NEPA questionnaire detailing expected environmental impacts from site preparation, borehole investigation, and the planned CO_2 injection at the John Twitty Energy Center. The standard form questionnaire (NETL Form F 451.1-1/3, November 2007) addressed expected impacts to air, water, solid and hazardous wastes, cultural and historic sites, vegetation and wildlife, endangered species, socio-economic conditions, and health and safety considerations. The questionnaire concluded that the project would not result in significant impacts to any of these parameters. The questionnaire was reviewed by DOE and resulted in a concurring opinion of no significant impacts. This was a critical path step enabling execution of final contracts and onsite mobilization.

Phase 2 project activities required additional NEPA evaluation at the other Missouri sites. City Utilities' contractor prepared individual questionnaires for the Thomas Hill and Iatan sites in September, 2011 and the

Luecke site in February 2012. The questionnaires again detailed expected impacts from air emissions, produced water discharge, waste material disposal, etc., and again resulted in a NEPA waiver for each site.

Task 1.c. Prepare and Submit Temporary Air Permit Applications to Missouri Pollution Control Program

As part of the NEPA questionnaire preparation for Phase 1, City Utilities calculated an emissions estimate for the diesel-powered drill rig expected to be deployed for the duration of the project. Consultation with the Missouri Department of Natural Resources Air Pollution Control Program (APCP) yielded an opinion that the project would require a temporary air emissions permit for the John Twitty Energy Center. This finding was based on APCP's classification of the drill rig as a non-mobile source of emissions, since the emissions emanate from a trailer-mounted diesel engine rather than the engine used to transport the rig over the road. CU received a temporary air permit (No. 102009-006) in October 2009. The permit assigned an emission point number to the drill rig and required CU to quantify annual diesel emissions for inclusion on the annual JTEC Emissions Inventory Questionnaire. The permit expired in September 2011 and was not renewed, owing to cessation of activities at JTEC.

For Phase 2 drilling and coring, CU again calculated emissions estimates for each additional borehole site and submitted permit applications for temporary air permits. In the intervening period, however, APCP had reviewed its policy on non-mobile diesel equipment and determined that permits were not required for the other Missouri sites.

Task 1.d. Explore and Leverage Outside Knowledge to Include Review of Data from Other Sites that are Exploring the Suitability of Carbon Sequestration.

The Co-Principal Investigator, Gary Pendergrass, participated in the Strategic Center for Coal Carbon Sequestration Peer Review Meeting in Pittsburgh in March 2010, and used the opportunity to network with carbon sequestration researchers from across the country. A number of recommendations and action items resulted from the Peer Review, and written responses to all were submitted to DOE in June 2010.

Mr. Pendergrass, and Technical Consultant, Steve Bodenhamer, met with DOE/NETL senior management in Pittsburgh in April 2011 to review the project and present a revised project plan. The revised project plan was approved and the project was re-scoped to provide a state-wide assessment of carbon sequestration feasibility.

In December 2011, Mr. Pendergrass met with the FutureGen management team and toured the FutureGen drilling site near Jacksonville, Illinois. Results from the borehole at the John Twitty Energy Center in Springfield, Missouri and the FutureGen borehole in Jacksonville, Illinois were compared, since drilling was conducted in the same geologic formations. The discussion was very useful, since the boreholes to be drilled at Thomas Hill Energy Center and Sioux Power Plant would be much closer to the Jacksonville site than the Springfield site.

Mr. Pendergrass participated in DOE/NETL Carbon Storage R&D Project Review Meetings in Pittsburgh in August 2012 and August 2013. He made formal project presentations at these meetings and used the opportunities to network with other research teams.

APPENDIX 1.A - BIOGRAPHIES

Following are brief biographies on the individuals named in the Organization Chart. The first one listed for each respective organization served as the lead individual for that organization.

CITY UTILITIES OF SPRINGFIELD

David M. Fraley, PhD

Dave Fraley is Director of Environmental Affairs for City Utilities of Springfield, Missouri. He holds a BS in Environmental Chemistry from Missouri State University and MA and PhD degrees in analytical environmental chemistry from the University of Missouri - Columbia. He has worked for City Utilities since 1981. During his tenure with CU, he has been responsible for compliance programs under federal and state laws governing clean air, clean water, toxic substances, and hazardous waste. He serves on the Greene County Local Emergency Planning Committee (dealing with hazardous chemicals in the community), the Ozarks Clean Air Alliance, the Springfield Environmental Collaborative, and the Chamber of Commerce Environmental Committee. He has conducted training sessions on a variety of environmental issues at local, regional, and national workshops.

Gary J. Pendergrass, MS, PE, RG, F.NSPE

Gary Pendergrass is a Registered Professional Engineer and Registered Geologist with over thirty years of experience in management of major engineering and environmental projects. Mr. Pendergrass is an accomplished project manager, and has a wealth of successful experience in governmental, community, and media relations and environmental litigation. Mr. Pendergrass holds a Bachelor of Science Degree in Engineering Geology and Stratigraphy from Missouri State University, and both Bachelor of Science and Master of Science Degrees in Geological Engineering from Missouri University of Science & Technology. Mr. Pendergrass currently serves as Principal and Environmental Group Leader with GeoEngineers, Inc. in Springfield, MO. Prior to that, Mr. Pendergrass served as Manager of Environmental Compliance with City Utilities of Springfield, MO. Previous positions in industry and as a consultant provided Mr. Pendergrass with extensive experience in major hazardous waste cleanup projects, e.g., the Eastern Missouri Dioxin Project in EPA Region VII, as well as landfill design and construction, dam inspection and rehabilitation, coal sourcing and supply, soil and groundwater remediation, and water resource development. Gary was recently named a Fellow Member of the National Society of Professional Engineers, and currently serves as Chair of the Missouri Air Conservation Commission and Vice-Chair of the Missouri Board of Geologist Registration.

William A. Alter III, PhD

Dr. Alter has held positions in the U.S. Air Force and at universities which enabled him to develop extensive experience in acquiring, managing and administering grants and contracts for academic, business and federal government entities. Dr. Alter currently is Manager of PaceLine, LLC, a consulting company that provides assistance to for-profit and not-for-profit organizations in development and administration of grants and contracts from governmental, philanthropic and corporate sources.

Currently, he is assisting City Utilities of Springfield in administration and compliance with the terms of a Cooperative Agreement from the U.S. Department of Energy for a project entitled Shallow Carbon Sequestration Demonstration Project.

Steven D. Bodenhamer, PE

Steve Bodenhamer is a consulting engineer and registered Professional Engineer in Missouri, Oklahoma, Kansas and Arkansas. He received a Bachelor of Science in Electrical Engineering degree from Missouri University of Science and Technology. He has 38 years management, engineering and consulting experience in mining, metals and manufacturing industries. Eleven years of his mining and metals experience included management and supervision of large diameter drilling projects, oil and natural gas development and production, and Class I injection well design, drilling and completion, and operations.

Rod Spence, MS, PE

Rod's educational background includes a BSME from the University of Arkansas – Fayetteville, and a MSME from Texas A&M University - College Station. He has 29 years of experience in power production, engineering, construction and project management, and has been responsible for several large projects including a $137 million Balance of Plant contract that was a large part of $550 million power station. Currently, Rod is responsible for coordinating City Utilities involvement in the Missouri Carbon Sequestration including coordinating development of requests for proposals, review of bids and award of contracts to vendors that are supporting this project. He also is managing various capital projects to support City Utilities' electric power generating stations.

MISSOURI GEOLOGICAL SURVEY

Jerry Prewett, BS, RG

Jerry Prewett has been with DNR for over 20 years. He served 9 years with the Missouri Geological Survey, Environmental Geology Section. His primary duty was groundwater protection related to domestic, municipal, and industrial waste generators. He served as chief of the division's Geologic Resources Section helping to collect and maintain information about Missouri's geologic, stratigraphic, and mineral resources, and hazard assessment. He has directed Missouri's geologic survey program focusing on groundwater protection through proper well construction and plugging, environmental oversight, and resources assessment and evaluation. Most recently he was appointed Deputy Director and Assistant State Geologist for the Missouri geological survey. He received his Bachelor of Science in Geology in 1992 from Missouri State University in Springfield, Missouri. Mr. Prewett is currently president of the Association of Missouri Geologists, and is registered with Missouri's Board of Geologist Registration, giving credential to support health, safety and welfare of Missouri Citizens through sound geologic practices.

Jeffrey Crews, BS

Jeffrey Crews has been working with the Department of Natural Resources, Missouri Geological Survey for seven years. He originally served for two years with the Environmental Geology Section as a Geologist where he gained experience with environmental drilling practices and hydrology in carbonate terrains. He later joined the Geologic Resources Section, where he developed an experience in subsurface geology while working on mapping water quality of various aquifers throughout the state, as well as determining the aquifer thicknesses for the major aquifers through the state. Jeffrey attended the University Missouri–Rolla, now Missouri University of Science & Technology, and received his Bachelor of Science in Geology and Geophysics in 2004.

John Pate, BS

John Pate has been employed with the Missouri Department of Natural Resources-Missouri Geological Survey for over 4 years in the Environmental Geology Section's Subsurface Unit. His primary duty has been evaluating contamination from leaking above-ground or underground storage tanks, with a focus on how it affects private and public water sources. Before coming to the Missouri Geological Survey he worked for a geotechnical firm inspecting piers, drilling exploratory bore holes and testing concrete. Mr. Pate received his Bachelor of Science in Geology in 2007 from the University of Tennessee at Martin.

Charles Vierrether, MS, RG

Christopher Vierrether has been employed by the Missouri Department of Natural Resources – Missouri Geological Survey for more than twenty years. Since February, 2012, he has served as the Energy Resources Unit Chief. This unit is responsible for the tracking and regulation of Missouri's oil, gas and coal resources and associated wells. This unit is also responsible for the tracking and regulation of underground injection control class II and class V wells. Prior to this, Mr. Vierrether has worked in several positions involving various aspects of geology as a staff geologist for the survey. Mr. Vierrether has conducted field evaluations and wrote associated reports on liquid and solid waste site, reviewed and assessed preliminary and detailed liquid and solid waste site investigations, and investigated sink holes and other geologic collapses. He performed geologic mapping of stratigraphic units and structural features, and digitally compiled more than 45 published and unpublished maps. He conducted inspections and enforcement of various well types and water quality issues associated with wells. Mr. Vierrether graduated from the Missouri University of Science & Technology (University of Missouri- Rolla) with his M.S. in Geology and Geophysics in August of 1988, and Southeast Missouri State University with a B.S. in Geology (with Honors and Distinction) in May of 1985. Christopher Vierrether has been a registered geologist in the state of Missouri since April, 1996.

MISSOURI STATE UNIVERSITY

Douglas Gouzie, PhD, RG

Douglas Gouzie is an Associate Professor of Geology at Missouri State University with expertise in the development and environmental management of cave and karst systems. He earned his PhD in Geology in 1986 from the University of Kentucky. Prior to joining Missouri State in 2005, Dr. Gouzie's career included a faculty position at Emory University, work as a private environmental consultant with Law Environmental Inc., and over ten years of government service, including both at the federal government level – Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry, and state government level – California Environmental Protection Agency- Central Coast Water Quality Board. Dr. Gouzie has performed or managed dozens of groundwater investigations involving karst or fractured rock aquifers, along with a number of contaminated site investigations and environmental health evaluations of sites on, or proposed for, the NPL (Superfund) List. He has an extensive broad background in environmental monitoring, remediation, and management and is a Registered Professional Geologist in Florida, Georgia, North Carolina, and Missouri.

Melida Gutiérrez, PhD

Melida Gutiérrez holds a PhD in Geohydrology from the University of Texas at El Paso (1992) and holds a Postgraduate Course in Environmental Science from the International Institute of Hydrology in Delft, The Netherlands (1985). Since 1993 she has been at Missouri State University in the Geography, Geology and

Planning Department, teaching the courses of physical geology and geochemistry. Her research focuses on soil and water contamination, stream water quality and geochemical modeling.

Thomas Plymate, PhD

Thomas Plymate holds a PhD in Geology from the University of Minnesota (1986). He has been on the Geology faculty of Missouri State University since 1986 and has been serving as Department Head for the Department of Geography, Geology, and Planning since 2005. Dr. Plymate research interests include the Proterozoic igneous and metamorphic geology of northern Colorado and the Proterozoic igneous history of the St. Francois Mountains of southeastern Missouri. He has taught Petrology, Optical Mineralogy, X-Ray Mineralogy, Geologic Report Writing, and a variety of other Field Geology and Introductory Geology courses during his tenure at Missouri State University. He also served as Co-Chair of the Joint North-Central/South- Central Geologic Society of America Section meeting in 2010 and was President of the Association of Missouri Geologists in 2004.

Charles Rovey, PhD

Charles Rovey received a PhD in Geoscience from the University of Wisconsin-Milwaukee in 1990. He is currently a Professor of Geology at Missouri State University with active research interests in the hydrostratigraphy of the Ozark and St. Francois aquifer systems of Missouri and the regional stratigraphy of pre-Illinoian glacial sediments.

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

Shari Dunn-Norman, PhD

Dr. Shari Dunn-Norman is Associate Professor and Head of Petroleum Engineering at Missouri University of Science and Technology. She holds a B.S. in Petroleum Engineering from the University of Tulsa, and a Ph.D. in Petroleum Engineering from Heriot-Watt University, Edinburgh, Scotland. After working in both domestic and international assignments for the Atlantic Richfield Companies (ARCO), Dr. Dunn-Norman joined Herriot-Watt University to finish her Ph.D., developing a computational model of well completion design. Since that time, her research has focused on well construction for the protection of underground sources of drinking water, CO_2 injection design, hydraulic fracturing and offshore operations. She has published numerous papers related to area of review for Class 2 injection wells, hydraulic fracturing, and has co-authored a book on well construction. Dr. Dunn-Norman's research has been supported by grants from both government agencies and private companies, with core research support primarily coming from the U.S. Department of Energy and the American Petroleum Institute. Dr. Dunn-Norman has served as the Chair of the Professionalism Committee for the Society of Petroleum Engineers and currently serves on the Drilling Engineering review committee. She served on the U.S. Environmental Protection Agency (EPA) Science Advisory Board 2011 Ad Hoc Panel to review EPA's draft Hydraulic Fracturing Study Plan. Dr. Dunn-Norman currently teaches well completions for hydraulic fracturing for Petroleum ETC, a private corporation that operate events worldwide on topics ranging from multiphase pumping, multiphase metering, fracturing to reservoir engineering.

Baojun Bai, PhD

Dr. Bai is an Associate Professor of Petroleum Engineering and holds the Lester Birbeck Chair position at Missouri University of Science and Technology. Previously, he was a reservoir engineer and head of the conformance-control team at the Research Institute of Petroleum Exploration and Development (RIPED), PetroChina. Dr. Bai also was a post-doctoral scholar at the California Institute of Technology and a graduate research assistant at the New Mexico Petroleum Recovery Research Center for Enhanced Oil Recovery (EOR) projects. He has more than 18 years of experience in the EOR area. He holds PhD degrees in petroleum engineering from New Mexico Institute of Mining and Technology and in Petroleum Geology from China University of Geoscience-Beijing. Bai published more than 100 papers in the areas of EOR, conformance control, CO2 sequestration, and unconventional oil & gas development. Bai serves on the Journal Petroleum Technology Editorial Committee and a technical editor for SPE Journal and SPE Reservoir Engineering and Evaluation.

David J. Wronkiewicz, PhD

Dr. Wronkiewicz received his PhD in Geochemistry from the New Mexico Institute of Mining and Technology in May 1989. His research and professional experience includes more than 25 years of academic, laboratory, field research, and education activities in the general areas of geochemistry, mineralogy, and environmental studies. This includes employment within the university-academic, national research laboratory, and industry sectors. He currently holds the titles of Associate Professor in the Department of Geological Sciences & Engineering and Senior investigator in the Environmental Research Center at the Missouri University of Science and Technology. His research expertise lies within the areas of environmental geochemistry (contaminant metal mobility, nuclear waste management, and carbon sequestration), corrosion-weathering effects, microanalysis of alteration phases, natural analogue studies, sedimentary geochemistry, and the economic geology of metal deposits.

APPENDIX 1.B – STUDENTS INVOLVED IN THE PROJECT

Missouri State University

Graduate Students

Marissa Berger
Elizabeth Johns
Barbara LeVangie
Emme Mayle
Bradley Mitchell
Lea Nondorf

Undergraduate Students

Ashley Dameron
Laura Thayer

Missouri University of Science and Technology

Graduate Students

David Davidson
Todd Miller
Robert A. Swain
Fang Yang

Undergraduate Students

Thomas Herbst
Hanani Nurai

APPENDIX 1.C – PRESENTATIONS AND PUBLICATIONS FROM THE PROJECT

MISSOURI STATE UNIVERSITY

Published Journal Articles to Date

Nondorf, L., Gutierrez, M., and Plymate, T., 2011. *Modeling carbon sequestration reaction for a proposed site in Springfield, Missouri.* Environmental Geosciences (AAPG), v 18, n 2, p. 91-99.

Professional Presentations with Published Abstracts

Johns, E. and Gouzie, D., 2013. Site Specific Geochemical Modeling of Groundwater, Rock, and Carbon Dioxide Interactions: Implications for Geologic Carbon Sequestration. In Geol. Soc. of Amer. Abstracts with Programs, V45, n4, p. 2, May 2013.

Mayle, E. and Rovey, C., 2013. Relationship between Depth and Hydraulic Conductivity within the St. Francois Aquifer in Missouri. In Geol. Soc. of Amer. Abstracts with Programs, V. 45, n. 4, p.2, May 2013.

Shields, S. and Plymate, T., 2013. Petrographic Analysis of the Lamotte Sandstone: Potential for Carbon Sequestration. In Geol. Soc. of Amer. Abstracts with Programs, V45, n4, p. 1, May 2013.

Berger, M. and Plymate, T., 2011. Petrographic Analysis to Determine Spatial Variation of Porosity and Mineralogy in the Lamotte Sandstone in SW Missouri. In Geol. Soc. of Amer. Abstracts with Programs, V43, n1, p. 117, March 2011.

Starkey, M. and Gouzie, D., 2011. Bulk Elemental Analysis of the Lamotte Sandstone Using Non-Destructive X-Ray Fluorescence. In Geol. Soc. of Amer. Abstracts with Programs, V43, n1, p. 117, March 2011.

Gutierrez, M. and Plymate, T., 2011. Modeling solubility and mineral trapping of CO_2 at a proposed carbon sequestration site in SW Missouri. In Geol. Soc. of Amer. Abstracts with Programs, V43, n1, p. 93, March 2011.

Rovey, C., Butcher, D., and Rono, N., 2011. Suitability of the St. Francois Confining Unity as a Caprock above CO2 Injection Zones in Missouri. In Geol. Soc. of Amer. Abstracts with Programs, V43, n1, p. 94, March 2011.

Berger, M. and Plymate, T., 2010. Petrographic Analysis to Determine Spatial Variation of Porosity and Mineralogy in the Lamotte Sandstone in SW Missouri. In Geol. Soc. of Amer. Abstracts with Programs, V45, n5, Oct 2010.

Gutierrez, M. and Nondorf, L., 2010. Variability in the Geochemical Modeling of Carbon Sequestration of a Sandstone Aquifer. In Geol. Soc. of Amer. Abstracts with Programs, V. 42, n. 2, p. 53, April 2010.

Mitchell, B. and Rovey, C., 2010. Hydrologic Assessment of the Ozark Aquifer in Greene County, Mo. In Geol. Soc. of Amer. Abstracts with Programs, V. 42, n. 2, p. 42, April 2010.

Nondorf, L. and Gutierrez, M., 2010. Simulating the Effects of Carbon Sequestration on the Lamotte Sandstone in SW Missouri Using Geochemist's Workbench. In Geol. Soc. of Amer. Abstracts with Programs, V. 42, n. 2, p.53, April 2010.

Starkey, M. and Gouzie, D., 2010. Bulk Elemental Analysis of the Lamotte Sandstone Using Non-

Destructive X-Ray Fluorescence. In Geol. Soc. of Amer. Abstracts with Programs, V42, n5, Oct 2010.

Starkey, M. and Gouzie, D., 2010. Geochemical variation of the Lamotte Sandstone in southwest Missouri. In Geol. Soc. of Amer. Abstracts with Programs, V. 42, n. 2, p. 53, April 2010.

Gutierrez, M. and Nondorf, L., 2009. Modeling Geochemical Parameters in the St. Francois Aquifer Using Well Data from Springfield, Missouri. In Geol. Soc. of Amer. Abstracts with Programs, V. 41, n. 2, p.47, April 2009.

Starkey, M. and Gouzie, D., 2009. Geochemical variation of the Lamotte Sandstone in southwest Missouri. In Geol. Soc. of Amer. Abstracts with Programs, V. 41, n. 7, p. 146, 2009.

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

Publications

Yang F., Bai, B., Tang, D., and Dunn-Norman, S, Wronkiewicz, D., Comparison of completion and heterogeneity effect on CO2 sequestration in shallow and deep saline aquifers, Society of Petroleum Engineers - International Oil and Gas Conference and Exhibition in China 2010, IOGCEC, vol., p. 1841-1851 (2010). http://www.onepetro.org/mslib/servlet/onepetropreview?id=SPE-131381-MS

Fang Yang (2012) "Modeling Carbon Sequestration in Transition Zone to Optimize Storage Potential" http://laurel.lso.missouri.edu/search/?searchtype=a&SORT=D&searcharg=Yang%2C+Fang&searchscope=5 (MS Thesis)

Todd Miller (2012) "Evaluation of the Reagan and Lamotte Sandstones in Southwestern Missouri for Carbon Dioxide Sequestration" http://laurel.lso.missouri.edu/search~S5?/aMiller%2C+Todd/amiller+todd/1%2C3%2C42%2CB/frameset&FF=amiller+todd+j+todd+jeffrey&1%2C%2C2/indexsort=- (Ph.D. Dissertation)

Presentations

Davidson, David A., Wronkiewicz, David J., Potential Geochemical Reactions from Carbon Sequestration in the Lamotte and Bonneterre Formations in Southwest Missouri, Geological Society of America, Abstract, Spring 2010 meeting Branson, MO (abstract).

Fang Yang, B. Bai, S. Dunn-Norman and D. Wronkiewicz, Modeling CO_2 Injection in the Lamotte Formation, Southwest Missouri, Geological Society of America, Abstract, Spring 2010 meeting Branson, MO (abstract).

Herbst, T., Nahar Nurul, H., Swain, R., and Wronkiewicz, D.J., Investigation of Mineral Weathering Products Following CO_2 Injection and High Pressure Tests, Missouri S&T Undergraduate Showcase, Rolla, MO, 4/10/12.

Table 1.3: Research Organizations with Lead Responsibility for Tasks in the Shallow Carbon Sequestration Demonstration Project

Tasks/Subtasks	City Utilities of Springfield, Missouri	Missouri University of Science & Technology	Missouri State University	Missouri Department of Natural Resources
1. Management and Planning				
1.a. Coordinate with DOE Project Officer to modify and finalize the PMP and Manage Research Team	Lead in Design and Refinement of Scope of Work, Manage Subcontracts, Coordinate Mtgs, Liaison with DOE, Submit Technical & Financial Reports to DOE	Participate in Mtgs, 'Contribute to Design and Refinement of Scope of Work and Submit Progress Reports & Invoices	Participate in Mtgs, 'Contribute to Design and Refinement of Scope of Work and Submit Progress Reports & Invoices	Participate in Mtgs, 'Contribute to Design and Refinement of Scope of Work and Submit Progress Reports & Invoices
1.b. Prepare and Submit NEPA Questionnaires to DOE for the four Missouri power plant sites	Compile Data and Submit Application to DOE			
1.c. Prepare and Submit Temporary Air Permit Applications to Missouri Air Pollution Control Program	Compile Data and Submit Application to MO Dept. of Natural Resources			
1.d. Explore and leverage outside knowledge to include review of data from other sites that are exploring the suitability of carbon sequestration	Compile data and submit to DOE			
2. Site Characterization				
2.a. Complete existing information and provide descriptions of general geology at each site	Compile and Analyze Geologic Information			Provide geologic information for the four sites.
2.b. Perform a 3D Surface Seismic Reflection Survey at the John Twitty Energy Center site	RFP, Manage Vendor Contract, Analyze Results & Integrate into Reports	Incorporate Data into Reservoir Report		
2.c. Determine the hydrogeology of the Ozark Aquifer at the John Twitty Energy Center site	Correlate and Integrate into Reports		Collect and Analyze Data for Report	
2.d. Determine the baseline water chemistry of the target formation at each of the four Missouri power plant sites	Correlate and Integrate into Reports	Obtain and Analyze WaterSamples from the MO Sites		Review Literature and Provide Contour Maps for the three Other Missouri Sites.
3. Physical Suitability of the Confining Layer and Target Formation for Carbon Sequestration at the Four Missouri Power Plant Sites				
3.a. Drill and Complete a Borehole at the four Missouri power plant sites	RFP, Manage Contract, Vendor Develops Exploratory Well and Obtains Core Samples			
3.b. Determine petrologic and mineralogic characteristics of the confining layer and target formation		Reservoir Analysis of Core Samples	Geologic Analysis of Core Samples	Log & Describe Core & Cuttings
3.c. Determine permeability of the confining layer and target formation	Vendor Performs Pressure Test	Incorporate MSU Analysis into Reservoir Analysis	Analyze Results	
3.d. Determine the injection rate profile for the target formation	Vendor Performs Pump and Pressure Test	Incorporate MSU Analysis into Reservoir Analysis	Analyze Results	
3.e. Retrieve and analyze fluid samples from the target formation	Vendor Performs Pump Test	Analyze Fluid Samples, Report Data and Incorporate into Reservoir Analysis		
4. Lab-based Characterization of the Confining Layer and Target Formation				
4.a. Determine the permeability of core samples from the confining layer and target formation at the four Missouri power plant sites	Correlate and Integrate into Reports	Conduct Lab Studies and Incorporate Info Reservoir Analysis		
4.b. Determine porosity, permeability, grain size distribution, pore throat size and shape, and minerals present in representative core samples at the four Missouri power plant sites	Correlate and Integrate into Reports	Conduct Lab Studies and Incorporate Into Reservoir Analysis		

CHAPTER II - CITY UTILITIES OF SPRINGFIELD

A. BRIEF OVERVIEW OF CITY UTILITIES' ROLE

As described in Chapter I., City Utilities was the recipient of the Cooperative Agreement from the U.S. Department of Energy. Beyond its responsibilities related to the management of the project, City Utilities had primary responsibility for the following tasks:

- 1.a. Coordinate with DOE Project Officer (PO) to Prepare and Modify the Project Management Plan (PMP) and Manage the Management Team
- 1.b. Prepare and Submit NEPA Questionnaires to DOE
- 1.c. Prepare and submit Temporary Air Permit Applications to MDNR - Air Pollution Control Program
- 1.d. Explore and leverage Outside Knowledge, including review of data from other sites regarding the utility of Carbon Sequestration
- 2.a. Complete Existing Information and Provide Descriptions of General Geology at Each Site
- 2.b. Perform a 3D Surface Seismic Reflection Survey at the John Twitty Energy Center Site
- 3.a. Drill and Complete a Borehole at the Four Missouri Power Plant Sites

In addition, CU was responsible for directing vendors in their performance on the following tasks.

- 3.c. Determine Permeability of the Confining Layer and Target Formation
- 3.d. Determine the Injection Rate Profile for the Target Formation
- 3.e. Retrieve and Analyze Fluid Samples from the Target Formation

B. EXPERIMENTAL METHODS

Task 1.b Prepare and Submit NEPA Questionnaires to DOE

The Department of Energy (DOE) requires careful consideration of the potential environmental consequences of all proposed actions during the early planning stages of a project or activity that falls within the purview of the National Environmental Policy Act (NEPA) Implementing Procedures (10CFR 1021). DOE policy directs at the earliest possible stage a decision on whether such actions will require preparation of an Environmental Assessment, an Environmental Impact Statement, or a Categorical Exclusion. To comply with these requirements, an Environmental Questionnaire (NETL Form F 451.1- 1/3) must be completed for each proposed action to provide DOE with the information necessary to determine the appropriate level of NEPA review and documentation.

NEPA Questionnaires were prepared and submitted for each of the four borehole sites. These questionnaires addressed fuel consumption, air quality, water quality, solid waste generation, land disturbance and potential environmental impact. Time estimates were made for the drilling and coring operations for each borehole based on assumed rates of penetration for the projected formations to be encountered. Estimated horsepower of the equipment to be utilized and time requirements for drilling and coring operations were used to calculate projected fuel consumption and air emissions. Air quality estimates were made based on standard air emission assumptions for diesel engines.

Volume estimates were made for produced water and cuttings for each borehole based on water production rates for fluid circulation requirements of air rotary drilling and the volume of the borehole. Solid waste estimates were based on these produced water and cuttings estimates. Water quality was based on decanting and filtration of produced water from the reserve pits.

Land disturbance estimates were based on the footprint consistent with the drilling and coring equipment and systems to be used.

The submission of the NEPA Questionnaires for the boreholes resulted in modifications to the Cooperative Agreement. Modification #001 to the Cooperative Agreement was issued on April 24, 2009 for Exploratory Borehole #1 at John Twitty Energy Center. Modification #005 to the Cooperative Agreement was issued by DOE on January 12, 2012 for Exploratory Borehole # 2 at Thomas Hill Energy Center (designated in the Mod as Randolph City) and for Exploratory Borehole #3 at Iatan Generating Station (designated in the Mod at Platte City). Modification #006 to the Cooperative Agreement was issued by DOE on March 23, 2012 for Exploratory Borehole #4 at the Sioux Power Plant (designated in the Mod as Luecke Quarry) Site. These amendments stated, "This award has received a categorical exclusion (CX) for research and development lab work restricted to permitted indoor research facilities and settings. These CXs are valid for drilling at the Randolph City, Platte City, and Luecke Quarry, MO sites." Modification #007 was issued on April 6, 2012 correcting the site designations to Randolph County and Platte County.

Task 2.a. Compile Existing Information and Provide Descriptions of General Geology at Each Site

Existing topographical, physiographical, geological and hydrological data were compiled for each site and reviewed to characterize stratigraphy, geological structure, and anticipated depths of the confining layer and target formation. Specific drilling locations at, or near, each power plant site were selected in coordination with the respective electric utility company to facilitate drilling operations and to minimize impact on plant operations.

The general geological setting of each site is described in the following:

John Twitty Energy Center occupies an upland site on the Springfield Plateau in southwestern Missouri and is underlain by Mississippian-, Ordovician-, and Cambrian-age limestones, dolomites, sandstones, and shales overlying Precambrian basement rock. Strata is generally flat lying but may be modified locally by minor folding. The thickness of the basal sandstone unit (Lamotte Sandstone) varies as a result of the irregular, eroded Precambrian surface. Some historical faulting has occurred in the area, but no active faults are known to exist.

Thomas Hill Energy Center occupies an upland site on the Dissected Till Plains of north-central Missouri and is directly underlain by glacial tills and loess of Pleistocene-age deposited on Pennsylvanian-age sedimentary strata. Strata underlying the Pennsylvanian-age shales, sandstones, limestones, and coal beds consist of Mississippian-, Devonian-, Silurian-, Ordovician-, and Cambrian-age limestones, dolomites, sandstones and shales overlying Precambrian basement rock. Strata slopes gently to the northwest, but is modified locally by anticlinal structures. The thickness of the basal sandstone unit (Lamotte Sandstone) varies as a result of the irregular, eroded Precambrian surface. Some historical faulting has occurred in the area, but no active faults are known to exist.

Iatan Generating Station is located within the floodplain of the Missouri River in northwestern Missouri and is directly underlain by a thick sequence of alluvial deposits. The alluvial deposits are directly underlain by Pennsylvanian-age shales, sandstones, limestones, and coal beds which are, in turn, underlain by Mississippian-, Devonian-, Ordovician-, and Cambrian-age limestones, dolomites, sandstones, and shales overlying Precambrian basement rock. Strata slopes gently to the northwest, toward the center of the Forest City Basin. Some historical faulting has occurred in the area, but no active faults are known to exist.

Sioux Power Plant occupies a floodplain setting between the Mississippi and Missouri Rivers in eastern Missouri. Since no drilling site was available within the plant site, proper, a drilling site was selected adjacent to the Missouri River. The drilling site is directly underlain by Quaternary alluvial deposits which are, in turn, underlain by Mississippian-, Devonian-, Silurian-, Ordovician-, and Cambrian-age limestones, dolomites, sandstones, and shales overlying Precambrian basement rock. Regionally, strata slopes to the south, but may be modified locally due to the existence of anticlines, synclines and historical faulting. No active faults are known to exist in the area.

Task 2.b. Perform a 3D Seismic Reflection Survey at the John Twitty Energy Center Site

A 3D seismic reflection survey was conducted at the John Twitty Energy Center in an attempt to image the irregular Precambrian basement rock surface at the site. The seismic survey was completed successfully, but extensive karst development within the Eminence and Potosi Formations prevented clear representation of the Precambrian surface. The 3D Seismic Reflection Survey Report is provided in Appendix 2.A.

Task 3.a. Drill and Complete a Borehole at the Four Sites

JOHN TWITTY ENERGY CENTER (JTEC) SITE Exploratory Borehole #1, at the JTEC site, was designed to provide the maximum amount of geological, geophysical and hydrogeological information to determine the initial characteristics of the site to assess the feasibility of shallow carbon sequestration. In addition, the borehole was to be designed to serve as a monitoring well in the event gaseous carbon dioxide was injected as a demonstration into a future injection well to be sited nearby. Well design was intended to meet the requirements of the Wellhead Protection Program of the Missouri Department of Natural Resources for monitoring well construction.

The drilling plan involved setting conductor pipe through unconsolidated overburden. A borehole would then be advanced using air rotary techniques through the Springfield Aquifer and the Northview Shale (Ozark Aquifer confining unit), projected to be 280 feet below ground surface (BGS), in compliance with the well construction regulations of the Missouri Department of Natural Resources for Special Area “C” (Springfield, MO Area). The borehole would be calipered to determine the amount of cement required for pressure cementing of the surface casing. Surface casing, fitted with a cementing shoe and valve, would then be set and cemented to the surface using pressure cementing methods commonly referred to as the Halliburton method.

Drilling would then continue, through the surface casing, to the top of the Derby-Doerun Formation (considered the upper formation of the confining layer for carbon sequestration) projected to be 1,500 feet BGS. Upon reaching the Derby-Doerun Formation, downhole geophysical logs would then be run in the upper formations to acquire geophysical data using electrical, gamma ray and caliper logging methods.

Following geophysical logging of the upper formations, 2½" diameter continuous core would be cut from the top of the Derby-Doerun Formation to the bottom of the Davis Formation (top of the Bonneterre Formation), projected to be 1,800 feet BGS. This continuous core would then be tested to determine the characteristics of the confining layer. Upon completion of the coring of the confining layer, downhole geophysical logs would then be run to acquire geophysical data from the confining layer using electrical, gamma ray, nuclear and sonic logging methods. Upon completion of downhole geophysical logging, the cored hole in the confining layer would be pressure tested to determine the hydrogeologic characteristics of the confining layer.

Upon completion of pressure testing, the borehole would then be reamed to a diameter necessary to accommodate the setting and pressure cementing of long string casing. Long string casing would be set and pressure cemented to the surface to isolate the target formations (Bonneterre and Lamotte) from the upper formations. A cement bond log would then be run to determine the integrity of the cementing job. This cemented and logged long string casing would then allow the borehole to be utilized as a monitoring well in the event gaseous carbon dioxide was injected in a future injection well to be sited nearby.

Coring would then resume through the target formation to Precambrian basement rock, projected to be 2,100 feet BGS. This continuous core would then be tested to determine the characteristics of the target formation. Upon reaching the Precambrian surface, downhole geophysical logs would then be run to acquire geophysical data from the target formation using electrical, gamma ray, nuclear and sonic logging methods. Upon completion of downhole geophysical logging, the cored hole in the target formation also would be pressure tested to determine the hydrogeologic characteristics. A fluid sample would be obtained from the target formation for geochemical analysis.

Geological information obtained from Exploratory Borehole #1 would be used to support the application for an injection well permit for the planned demonstration injection of gaseous carbon dioxide. The borehole would then be used as a monitoring well for the demonstration injection.

2. OTHER MISSOURI SITES

Upon completion of Exploratory Borehole #1, the determination was made that further assessment work at the JTEC site would not be performed. This decision was based on finding that the concentration of Total Dissolved Solids in the formation water was well below the target of 10,000 mg/L. Therefore, a shift in the focus of the project was proposed. This shift involved a state-wide assessment of carbon sequestration feasibility rather than focusing on one site. Three other sites were identified where drilling would be undertaken to acquire geological, geophysical and hydrogeological information to determine the initial characteristics of these sites to assess the feasibility of carbon sequestration. These exploratory boreholes would not be utilized as potential monitoring wells. Also, since these additional exploratory boreholes were to be drilled in northern Missouri, the requirements to install surface casing through a confining unit (i.e. Northview Formation) do not exist. Well design was intended to meet the requirements of the Wellhead Protection Program of the Missouri Department of Natural Resources for completion of test holes.

The plan for these exploratory boreholes involved drilling through the overburden and into a minimum of 30 feet of competent bedrock. This depth was expected to be approximately 150 to 200 feet BGS. Surface casing would then be set and cemented to the surface using the tremie method. The tremie method involves running a pipe into the annulus between the wall of the borehole and the casing to total depth and withdrawing it as cement is pumped through the pipe into the annulus.

Drilling would then continue, through the surface casing, to the top of the Derby-Doerun Formation, projected to be from 2,000 to 2,800 feet BGS, depending on the location. Upon reaching the top of the Derby-Doerun Formation, 2½" diameter continuous core would be cut from the top of the Derby-Doerun Formation to Precambrian basement rock, encompassing the confining layers and target formations, projected to be from 2,700 to 3,200 feet BGS, depending on location. This continuous core would then be tested to determine the characteristics of the confining layer and target formation. Upon completion of coring of the confining layer and target formation, downhole geophysical logs would be run to acquire geophysical data from the confining layer and the target formation using electrical, gamma ray, nuclear and sonic logging methods. Upon completion of downhole geophysical logging, the cored hole in the confining layer and target formation would be pressure tested to determine the hydrogeologic characteristics. A fluid sample would be obtained from the target formation for geochemical analysis.

Once the downhole data was obtained, the exploratory borehole would be plugged and abandoned by cementing the hole using the tremie method from total depth to the surface as required by the regulations of the Wellhead Protection Program of the Missouri Department of Natural Resources.

Three sites for the above scope of work were selected at the Thomas Hill Energy Center in Randolph County, the Iatan Generating Station in Platte County and the Luecke Quarry Site. The Luecke Quarry Site is located in St. Louis County near the Sioux Power Plant Site. The quarry site was selected because there wasn't any space available for drilling within the Sioux Power Plant site. For purposes of this report, the quarry site will be referred to as the Sioux site.

C. RESULTS AND DISCUSSION

Task 3.a. Drill and Complete a Borehole at the Four Sites

1. JOHN TWITTY ENERGY CENTER (JTEC) SITE

After completing a competitive selection process, a contract was issued on April 25, 2010 to Layne Christensen Company for drilling and completion of Exploratory Borehole #1 with an option for drilling and completion of a second exploratory borehole. This contract included drilling, casing, downhole geophysical logging, coring, formation fluid sample retrieval and downhole pressure testing of the confining layer and target formation.

Following completion of the drilling site pad, access road and reserve pits, Layne mobilized drilling equipment and began drilling on May 20, 2010 as shown in Figure 2.1. Setting and cementing of conductor pipe to a depth of 24 feet BGS was completed on May 22, 2010. Difficulty was encountered in drilling in the shallow formations due to issues with karst. Circulation was lost at approximately 200 feet BGS, necessitating grouting back the hole and re-drilling. Drilling through the Springfield Aquifer and Northview Formation to a depth of 278 feet BGS and setting and cementing of surface casing (9 5/8" x 36 lb/ft, J-55, ST&C) were completed on June 8, 2010.

FIGURE 2.1- DRILLING RIG AND TENDER AT THE JTEC SITE ON MAY 21, 2010

Drilling through the Ozark Aquifer progressed slowly due to prolific groundwater production. In using air-rotary drilling equipment, without the use of foam or other additives, the amount of produced groundwater inhibited the return of drill cuttings resulting in low penetration rates. The target depth to begin coring of the confining layer of 1,455 feet was reached on June 30, 2010. Cuttings from the borehole were field logged by a geologist from the Missouri Geological Survey (MGS) of the Missouri Department of Natural Resources. Management of drill cuttings and produced water, using a three cell reserve pit system with final effluent filtration, worked well. The concentration of Total Suspended Solids in the discharged water was well below the target of 100 parts per million.

Continuous coring (2½” diameter) of the confining layer began on July 9, 2010 at 1,455 feet BGS (see Figure 2.2) and after encountering problems with seating of the coring casing, reached a depth of 1,727 feet BGS on July 23, 2010. At this point it was determined that the base of the Davis Formation (and the bottom of the confining layer) had been reached and the coring crew was released. This determination was made partially based on the cuttings log from the on-site water well drilled in 1972.

FIGURE 2.2- CORING RIG AND TENDER AT THE JTEC SITE, JULY 6, 2010

Coring of the confining layer produced continuous and competent core from the Derby-Doerun Formation (1,521-1,605 feet BGS) and Davis Formation (1,605-1,727 feet BGS). This core was field logged by a geologist from the MGS. The core was boxed, photographed and stored in an on-site, secure, climate controlled, office/storage trailer for reference and inspection by the Research Teams and Funding Partners. The core handling specialist from MGS sawed the core and distributed research samples to MSU and Missouri S&T researchers on August 3, 2010.

Open hole wire line logs of the confining layer were run in the cored hole on July 27, 2010. The logs consisted of Compensated Neutron, Compensated Density, Gamma Ray and Acoustic Televiewer.

Analysis of the data from these logs was performed by the Research Teams. The Acoustic Televiewer log revealed no fractures in the Davis Formation.

Pressure testing of the confining layer using straddle packers spaced at 20 feet was performed in the cored hole from July 28 – August 2, 2010. Preliminary results indicated the conductivity of the Davis Formation is approximately 1×10^{-11} cm/sec.

The Acoustic Televiewer Log was equipped with deviation from vertical capability. The deviation of the cored hole in the confining layer was found to be approximately 3 degrees from vertical. Due to concern that the reaming of the cored hole in the confining layer would not follow the cored hole, the decision was made to grout the cored hole back to 1,467 feet. Grouting of the cored hole was performed on August 4, 2010 with grout back to 1,459 feet. The confining layer was re-drilled to 8 ¾" diameter from 1,459 to 1,707.9 feet BGS from August 6-10, 2010.

Downhole video recording of the hole from the surface to 1,700 feet BGS was made on August 12, 2010. This downhole video recording revealed an area of solution cavities and vugs in the Eminence Formation at approximately 1,300 feet BGS.

Open hole wire line logs from 287 feet BGS (bottom of surface casing) to 1,700 BGS feet were run on August 13-15, 2010. The logging suite consisted of Temperature Log, Caliper Log, Gamma Ray Log, Resistivity Log, Spontaneous Potential Log and Sonic Log.

Review of Gamma Ray logs from the onsite water well drilled in 1972 indicated the possibility that additional confining layer lay below 1,700 feet BGS. It was decided that this additional confining layer should be cored, logged and pressure tested. Additional continuous coring from 1,707.5 to 1,787 feet BGS was performed on September 3-4, 2010. This core revealed an additional shale layer, and that the top of the target formation was at 1,780 feet BGS. Coring of this additional confining layer produced continuous and competent core 1,727 – 1,787 feet BGS. This core was field logged by a geologist from MGS. The core was boxed, photographed and stored in an on-site, secure, climate controlled, office/storage trailer for reference and inspection by the Research Teams and Funding Partners.

Open hole wire line logs of this additional confining layer were run in the cored hole on September 8, 2010. The logging suite consisted of Compensated Neutron Log, Compensated Density Log, Gamma Ray Log and Acoustic Televiewer Log. The Acoustic Televiewer Log revealed no fractures in this additional shale layer.

Pressure testing of this additional confining layer using straddle packers spaced at 20 feet was performed on September 15-16, 2010. Preliminary results indicate the conductivity of this additional shale layer is approximately 1×10^{-11} cm/sec.

The additional confining layer interval was reamed to 8¾” diameter from 1,707 to 1,780 feet BGS on September 23, 2010.

Specific sections of the additional confining layer core were selected by MSU and Missouri S&T for testing at their respective facilities. The core handling specialist from MGS sawed the core and distributed the samples to the two universities on September 23, 2010.

Open hole wire line logs in the additional confining layer from 1,600 to 1,780 feet BGS were run on September 25, 2010. The logging suite consisted of Temperature Log, Caliper Log, Gamma Ray Log, Resistivity Log, Spontaneous Potential Log and Sonic Log.

Downhole video recording of the borehole from the surface to 1,780 feet was made on September 28, 2010. This video recording confirmed a zone of solution cavities and vugs in the Eminence Formation at approximately 1,300 feet BGS. Information from this video recording was used to formulate a plan for placement of lost circulation material and cementing for the long string casing.

A meeting was held with MGS representatives to discuss the problems of cementing the long string casing in the Ozark Aquifer on October 7, 2010. A proposal was made to continue with the exploratory work in Exploratory Borehole #1; but that the borehole would not be used as a monitoring well for carbon dioxide injection and that it would be plugged prior to such carbon dioxide injection. This proposal was accepted by MGS on October 21, 2010.

Continuous coring (2½" diameter) of the target formation began on November 3, 2010 at 1,780 feet BGS. Coring was temporarily suspended at 1,876 feet BGS on November 5, 2010 in order to temporarily install a 10 gallon per minute submersible pump and obtain a representative fluid sample of the Reagan Formation, the upper portion of the target formation. After stabilized conditions were achieved, a fluid sample was obtained on November 7, 2010 for analysis by Missouri S&T.

Continuous coring of the target formation resumed on November 7, 2010 and continued to 2,186 feet BGS, approximately 40 feet into Precambrian basement rock, on November 15, 2010. The coring of the target formation produced continuous and competent core of the Reagan, Bonneterre and Lamotte Formations. This core was field logged by a geologist from MGS (see Figure 2.3). The core was boxed, photographed and stored in an on-site, secure, climate controlled, office/storage trailer for reference and inspection by the Research Teams and Funding Partners. Core samples were distributed to MSU and Missouri S&T researchers on January 4, 2011.

FIGURE 2.3- CORE INSPECTION BY MGS PERSONNEL AT THE JTEC SITE, JULY 10, 2010

Open hole wire line logs of the target formation were run in the cored hole on November 19-20, 2010. The logs consisted of Temperature/Pressure Log, Gamma Ray Log, Electric Logs, Sonic Log, Acoustic Televiewer Log, Density Log, Neutron Log and Caliper Log.

A 50 gallon per minute submersible pump was temporarily installed to obtain a representative fluid sample from the complete target formation. After stabilized conditions were achieved a fluid sample was obtained on November 23, 2010 for analysis by Missouri S&T.

Pressure testing of the target formation using straddle packers spaced at 40 feet was performed in the cored hole from November 29 to December 6, 2010. Preliminary results indicate the conductivity of the target formation ranges from 1.0×10^{-8} cm/sec to 1.0×10^{-10} cm/sec.

Fracture testing of the target formation using straddle packers spaced three feet apart was performed in the cored hole from December 8-10, 2010. The resulting data from fracture testing was analyzed by Missouri S&T. Open hole wire line logs of the target formation were again run in the cored hole on December 29 and 30, 2010 following fracture testing. These logging suites consisted of Temperature Log, Acoustic Televiewer Log and Sonic Log. The purpose of these logs was to detect any changes in downhole conditions following fracture testing.

A 10 gallon per minute submersible pump and packer assembly were temporarily installed to obtain a representative fluid sample of the Lamotte Formation, the lower portion of the target formation. After stabilized conditions were achieved, a fluid sample was obtained on January 7, 2011 for analysis by Missouri S&T.

A downhole video recording of the cored hole from 1,780 to 2,156 feet (target formation) was made on January 18, 2011.

The results of target fluid sampling from the Reagan Formation (upper portion of the target formation), target formation as a whole, and the Lamotte Sandstone (lower portion of the target formation) indicated Total Dissolved Solids of approximately 150 mg/L. This level is significantly below the 10,000 mg/L limit under the Safe Drinking Water Act for pursuit of an injection permit.

Core from the Confining Layer and Target Formation was transferred to the McCracken Core Library and Research Center (McCracken Library) of MGS on March 21, 2011.

Following determination that the JTEC site is not suitable for carbon dioxide injection, due to the low Total Dissolved Solids concentration of the target formation fluid, it was decided to plug and abandon the exploratory borehole. Plans and specifications for plugging and abandonment, in consultation with the Wellhead Protection Program, were formulated. The plan called for conversion of Exploratory Borehole #1 to an irrigation well.

With approval of the Wellhead Protection Program, the contractor plugged back Exploratory Borehole #1 from 2,186 feet BGS to approximately 1,200 feet BGS with cement using the tremie method on July 7, 2011.

Cementing was confirmed to 1,038 feet BGS. The 5½" diameter long string casing was cut at 1,002 feet BGS using an explosive charge on July 8, 2011. Casing from 1,002 feet BGS was then removed from the borehole for use at the other sites.

The resulting 1,002-foot deep Ozark Aquifer borehole will be used by City Utilities as an irrigation well for fugitive dust control as permitted by the Missouri Department of Natural Resources.

2. THOMAS HILL ENERGY CENTER SITE

After completing a competitive selection process, a contract was issued on February 13, 2012 to Layne Christensen Company for drilling and completion of Exploratory Borehole #2. This contract included drilling, casing, downhole geophysical logging, coring, formation fluid sample retrieval and downhole pressure testing of the confining layer and target formation.

Following completion of site preparation, including establishment of electrical service, wireless communications and temporary field office, drilling began on February 20, 2012.

After rotary mud drilling through glacial till; limestone was encountered at 118 feet BGS. A 9-7/8" diameter borehole was advanced to 151 feet through cherty limestone using a tri-cone bit. At this point, the borehole was reamed to 17" diameter with a surface casing point of 151 feet BGS.

Surface casing (9 5/8" x 36 #/ft, J-55, ST&C) was set and tremie cemented to the surface on February 29, 2012. Reserve pits were constructed and drilling out the cement heel in the surface casing began on March 6, 2012 using an 8¾" diameter hammer bit.

Air rotary drilling proceeded to a depth of 997 feet BGS. Vertical deviation measurements were taken at approximately 100 foot intervals with results of less than one degree deviation. Drilling cuttings from the borehole were field logged by a geologist from MGS. Management of drill cuttings and produced water, using a three cell reserve pit system with final effluent filtration, worked well. The concentration of Total Suspended Solids in the discharged water was well below the target of 100 parts per million.

Concerns were raised by the drilling contractor, at 997 feet BGS, on March 14, 2012 regarding the salinity of the produced water from the St. Peter Sandstone. Field conductivity measurement (14,450 μS/cm) indicated a high level of salinity in the produced water at that point. It was decided to convert to mud rotary drilling, thereby recirculating the drilling fluids, to minimize the potential impact of high salinity water being discharged on the surface. Drilling operations were suspended while the appropriate equipment for mud rotary drilling was obtained.

A sample of the St. Peter Sandstone water was obtained March 19, 2012 and analyzed for Total Dissolved Solids (TDS). Conductivity of the sample was measured in the laboratory and found to be 1,410 μS/cm as compared to the field measurement of 1,358 μS/cm. TDS concentration of the sample was 568 mg/L.

The observation of high salinity in the produced water may have been a temporary anomaly at that depth. However, it was decided to convert to a mud rotary drilling program for the rest of the approximately 2,100 feet of 8¾" diameter hole. When all of the required mud rotary drilling equipment was in place, drilling progressed from a depth of 997 to 1,513 feet BGS on April 14, 2012 (see Figure 2.4), when circulation was lost. At that point, drilling ceased, awaiting delivery of lost circulation materials. Lost circulation materials were introduced into the borehole with drilling resuming on April 25, 2012 and continued to a depth of 1,950 feet BGS on May 11. At this point the depth limit of the drilling rig was reached and the decision was made to demobilize the drilling rig and begin coring operations.

Figure 2.4: Drilling Rig and Mud System at the Thomas Hill site, April 4, 2012.

Following installation of temporary coring casing, continuous coring (2½" diameter) began on June 4 at a depth of 1,950 feet BGS. Precambrian basement rock was encountered at 2,530 feet BGS on June 21, 2012. Coring progressed an additional 27 feet to ensure that competent basement rock had been encountered. Coring was terminated on June 23, 2012 at a total depth of 2,577 feet. It was determined from preliminary inspection of the core that the top of the Derby-Doerun (confining layer) had been encountered above 1,950 feet. This core was field logged by a geologist from MGS. The core was boxed and stored in an on-site, secure office/storage container for reference and inspection by the Research Teams and Funding Partners. The core was photographed on site July 9-10, 2012 and transported to the McCracken Library on July 16, 2012. Core intervals were selected by the two universities on August 1, 2012 for petrological and mineralogical characterization. Core samples were cut by McCracken personnel and provided to the universities the same day.

Pump testing of the target formation was performed by MSU on July 9 - 10, 2012. The borehole was packed off at 2,330 feet BGS, at the top of the Lamotte Formation. Initial static water level was measured at 156 feet BGS. Steady state pumping at 12 gallons per minute, over 23 hours, resulted in a drawdown to 300 feet BGS.

After reaching steady state conditions, water samples were taken by Missouri S&T on July 10, 2012. Initial measurements in the field indicated a conductivity of 43,390 µS/cm. This field conductivity measurement indicates a TDS concentration of at least 25,000 mg/L. Initial Missouri S&T laboratory measurements indicated a TDS concentration of approximately 55,000 mg/L.

Following pump testing and water sampling, downhole geophysical logs were run on July 18 -19, 2012 from 1,950 feet BGS to total depth (TD) of 2,577 feet BGS. These logging suites consisted of Acoustic Televiewer Log, Temperature Log, Caliper Log, Pressure Log, Gamma Ray Log, Spontaneous Potential Log, Resistivity Log, Compensated Neutron Log, and Compensated Density Log.

Downhole pressure testing was placed on hold until drilling and coring at the Iatan and Sioux sites could be completed.

An attempt was made to remove the temporary coring casing for future use at the Sioux site on July 23-24, 2012. The temporary casing was found to be stuck, but a hammer bit was used to free the casing, with the casing removal accomplished August 23-24, 2012.

The site was cleaned up and temporarily secured on August 30, 2012.

Gamma Ray and Electric Logs were attempted from 150 to 1,950 feet BGS by MGS on November 8, 2012. An obstruction in the hole prevented their logging tools from traveling below 1,138 feet BGS. Consequently, no data was obtained at this site.

Following completion of work at the Iatan and Sioux sites, activity resumed at the Thomas Hill site. Beginning July 8, 2013 an attempt to open the hole by washing in BQ tubing was undertaken. This attempt was unsuccessful in opening the hole below 1,280 feet BGS. A mud rotary drilling rig was set on the hole and the drilled hole was opened to the top of the cored interval at 1,970 feet BGS. A drill string consisting of 3” and 3½” drill rods was run in to open the cored interval down to Precambrian basement rock. Problems were encountered with the back pressure in the small drill rods - rendering them unusable. Temporary coring casing was the run in the drilled hole and HQ and NQ coring rods were run in and successfully opened the cored interval to Precambrian basement rock. The material blocking the drilled and cored intervals consisted of sloughed shale and fractured rock from the upper formations.

After removal of the temporary casing, a straddle packer string was run in the borehole to perform pressure testing in the cored interval on August 22, 2013. Upon entry in the cored interval, the packer string would not continue downward due to re-filling of the cored interval by sloughed material from the upper formations. The decision was made to abandon pressure testing and plug the borehole.

The borehole was plugged with cement using the tremie method from the top of the cored interval, 1,950 feet BGS, to the surface on September 9-10, 2013. The site was restored and released to the Thomas Hill Energy Center on September 11, 2013.

3. IATAN GENERATING STATION

After completing a competitive selection process, a contract was awarded to Layne Christensen Company of St. Louis, Missouri (Layne) on September 24, 2012 for drilling and completion of Exploratory Borehole #3. This contract included drilling, casing, downhole geophysical logging, coring, formation fluid sample retrieval, and downhole pressure testing of the confining layer and target formation.

The contractor mobilized an “Advance Casing While Drilling Rig,” also known as a “Barber Rig,” to Iatan on November 28, 2012 to set 16’’ conductor pipe through the alluvium to expedite drilling of Exploratory Borehole #3 (see Figure 2.5). The rig installed 94 feet of conductor pipe to bedrock, completing installation on December 1, 2012.

FIGURE 2.5- ADVANCE CASING WHILE DRILLING SYSTEM AT THE IATAN SITE, NOVEMBER 30, 2012

Site preparation and mobilization of the deep drilling rig and supporting equipment was completed during the last week of December 2012. Drilling of Exploratory Borehole #3 commenced on January 8, 2013. A 14-7/8” diameter borehole was air rotary drilled from a depth of 99 feet BGS (bottom of previously set conductor pipe) to 148 feet BGS. Then, 150 feet of 10¾” diameter x 0.375“ wall, welded joint, surface casing was installed and cemented to within three feet of the surface on January 10, 2013 using the tremie method.

Air rotary drilling of an 8¾” diameter borehole, using a downhole air hammer, began on January 11, 2013. Drilling progressed fairly well with some delays due to freezing weather and hydraulic hose problems. Vertical deviation measurements were taken at approximately 100 foot intervals with results of less than one degree deviation. Drilling cuttings from the borehole were field logged by a geologist from MGS. Management of drill cuttings and produced water worked well using a three cell reserve pit system with final effluent filtration (see Figure 2.6). The concentration of Total Suspended Solids in the discharged water was well below the target of 100 parts per million.

FIGURE 2.6- DRILLING RIG AND CUTTINGS MANAGEMENT AT THE IATAN SITE, MARCH 2, 2013.

As drilling depth increased, produced water also increased to the point that the downhole hammer became ineffective at 1,322 feet BGS on January 22, 2013. The bit was changed to an 8½" diameter tri-cone and air rotary drilling continued. Drilling progressed well with some delays due to mechanical problems with the air pressure booster and heavy snow on a few days. On February 28, 2013, the tri-cone bit disintegrated at 2,088 feet BGS.

The drill string was tripped out and a fishing magnet was run into the borehole to retrieve the pieces of the tri-cone bit. In two attempts to "fish" the pieces of bit from the borehole, sloughing of shale up hole from the Mississippian and Devonian Series presented a risk of "sticking" the drill string in the hole. This sloughing problem was exacerbated by the high air pressure required to lift the column of water in the borehole.

An initial decision was made to run in temporary casing and continue drilling operations using "slimhole" equipment to overcome the sloughing problem. The casing to be used was to come from coring casing still in place in Exploratory Borehole #4 at the Sioux site. Adequate casing was removed from Exploratory Borehole #4 to enable continuation of the drilling at the Iatan site. However, after consideration of the risks involved with the shale sloughing problem, potential drill string failure using slimhole methods, project schedule and remaining project budget, the decision was made to abandon drilling of Exploratory Borehole #3.

Cuttings collected from Borehole #3 were transferred to the McCracken Core Library for processing and storage.

Plugging and abandonment of Exploratory Borehole #3 was completed on April 25, 2013 by cementing the 8½" drilled hole from TD of 2,088 feet BGS to the surface. The plugging and abandonment operation was delayed for several days due to wet weather which made the site inaccessible to cement trucks.

Equipment demobilization and site restoration, with final inspection by Kansas City Power and Light personnel, was completed on May 2, 2013.

4. SIOUX POWER PLANT SITE

After completing a competitive selection process, a contract was awarded to Layne Christensen Company on June 28, 2012 for drilling and completion of Exploratory Borehole #4. This contract included drilling, casing, downhole geophysical logging, coring, formation fluid sample retrieval, and downhole pressure testing of the confining layer and target formation.

Drilling of Exploratory Borehole #4 began on October 3, 2012. Bedrock was encountered at 90 feet BGS. However, after drilling to 111 feet BGS, there arose concern regarding the competency of the St. Louis Formation with regard to cementing of surface casing. The borehole was subsequently reamed and 16" conductor pipe was set and cemented to 92 feet BGS.

Attempts to drill beyond the bottom of the conductor pipe were met with problems of encroaching fine materials, necessitating pressure grouting just below the conductor pipe. An 8¾" pilot hole was then drilled beyond the bottom of the conductor pipe. This pilot hole encountered lost circulation problems early, requiring the application of lost circulation materials. Drilling conditions improved, and the pilot hole was advanced to 203 feet BGS on October 14, 2012 (see Figure 2.7).

The bottom of the St. Louis Formation was determined to be at 135 feet BGS. The pilot hole was reamed to 15" diameter down to 200 feet BGS, and surface casing (9 5/8" x 36 #/ft, J-55, ST&C) was run in and cemented on October 25, 2012 (see Figure 2.7). Approximately 65 feet of the surface casing was cemented into the Warsaw Formation.

FIGURE 2.7- DRILLING RIG AND TENDER AT THE SIOUX SITE, OCTOBER 13, 2012.

A Blowout Preventer was installed on the surface casing and drilling of an 8¾" borehole using an air rotary hammer began on October 27, 2012. Good drilling progress was made with depth reaching 988 feet BGS on October 31, 2012. Vertical deviation measurements were taken at approximately 100 foot intervals with results of less than one degree deviation. Drilling cuttings from the borehole were field logged by a geologist from MGS.

At this point drilling operations were converted to mud rotary drilling as a safety precaution due to the proximity of Laclede Gas Company's underground natural gas storage facility.

Mud rotary drilling began on November 6, 2012. Drilling for the next 1,400 feet progressed well, averaging 80 feet per day. No problems involving the natural gas storage facility were encountered. On December 8, 2012, lost circulation problems were encountered at 2,500 feet BGS in the Eminence Formation. Several applications of lost circulation materials did not improve the situation. On December 9, 2012, it was decided to terminate mud rotary drilling operations at 2,514 feet BGS and begin coring.

Temporary coring casing was run in and the deep drilling rig was rigged down and prepared for mobilization to Iatan.

After rigging up and running in casings and core rods, the contractor was able to cut 10 feet of core (see Figure 2.8) before suspending operations for the Christmas holidays. Coring was resumed on January 3, 2013 at 2,525 feet BGS. Coring progressed well with few problems. The top of the Lamotte Sandstone was encountered at a depth of 3,480 feet BGS.

FIGURE 2.8- CORE RETRIEVAL AT THE SIOUX SITE, JANUARY 5, 2013

On January 28, 2013, at 3,625 feet BGS, the coring rig reached its torque and pull back capacity. At this point, the coring operation had not yet reached Precambrian basement rock. Consideration was given to continuing coring to Precambrian using smaller diameter downhole coring equipment. However, it was decided that coring activities would be terminated since coring had already increased from a planned 370 feet to 1,100 feet, significantly impacting the costs of Exploratory Borehole #4. Core and cuttings from the borehole were transported to the McCracken Core Library for photography, storage and further analysis. Core samples were selected, cut and distributed to the two universities for petrological and mineralogical characterization.

Downhole geophysical logging and pressure testing were placed on hold until drilling and coring of Exploratory Borehole #3 at Iatan Generating Station was completed.

The temporary casing was partially removed. The casing parted during pulling and 500 feet remained in the hole from about 2,000 feet to 2,500 feet BGS. The Wellhead Protection Program was advised of this condition and a variance for plugging and abandonment was granted.

On May 13, 2013, an attempt was made to perform downhole geophysical logging of Borehole #4. Upon running in the first tool, an obstruction was encountered at approximately 800 feet BGS. Downhole video recording indicated a highly fractured zone at this depth and a piece of rock bridging the borehole. The decision was made to drill out the bridge and attempt to open the hole to TD for pressure testing.

On June 6, 2013, the contractor rigged up a mud rotary drilling rig and tripped in, rotating without mud circulation to 930 feet BGS. Without mud circulation, the drill string was at risk of hanging up at this depth. The driller decided to trip out and found the bit to be plugged with shale. A second downhole video of the borehole found significant voids at 823 feet BGS and the hole bridged at 835 feet BGS.

It was determined that the downhole conditions posed a significant risk to the drill string and any packers that would be run in for pressure testing. The decision was made to abandon plans for pressure testing of Borehole #4 due to the risk of losing downhole equipment. A plan was submitted to the Wellhead Protection Program of the Missouri Department of Natural Resources to plug and abandon Borehole #4 from 900 feet BGS to the surface. On June 12, 2013 the contractor ran in BQ tubing for use as a tremie to 900 feet BGS, but could not advance any further into the borehole.

Following discussions with the Wellhead Protection Program, a revised plugging and abandonment plan was submitted which called for a potential sacrificial drill string to be employed to rotary mud drill to the top of the orphan casing in the hole at 2,000 feet BGS and then plug back to the surface with cement through the drill string. It was recognized that there was a potential of “sticking” the drill string in the borehole during this operation.

Upon receipt of concurrence regarding the revised plugging and abandonment plan from the Wellhead Protection Program, the contractor pulled the 900 feet of BQ tubing but was not able to provide a sacrificial drill string. On June 24, 2013, mud rotary reaming commenced using a good drill string.

Reaming was advanced to 2,000 feet BGS, drilling mud circulated, and the drill string tripped out. Cementing of the borehole was undertaken in stages, using the tremie method, and was completed to the surface on July 1, 2013.

The site was restored and closed on July 18, 2013.

D. CONCLUSIONS FOR EACH SITE AND RECOMMENDATIONS

1. JOHN TWITTY ENERGY CENTER SITE

The drilling and completion plan for Exploratory Borehole #1 was accomplished as planned except for cementing of the long string casing. Rotary air drilling to the top of the confining layer was accomplished without unforeseen difficulty. Core was cut and retrieved from the confining layer and target formation producing a continuous physical specimen for laboratory analysis and research and a public record in the

MGS McCracken Core Library. The planned downhole geophysical logs were run with clear data retrieved and recorded for analysis by the Research Teams. Discrete fluid samples were retrieved from various zones of the target formation. Pump tests of the various zones of the target formation were conducted. Pressure testing of the confining layer and pressure/fracture testing of the target formation was conducted in zones of interest.

Cementing of the long string casing was not successful, due to fractures and solution cavities predominantly in the Eminence Formation. The Potosi Formation also has similar fracture and solution cavities, but to a lesser extent. It is these fractures and solution cavities that make the Ozark Aquifer very prolific, but present challenges in drilling though this zone. The primary challenge is lost circulation of drilling fluids and therefore loss of cement in these formations. The knowledge gained from this experience indicates that a change in future drilling and completion plans would be required for these formations. These changes could involve downhole video inspection after drilling through these formations and, from the information obtained, the application of lost circulation materials and cement plug back of these formations and re-drilling.

2. THOMAS HILL ENERGY CENTER SITE

The drilling and completion plan for Exploratory Borehole #2 was accomplished as planned except for pressure testing of the confining layer and pressure/fracture testing of the target formation. Rotary air and rotary mud drilling to the top of the confining layer was accomplished without unforeseen difficulty except for lost circulation problems in the Eminence Formation. Core was cut and retrieved from the confining layer and target formation producing a continuous physical specimen for laboratory analysis and research and a public record in the MGS McCracken Core Library. To enable analysis by the Research Teams, downhole geophysical logs were run with clear data retrieved and recorded; a discrete fluid sample was retrieved from the target formation; and pump testing of the Lamotte Sandstone was conducted.

The problem of lost circulation in the Eminence formation was similar to the problems experienced with Exploratory Borehole #1. At this site the problem was more acute since that section of the drilled hole was being drilled with mud rotary methods necessitating the circulation of drilling mud to the surface. The knowledge gained from this experience indicates that a change in future drilling and completion plans would be required for this formation. This change would involve having lost circulation materials on hand for cement plug back of this formation and re-drilling.

The problem of abandonment of pressure testing of the confining layer and the pressure/fracture testing of the target formation was due to swelling and caving in the drilled hole above the confining layer. This problem resulted from holding the drilled borehole open for a period of ten months while drilling/coring was pursued at the Sioux and Iatan sites. Pressure testing could have been successfully completed if such testing had been performed while the temporary coring casing was in place. Future drilling and completion plans should provide for all downhole logging and pressure testing in the cored interval to be performed while the temporary coring casing is in place.

3. IATAN GENERATING STATION

The drilling and completion plan for Exploratory Borehole #3 was not accomplished as planned due to the swelling and sloughing of the borehole in the upper shale formations before the rotary air drilling operation reached the confining layer. The risk of sticking the drill string necessitated the abandonment of drilling operations. Therefore no data was obtained, and as a result no conclusions can be drawn regarding the potential of carbon sequestration at this site.

The knowledge gained regarding the swelling and sloughing shale in the upper formations would necessitate a change in future drilling and completion plans. This change would involve setting and cementing of an intermediate casing string through these formations. This intermediate casing would then allow air rotary drilling to the top of the confining layer without the risk of loss of the drill string and the borehole.

4. SIOUX POWER PLANT SITE

The drilling and completion plan for Exploratory Borehole #4 was accomplished as planned except for completion of coring, downhole geophysical logging of the confining layer and target formation, pressure testing of the confining layer, and pressure/fracture testing of the target formation. Difficulty was experienced in setting the conductor pipe and surface casing. Rotary air and rotary mud drilling to the top of the confining layer was accomplished without unforeseen difficulty except for lost circulation problems in the Eminence Formation. The lost circulation problems in the Eminence Formation necessitated commencement of coring operations earlier than planned. Core was cut and retrieved from the confining layer and target formation producing a continuous physical specimen for laboratory analysis and research and a public record in the MGS McCracken Core Library. To enable analysis by the Research Teams, a fluid sample was retrieved from the total target formation, and pump testing of the total target formation conducted.

The problem of drilling to set the conductor pipe and surface casing was due to the presence of Missouri River alluvium at the drilling site. The knowledge gained from this experience indicates that a change in future drilling and completion plans would be required for this formation. This change would involve using “advancing casing while drilling” techniques to set a conductor pipe to the top of competent bedrock, then drilling into bedrock to obtain an adequate depth for surface casing.

The problem of lost circulation in the Eminence Formation was similar to those experienced with Exploratory Boreholes #1 and #2. At this site the problem was acute since that section of the drilled hole was being drilled with mud rotary methods necessitating the circulation of drilling mud to the surface. The knowledge gained from this experience indicates that a change in future drilling and completion plans would be required for this formation. This change would involve having lost circulation materials on hand for cement plug back of this formation and re-drilling.

The problem of being unable to core the complete target formation and reach Precambrian basement rock was due to the Lamotte Sandstone being thicker and extending to a greater depth than anticipated. The knowledge gained from this experience indicates that a change in future drilling and completion plans would be required for this formation. This change would involve having lost circulation materials on hand for cement plug back of this formation and re-drilling. Also, this change would involve specifying coring equipment with adequate pull back and torque to handle the additional depth.

The problem of abandonment of downhole geophysical logging of the confining layer and target formation, pressure testing of the confining layer, and pressure/fracture testing of the target formation was due to swelling and caving of the drilled hole above. This problem resulted from holding the drilled borehole open for a period of four months. The downhole geophysical logging and pressure testing could have been successfully completed if such testing had been performed while the temporary coring casing was in place. Future drilling and completion plans should provide for all downhole logging and pressure testing in the cored interval be performed while the temporary coring casing is in place.

APPENDIX 2A. 3D SIESMIC REFLECTION SURVEY FINAL REPORT

Geophysical Services
Proposed Carbon Sequestration Site
Southwest Power Station

Springfield, Missouri

for

City Utilities of Springfield

May 3, 2011

GeoEngineers

3050 South Delaware
Springfield, Missouri 65804
417.831.9700

GeoEngineers
Earth Science + Technology

GEOENGINEERS

3050 South Delaware
Springfield, MO 65804
417.831.9700

May 3, 2011

City Utilities of Springfield
P.O. Box 551
Springfield, Missouri 65801

Attention: Mr. Dave Fraley, PhD

Subject: Report-Geophysical Exploration Services
Proposed Carbon Sequestration Site
Southwest Power Station
Springfield, Missouri
File No. 15723-001-01

Dear Dave:

We are pleased to present our report titled “Geophysical Exploration Services, Proposed Carbon Sequestration Site, Southwest Power Station, Springfield, Missouri.” Our services were undertaken at your request to characterize the subsurface conditions in the vicinity of the above-referenced project site.

If you have any questions concerning this report, or any other aspect of the project, please contact us.

Sincerely,
GeoEngineers, Inc.

Neil L. Anderson, PhD
Senior Geophysicist

Jonathan L. Robison, PE
Associate

NLA:JLR:kjb

Geophysical Services
Proposed Carbon Sequestration Site
Southwest Power Station

Springfield, Missouri

File No. 15723-001-01

May 3, 2011

Prepared for:

City Utilities of Springfield
P.O. Box 551
Springfield, Missouri 65801

Attention: Mr. Dave Fraley, PhD

Prepared by:

GeoEngineers, Inc.
3050 South Delaware
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Jonathan L. Robison, PE
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GeoEngineers

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APPENDICES

1.0 INTRODUCTION

This draft report summarizes the geophysical exploration services completed by GeoEngineers, Inc. (GeoEngineers), to evaluate the subsurface conditions at the proposed carbon sequestration project site at the City Utilities of Springfield (CU) Southwest Power Station in Springfield, Missouri. The location of the site is noted on the attached Vicinity Map, Figure 1. This report was completed in general accordance with the terms in our contract dated June 2009. Our services were authorized under purchase order CU-0000038388 by Mr. John Penrose of CU, on June 15, 2009.

This project is part of a feasibility study for a proposed carbon sequestration plant that would inject carbon dioxide gas generated by coal-fired electricity production into the subsurface. We understand that, if the results of the feasibility studies are positive, a small pilot plant will inject a limited amount of food-grade carbon dioxide, the results of that injection will be further studied and a recommendation made whether to move ahead with the project.

2.0 SCOPE OF SERVICES

Our scope of services was to evaluate the subsurface, using three-dimensional (3D) reflective seismic geophysical techniques. Of particular interest to the project team was the Bonneterre Formation and Lamotte Sandstone reported at depths of between 1,795 and 2,125 feet, and the overlying Derby/Doe Run- Davis confining layer that is noted at depths of between 1,545 feet and 1,795 feet. The Bonneterre and Lamotte formations are the target zone for carbon dioxide injection. Full fold data was desired in the 0.5 mile by 0.5 mile primary target area. An associated area of secondary interest is 0.8 mile by 0.8 mile, inclusive of the primary target area.

Specifically, our scope of services included the following:

1. Reviewed available project and site information and develop final instrumentation layout plan for acquiring the geophysical data.
2. Surveyed instrumentation and energy source locations and layout equipment.
3. Acquired geophysical data using Seistronix's advanced, high-resolution 24-bit EX-6 high-resolution exploration seismographs, matched with six element SM24 geophones.
4. Processed geophysical data using a Linux system with current capacity at a billion traces and Tsunami's Curved Ray Kirchhoff PreStack Time and Depth Migrations.
5. Interpreted geophysical data using Kingdom Suite 2D/3D reflection seismic interpretation/modeling software.
6. Re-processed geophysical data following completion of deep borehole.
7. Prepared this report for review by CU.

3.0 SITE DESCRIPTION

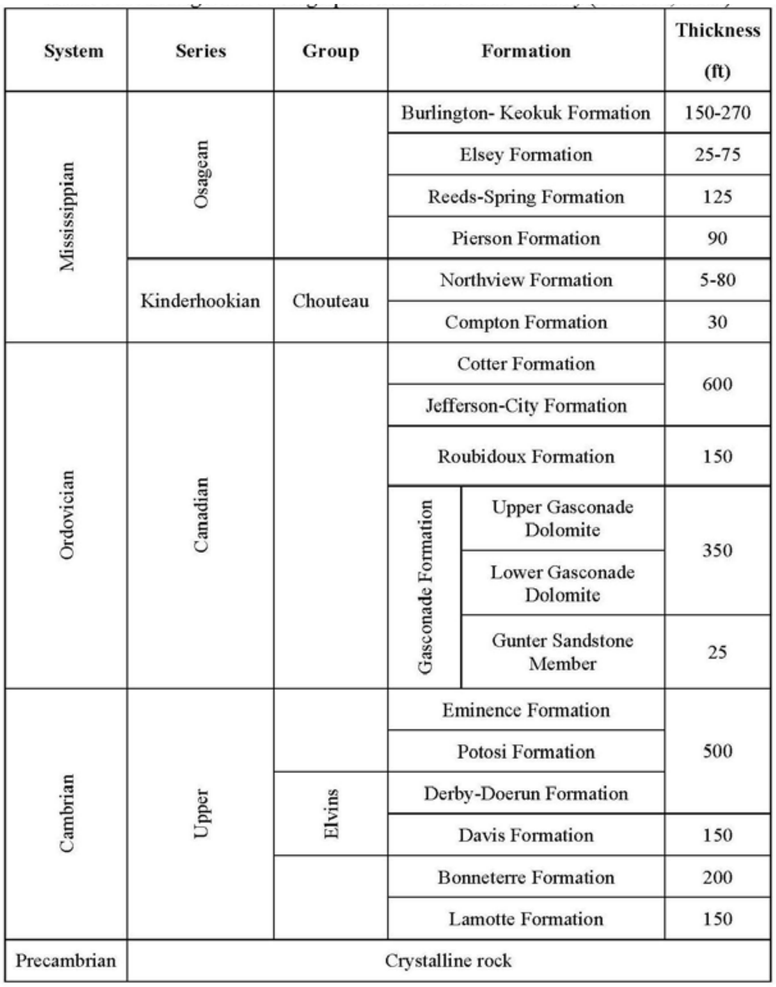
3.1 Surface Conditions

The roughly 300 Acre site is located in Southern Greene County. The land usage ranges from heavily developed to pasture and wooded areas with the CU Southwest Power Station and associated facilities in the northwest corner of the site, fly ash landfill and ponds in the center of the site, and undeveloped pasture and timber land in the southern and eastern portions of the site. The land surface is generally rolling in topography and generally slopes gently from the north to the south with the exception of steep slopes in the vicinity of the ash landfill and the west bank of Wilson's Creek, which flows near the southeast corner of the site.

3.2 Geological Conditions

3.2.1 Regional Geologic Setting

The Missouri Carbon Sequestration Project is located in the Springfield Plateau Sub-province of the Ozark Plateau Physiographic Province. The bedrock surface of the Springfield Plateau generally consists of thick Mississippian-age limestones and cherty limestones above Ordovician and Cambrian-aged strata. Bedrock generally dips gently toward the west with minor folding and faulting. Most of the area faults have less than 50 feet of displacement. The predominantly limestone strata of the area has been extensively weathered, and the irregular bedrock surface is hidden below a mantling of cherty clay residuum with thicknesses varying from a few to over 40 feet.



System	Series	Group	Formation		Thickness (ft)
Mississippian	Osagean		Burlington- Keokuk Formation		150-270
			Elsey Formation		25-75
			Reeds-Spring Formation		125
			Pierson Formation		90
	Kinderhookian	Chouteau	Northview Formation		5-80
			Compton Formation		30
Ordovician	Canadian		Cotter Formation		600
			Jefferson-City Formation		
			Roubidoux Formation		150
			Gasconade Formation	Upper Gasconade Dolomite	350
				Lower Gasconade Dolomite	
				Gunter Sandstone Member	25
Cambrian	Upper		Eminence Formation		500
			Potosi Formation		
		Elvins	Derby-Doerun Formation		
			Davis Formation		150
			Bonneterre Formation		200
			Lamotte Formation		150
Precambrian	Crystalline rock				

Table 3.1- Stratigraphic Units in Greene County, Missouri, Emmett, et. al., 1978

3.2.2 Local Surficial Geology

Geologic mapping of the Springfield 1 degree by 2 degrees quadrangle indicates that the project area is located in an area immediately underlain by Mississippian-aged Burlington-Keokuk limestone (Middendorf and others, 1987). The Burlington-Keokuk is composed of nearly pure calcium carbonate formed from the deposition of crinoid fragments. Formation thickness is highly variable due to weathering but can reach a maximum of 200 feet. Joints in the limestone influence both surface and subsurface drainage and have caused the bedrock surface to be weathered into cutters and pinnacles, commonly with 10-15 feet of relief. The clay residuum in the area of southwest Springfield is mapped as cherty clay solution residuum consisting of clay loam to silty clay loam containing subangular to angular fragments of chert up to one foot in diameter as individual clasts and relict chert layers (Whitfield and others, 1993).

3.2.3 Cambrian Stratigraphy

The crystalline Precambrian basement rocks of southwest Missouri are generally overlain by thick sequences of dolomites and limestones of Cambrian, Ordovician, and Mississippian age containing relatively thin layers or lenses of sandstone and shale. The project's primary focus is the basal unit of the Cambrian and Ordovician rocks, the Late Cambrian Lamotte Sandstone, which rests unconformably atop the Precambrian basement, which formed an uneven landscape with low relief prior to and during deposition of the Lamotte. The Lamotte Sandstone is a well-sorted quartz sandstone and is arkosic and conglomeratic at its base and contains some dolomitic and shaley lenses. The Lamotte grades upward into the Cambrian-aged Bonneterre Dolomite.

3.2.3 Exploratory Borehole Results

An exploratory/monitoring borehole (Exploratory Well #1) was drilled on site in 2010, after the completion of our fieldwork. The stratigraphic sequence as logged by the Missouri Department of Natural Resources (MDNR) geologist Jeff Crews is noted in Table 3.2 below.

TABLE 3.2: FORMATION TOPS FOR EXPLORATORY WELL #1 (ELEVATION 1236 FEET ASL)

Top Formation	Depth	Elevation	Thickness
Bottom Surface Casing	276	960	N/A
Cotter	274	962	35
Swan Creek (Cotter)	309	927	6
Cotter	315	921	101
Jefferson City	416	820	200
Roubidoux	616	620	144
Upper Gasconade	760	476	90
Lower Gasconade	850	386	270
Gunter	1120	116	25
Eminence	1145	91	360
Potosi	1505	-269	16
Derby/Doerun	1521	-285	80
Davis	1601	-365	179
Bonneterre (Reagan)	1780	-544	76
Lamotte	1988	-752	159
Pre-Cambrian	2147	-911	

The data from the exploratory boring was used to provide ground-truth for our geophysical interpretation. Following the drilling, downhole video was acquired which identified significant voids and fractures throughout the subsurface to depths of over 1,300 feet below ground surface (bgs). An example of one of the voids in the subsurface is shown below in Photograph 3.1, taken at a depth of 1,356.7 feet bgs, perpendicular to the boring.

Photograph 3.1- Exploratory Well #1 at 1,356.7 feet bgs

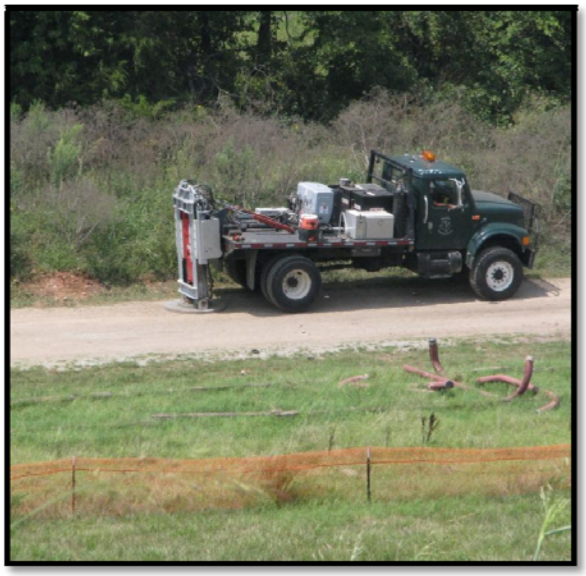
4.0 DATA ACQUISITION AND PROCESSING

In general, the data was acquired and processed in accordance with the procedures outlined in our proposal and contract dated June 2009. Ultimately, the processed data acquired proved to be of mediocre quality. We believe the poorer-than-anticipated data was likely a result of extensive fracturing and solutioning of the subsurface at great depth. We had anticipated extensive karst development in the formations near the surface, but unfortunately karst features extend to depths of greater than 1,300 feet.

4.1 Acquisition

Beginning July 28 and ending August 7, 2009, CJW Transportation Engineers (CJW), surveying sub-consultant, surveyed eleven source lines and five receiver lines at the locations indicated in the attached Site Plan, Figure 2. Each point illustrated on the Site Plan represents the location of either a geophone receiver (East-West lines) or a seismic source (North-South lines).

Beginning August 6 and ending August 9, 2009, Basin Geophysical (Basin), geophysical data acquisition subcontractor, installed receiver lines at the surveyed locations and performed the geophysical survey. Basin employed Seistronix high-resolution 24-bit EX-6 exploration seismographs, matched with six element SM24 geophones to receive the seismic energy created by their United Service Alliance's "XLR8" (Accelerate) energy source. The XLR8 unit was mounted on a 23,000-lb. International



Photograph 4.1- Basin XLR8 Acoustic Source

4800 4WD truck (Photograph 4.1). The 1,450 lb. hammer is accelerated by compressed nitrogen and generates over 500,000 ft/lbs of energy per shot. In total, Basin Geophysical acquired a total of 3,032 individual shot records.

4.2 Processing

Following acquisition of the data, the electronic files were shipped to Hardin International Processing (Hardin) in Plano, Texas. Hardin used a 34-step procedure to process the data. Their work report is attached as Appendix A. The ultimate processing report is the result of multiple iterations and re-processing, as the mediocre quality of the data led the processing team to try numerous techniques to enhance their product.

5.0 DATA INTERPRETATION

The 3-D reflection seismic data acquired at the City Utilities Carbon Sequestration Project site were interpreted manually and by using the automated Kingdom Suite 2D/3D reflection seismic interpretation software. The seismic interpretations were constrained using proximal borehole control (specifically, the stratigraphic sequence in the Exploratory Well #1 as identified by MDNR geologist Jeff Crew; Section 5.2.1 of this report) and interpreted Exploratory Well #1 check shot survey control provided by COLOG (Table 3.1).

5.1 Summary of Deliverables

A suite of representative extracted 2-D profiles are attached as Appendix B. A suite of nine time-structural and isochronous (time-thickness) maps are attached as Appendix C. The time-structure maps are indicative of real and/or apparent structure at the top of each mapped geologic horizon. The isochronous maps are indicative of real and/or apparent variations in the thickness of the mapped geologic units. A map depicting orientation of interpreted faults and other features of significance is presented below as Figure 5.1.

5.2 Reliability of Deliverables

5.2.1 Stratigraphic Sequence

The stratigraphic sequence encountered by Exploratory Well #1 (as identified by MDNR geologist Jeff Crews) was used to constrain the interpretation of the seismic data. The sequence in Exploratory Well #1 is noted in Table 3.1.

5.2.2 Check Shot Survey Control

The exploratory well #1 check shot survey data provided COLOG (Table 2) to constrain the interpretation of the seismic data. As noted in Table 5.1, COLOG was not able to acquire check shot control below a depth of 1580 and at numerous stations at depths above 1580, probably because the downgoing acoustic energy generated by the surface source was significantly attenuated as it passed through the extensively karsted shallow subsurface.

TABLE 5.1: CHECK SHOT SURVEY DATA

Station	Travel Time (seconds)	Velocity (feet/second)
270	Not Picked	--
293	0.01641	17910
311	Not Picked	--
345	0.03048	11344
400	0.02679	14956
450	0.02847	15827
505	Not Picked	--
530	0.03282	16164
566	Not Picked	--
605	Not Picked	--
680	Not Picked	--
750	Not Picked	--
800	Not Picked	--
890	Not Picked	--
1010	0.06000	16838
1070	Not Picked	--
1120	0.06655	16833
1145	0.06857	16702
1196	Not Picked	--
1348	Not Picked	--
1383	0.08103	17070
1438	Not Picked	--
1480	0.08606	17199
1512	Not Picked	--
1530	Not Picked	--
1580	0.09091	17382
1610	Not Picked	--
1655	Not Picked	--

The check shot survey data of Table 5.1 is not considered to be highly reliable for the following reasons:

1. COLOG was not able to acquire check shot survey travel time data at numerous subsurface stations (Table 5.1; depths for which travel times were not picked) because the downgoing acoustic energy generated by the surface source was significantly attenuated as it passed

through karsted rock. As a consequence, check shot survey control is not available at depths below 1580 ft, or at many depths above 1580 ft.

2. The reliability of the check shot survey data is highly suspect because of geologically unjustifiable inconsistencies. For example, downgoing acoustic energy is interpreted as arriving at stations 400 and 450 before arriving at station 345 (Table 5.1). We believe COLOG interpreted the check shot survey data to the best of their ability. The noted "inconsistency" is not an "error", rather it is an indication of just how difficult it was to acquire interpretable acoustic data at the study site.
3. The acoustic energy generated by the check shot survey source propagated through strata (especially in the shallow subsurface) that were extensively grouted and hence higher velocity than the non-grouted strata that were present where and when the 3-D reflection seismic data were recorded. Hence, check shot survey velocities are almost certainly high, relative to the actual velocity of undisturbed rock and soil.

5.2.3 Polarity of Identified Horizons

Three representative 2-D in-line reflection seismic profiles are attached as Appendix B. Each of the interpreted geologic horizons was assigned a polarity (peak or trough). Horizons across which increases in velocity/density are expected (based on lithologic descriptions) are correlated as peaks. Horizons across which deceases in velocity/density are expected are correlated as troughs. Horizons which could be confidently assigned a peak or trough were assigned either a peak or trough depending upon predicted arrival times.

Because of mediocre seismic data quality and lack of reliable check shot survey control, it was not possible to identify any reflector with a high degree of confidence. Nor was it possible to correlate any of the interpreted reflectors by simply following a specific peak or a specific trough across the entirety of the 3-D data set. In multiple places where data quality was suspect, trends (isochronous values mostly) were honored. In such places, geologic "picks" (interpreted arrival time of the reflection from a specific geologic horizon) may correspond to neither a peak nor a trough. Thorough analyses of the 3-D seismic data indicated that these multiple "picking" inconsistencies could not be attributable to any identifiable pattern of structural deformation. Rather, they were attributable to variable (poor to good) data quality.

5.3 Interpretation of the 3-D Data Set:

Because of mediocre seismic data quality and lack of reliable check shot survey control, it was not possible to identify any of the interpreted reflector with a high degree of confidence. Nor was it possible to correlate any of the interpreted reflectors by simply following a specific peak or a specific trough across the entirety of the 3-D data set. The interpretations presented herein are no more reliable than the check shot survey data or the mediocre quality 3-D data themselves.

5.3.1 Stratigraphic Interpretations

Analysis of the suite of contoured isochronous (time thickness) maps indicates that the time thickness of the Lamotte (Top Lamotte/TopPrecambrian; as interpreted) and the time thicknesses of the Top Bonneterre/Top Lamotte, Top Davis/Top Bonneterre, and Top Eminence/Top Davis intervals vary by up to 3 ms. It is unlikely that the time thicknesses of these units (particularly the latter three) actually changes so significantly in the study area. Rather, these time thickness variations are attributed to the quality of the seismic data, especially around the periphery of the study area where fold is lowest.

5.3.4 Structural Interpretations

Analysis of the suite of contoured time-structure maps indicates that time structure at the tops of the Precambrian, Lamotte, Bonneterre, Davis and Eminence varies by up to 24 ms (Appendix B). We do not believe that this time-structural relief is caused by "real" structure at these geologic levels. Rather, we believe that most of this interpreted time-structural relief can be attributed to shallow karst-related velocity variations. (These variations could also be due, at least in part, to the poor quality of the seismic data.)

Consider, for example, a situation where the average velocity of the upper 450 ft of soil and rock at one location (Station A) in the study area is 15000 ft/s (as per check shot survey control; Table 2). Assume the average velocity of the upper 450 ft of soil and rock at another location (Station B; extensively karsted location) is only 10000 ft/s. The "time thickness" of the upper 450 ft of sediment at Station A would be 60 ms; the "time thickness" at Station B would 90 ms (a difference 30 ms). Given the extremely karsted nature of the subsurface, the postulated average velocity variations (10000 to 15000 ft/s) in the uppermost 450 ft are not unreasonable.

The hypothesis that the interpreted time-structural variations are caused by karst-related velocity variations in the subsurface (mostly shallow) is supported by the suite of interpreted isochronous maps and interpreted seismic profiles that suggest the strata beneath the top of the Eminence and Lower Gasconade are relatively uniformly thick.

5.3.5 Features of Significant Interest

The most striking features on the time structure maps are the highlighted west-east and north-northwest contour trends. These contour trends correspond to areas where the time-depth to the top of the Lamotte (and other geologic horizons) is anomalously high, probably because the average velocity of the overlying rock and soil is anomalously low. These highlighted trends are remarkably consistent with the orientation of faults and lineaments as reported by McCracken (Figure 5.2).

In our opinion, the highlighted contour trends (if real) are probably associated with linear zones of intense fracturing and/or faulting and karstic weathering. The average velocity of the rock (and soil) in these postulated zones would be anomalously low; hence the seismic travel times to underlying geologic horizons would be anomalously high.

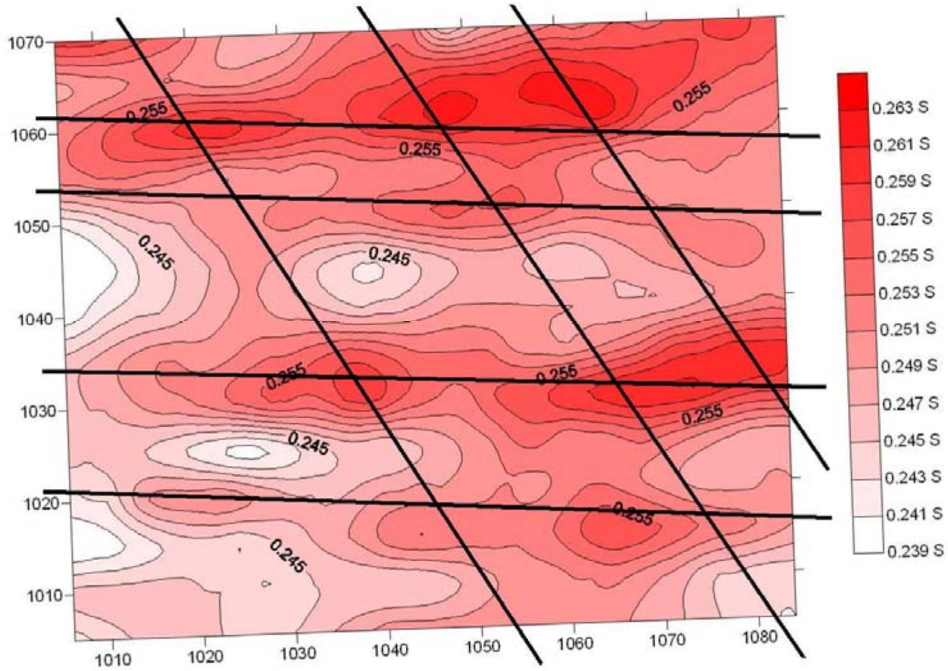


Figure 5.1: Interpreted lineaments superposed on north-south oriented Lamotte time-structure map. The highlighted linear time-structural lows are postulated to be caused by low velocity zones within shallow bedrock. If real, these "low velocity zones" are probably associated with linear karstic processes.

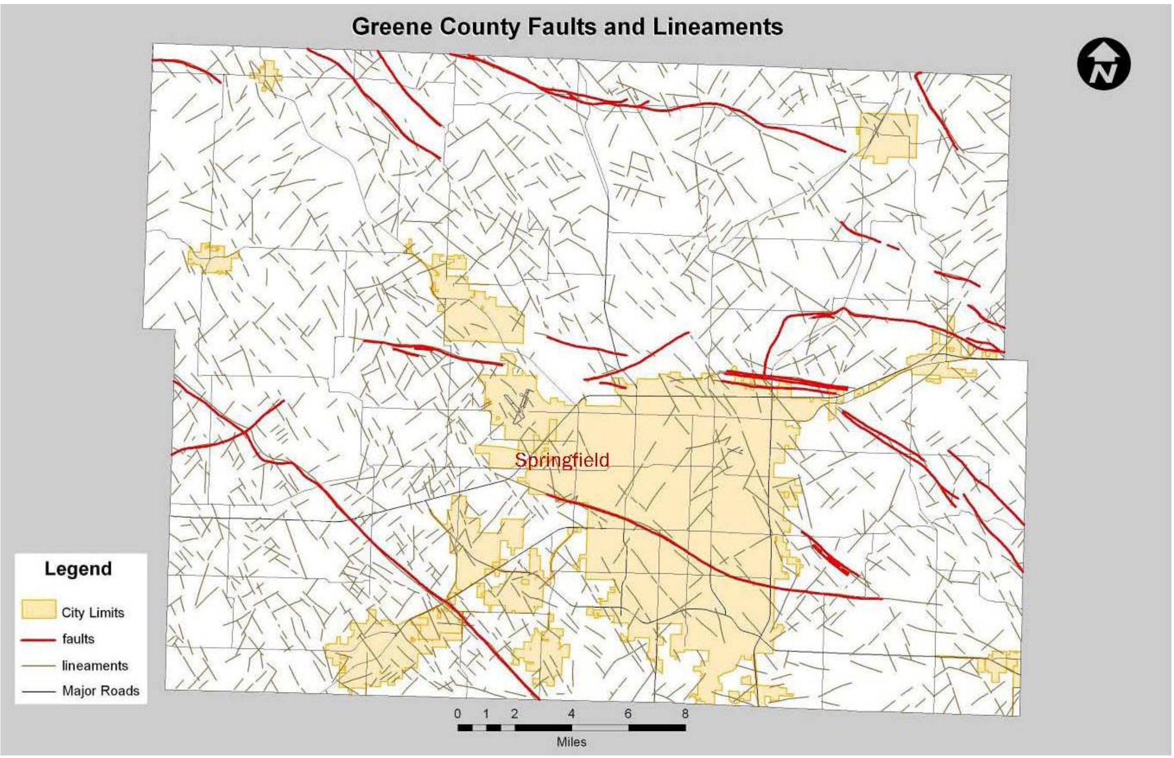


Figure 5.2: Map showing orientations of mapped faults and lineaments in southwest Missouri (modified after McCracken, 1971).

The 3-D reflection seismic data were interpreted using Kingdom Suite 2D/3D reflection seismic interpretation/modeling software. The seismic interpretations were constrained using proximal borehole control (specifically, the stratigraphic sequence in the H-12 borehole as identified by Palmer), with the understanding that the Mississippian section in southern Greene County is approximately 300 feet thick. We were unable to use "stacking velocities" to constrain interpretations at depths greater than about 400 feet, because the low quality of these data at depth rendered them unreliable. (The mediocre quality of the data is attributed to irregular surface topography, the presence of the ash pile, background noise generated by the plant and subsurface karst features of unknown extent and intensity.) At depths below 400 ft, the arrival times were estimated based on the assumption that the average velocity of the Cambrian/Ordivician sedimentary section is 14,000 ft/s.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The seismic data was acquired, processed, and interpreted in accordance with standard geophysical practices. Great care and expense were taken to reprocess and re-interpret the data. Unfortunately, because of the greater-than-anticipated fracturing and solutioning of the subsurface at depth, we do not believe that the data is highly reliable. Based on our study, the following conclusions may be drawn:

- The subsurface in the study area is karsted to such an extent that reliable 3-D reflection seismic data and reliable seismic check shot survey data could not be acquired.
- Reliable check shot survey data could not be acquired because vugs, joints, and open bedding seams that are filled with air, water and or clay attenuate seismic (acoustic) energy very rapidly making it difficult to record seismic signal that has propagated directly from a surface source to a borehole receiver. The fact that check shot survey data is an indication that the subsurface in the study area is extensively karsted. Normally, it is much easier to acquire quality check shot survey data than it is to acquire quality 3-D reflection seismic data.
- Reliable 3-D reflection seismic data could not be acquired in the study area for two principle reasons. First, vugs, joints, and open bedding seams attenuate seismic (acoustic) energy very rapidly making it difficult to record reflected seismic signal. Second, seismic energy propagates more slowly through zones of more intense karstification than through more intact carbonate. Because the study area is not uniformly karsted, reflected signals from the same horizon traveled at different velocities depending on rock quality along their respective ray paths. This made the processing of the reflection data extremely difficult.
- Karst processes do not appear to have affected the study area uniformly. Rather, the study area appears to be dissected by a number of prominent near-orthogonal zones of intense karstification (consistent with regional lineaments). These are probably associated with joints or fractures, but could be associated with unidentifiable faults with undetermined throw.
- There is significant time-structural relief at the level of the Eminence reflection, as interpreted. The time-structural relief at the top of the Eminence is not attributed to “real” structure (i.e. faulting) because the Eminence reflector more-or-less parallels all of the underlying reflectors, including the Precambrian. This near-parallel pattern suggests that the time structural relief observed at the top of the Eminence is caused by karst-related velocity variations mostly within the strata overlying the Eminence.
- There is no seismic evidence to suggest that the Eminence and pre-Eminence strata are faulted. The observed time-structural relief at the Eminence and pre-Eminence levels can be readily and entirely attributed to extensive karstification along near-orthogonal joints/fractures. However, it is possible that unidentifiable faults with undetermined throw are present in the study area. Such faults, if present, would need to extend to the Precambrian in order to be consistent with the 3-D seismic data set, as interpreted.

6.2 Recommendations

Because of the intense fracturing at depth, we do not recommend that additional surface geophysical methods be employed at this site. Cross-hole tomography and vertical seismic profiling (using a source discharged below the zone of intense weathering) would potentially hold some promise, should further subsurface characterization be desired.

7.0 LIMITATIONS

We have prepared this report for use by City Utilities of Springfield, their authorized agents, and other approved members of the investigation team involved with this project. The report is not intended for use by others, and the information contained herein is not applicable to other sites.

The data and report should be provided to prospective contractors, but our report should not be construed as a warranty of the subsurface conditions. Variations in subsurface conditions are possible between the explorations. Subsurface conditions may also vary with time.

Within the limitations of scope, schedule and budget, our services have been executed in accordance with generally accepted practices in this area at the time the report was prepared. No warranty or other conditions, expressed, written, or implied, should be understood.

Any electronic form, facsimile or hard copy of the original document (email, text, table and/or figure), if provided, and any attachments are only a copy of the original document. The original document is stored by GeoEngineers, and will serve as the official document of record.

Please refer to Appendix C, titled “Report Limitations and Guidelines for Use,” for additional information pertaining to use of this report.

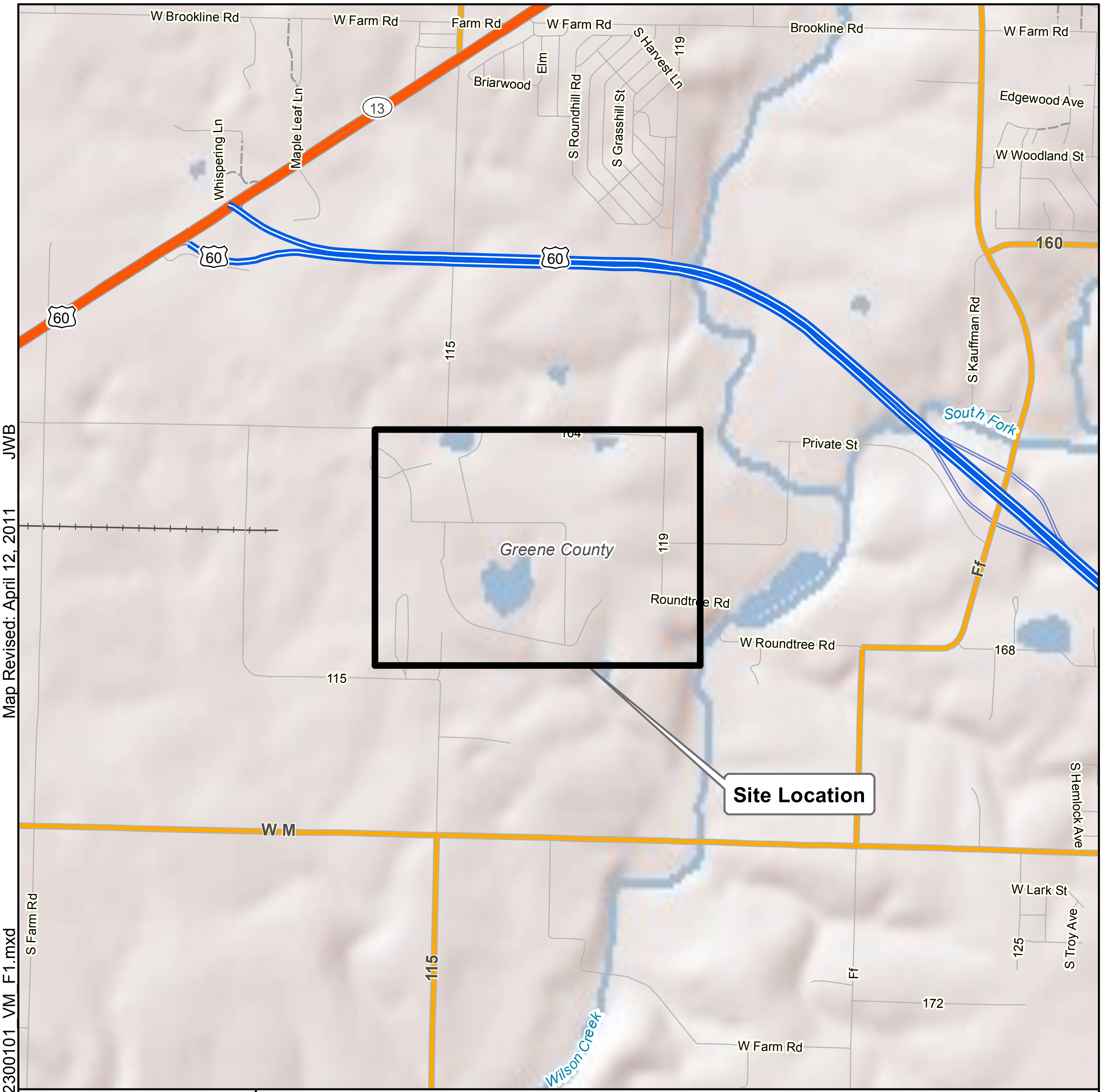
REFERENCES

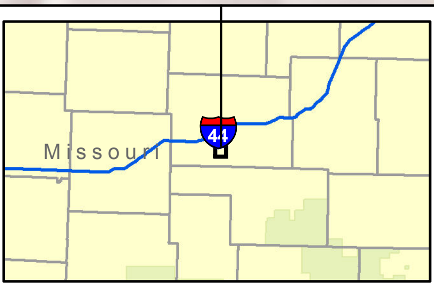
Middendorf, M.A., Thomson, K.C., Eason, G.L., and Sumner, H.S.,1987, Bedrock geologic map of the Springfield 1 degree x 2 degrees quadrangle, Missouri: U.S. Geological Survey, Miscellaneous Field Studies Map MF-1830-D, scale 1:250,000.

Whitfield, J.W., Ward, R.A., Denne, J.E., Holbrook, D.F., Bush, W.V., Lineback, J.A., Luza, K.V., Jensen, K.M., Fishman, W.D., Richmond, G.M., and Wiede, D.L., 1993, Quaternary geologic map of the Ozark Plateau 4 degrees x 6 degrees quadrangle, United States: U.S. Geological Survey, Miscellaneous Investigations Series Map I-1420(NJ-15), scale 1:1,000,000.

McCracken, M., 1971, Structural Features of Missouri, Missouri Geological Survey Report of Investigation Number 49.

After: Emmett, Feo F., Skelton J.; Luckey, R.R.; Miller, D.E.; Thompson, T.L.; and Whitfield, J.W.; 1978, Weter Resources and Geology of the Springfield Area, Missouri: Mo Dept. of Natural Resources, Geological Survey, Water Resources Report 34, page 21, Table 4.





Notes:
1. The locations of all features shown are approximate.
2. This drawing is for information purposes. It is intended to assist in showing features discussed in an attached document. GeoEngineers, Inc. cannot guarantee the accuracy and content of electronic files. The master file is stored by GeoEngineers, Inc. and will serve as the official record of this communication.
3. It is unlawful to copy or reproduce all or any part thereof, whether for personal use or resale, without permission.

Data Sources: ESRI Data & Maps, Street Maps 2008

Transverse Mercator, Zone 15 North, North American Datum 1983 (feet)

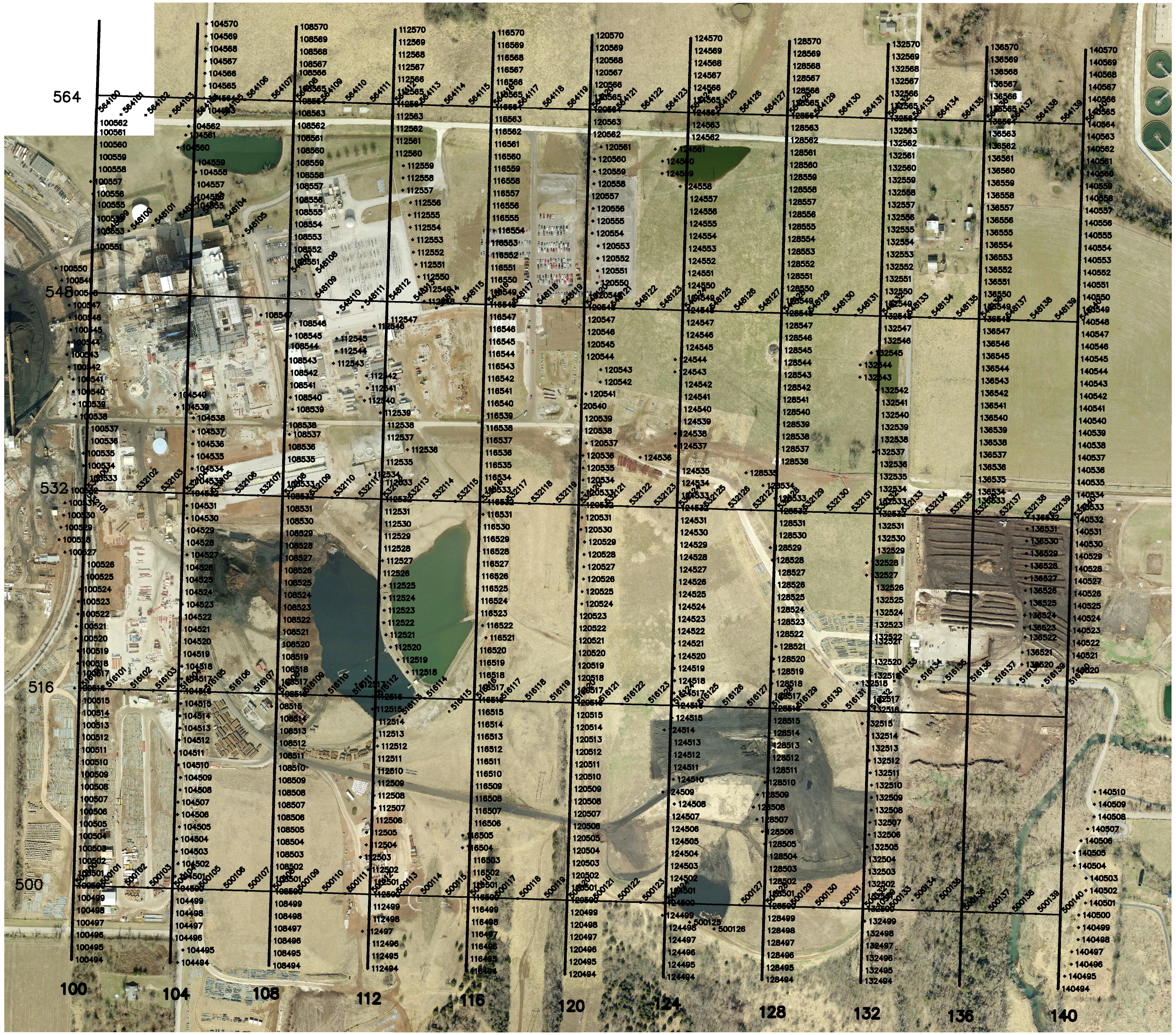
Vicinity Map

City Utilities of Springfield
Carbon Sequestration Geophysical Investigation
Greene County, Missouri

GeoEngineers

Figure 1

Office: Springfield   Path: P:\15\1572300101\GIS\1572300101 VM F1.mxd   Map Revised: April 12, 2011   JWB



LEGEND

EAST/WEST LINES = RECIEVER LOCATIONS

NORTH/SOUTH LINES = SOURCE LOCATIONS

N
W
E
S

500 0 500

FEET

SITE PLAN

CITY UTILITIES OF SPRINGFIELD - CARBON SEQUESTRATION GEOPHYSICAL INVESTIGATION

GEOENGINEERS

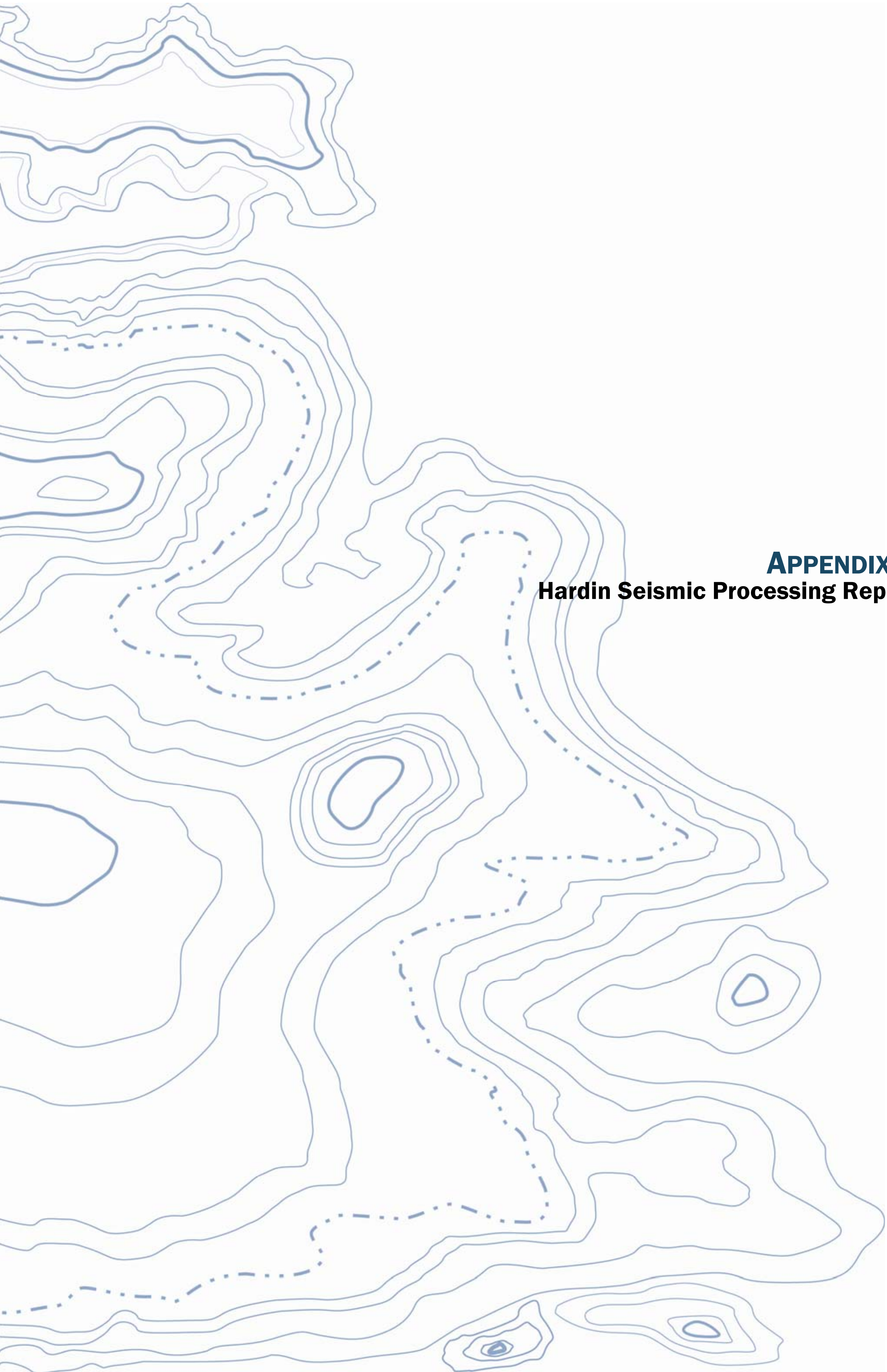
FIGURE 2

JLR : JLH

P:\15\15723001\01\CAD\Carbon Image.dwg\TAB:Figure 1 modified on Jan 14, 2011 - 9:45am

APPENDICES

GeoEngineers



APPENDIX A

Hardin Seismic Processing Report

GEO-ENGINEERING CITY UTILITIES

Seismic Processing Report

Carbon Sequestration 3D Project

Greene Co. Missouri

Submitted by:

Hardin International Processing, Inc.
Plano, TX
Ph# 972-312-9221
Email: hpatel@hardinintl.com
Website: hardinintl.com

October 2009

Processing Geophysicist:
Harshad Patel

Randy Conner

Data Processing Personnel

Name	Job Title
Harshad Patel	Sr. Processing Geophysicist
Randy Conner	President

Data Processing Software

Promax Version R.5000.0.0.0

Data Processing Equipment

128 CPU BEOWULF CLUSTER

Summary of Project

HARDIN INTERNATIONAL PROCESSING processed a 0.8 Square mile 3-D seismic data for GeoEngineering /City Utilities with delivery of final product in September 2009.

Scope of Work:

Client : GeoEngineering City Utilities
Carbon Sequestration Project
Location : Greene Co. Missouri
Survey Size : 0.8 square miles
Expectations : Process data using state of the art techniques Including pre-stack Kirchhoff time migration, Depth Velocity Model building, Pre-stack depth Migration. It was anticipated there will be two Phases of reflection seismic data acquisition. Phase-I data will be acquired prior to the drilling of the injection well, Phase-II data will be acquired after the test injection process has been completed. It is anticipated that the Phase-I and Phase-II data Sets will be acquired approximately 18 months apart. The Phase-I and Phase-II seismic data sets will be Acquired and processed using identical parameters to Ensure the data sets can be compared and contrasted directly

SURVEY INFORMATION:

Acquisition Parameters : Basin Geophysical LLC
J. Craig Walter
craig@basingeo.com
Exploration / Operator Co. : City Utilities
Gary Pendergrass
gary.pendergrass@cityutilities.net
Consulting : GeoEngineers
Jon Robison PE
jrobision@geoengineers.com
Neil Anderson Geophysicist
nanders@mst.edu
Survey : CJW Transportation
James Gray
jgray@gocjw.com

Acquisition Parameters

Acquired : August 2009
Processed survey size : 0.54 sq miles
Recording System : Seistronix EX-6
Sample Rate : 1 Milliseconds
Record length : 1.5 Seconds
Source : XLR8
Source : Stacks:4
Source Spacing : 50 feet
Source Line Interval : 400 feet
Number of Lines : 11
Number of shots : 768
Source Line Orientation : N-S
No of Receiver Lines : 5 lines
No of Stations per Line : 205
Patch : 4000 feet X 3800 feet
Group Interval : 100 feet
Receiver Line Interval : 800 feet
Receiver Line Orientation : E-W
Receiver Array : 6 Phones/str 110’ Long
Recording Format : SEG-2X
Field Filters : OUT
Bin Size : 50 x 50 feet

FIELD SHOT AND RECEIVER LINES LAYOUT

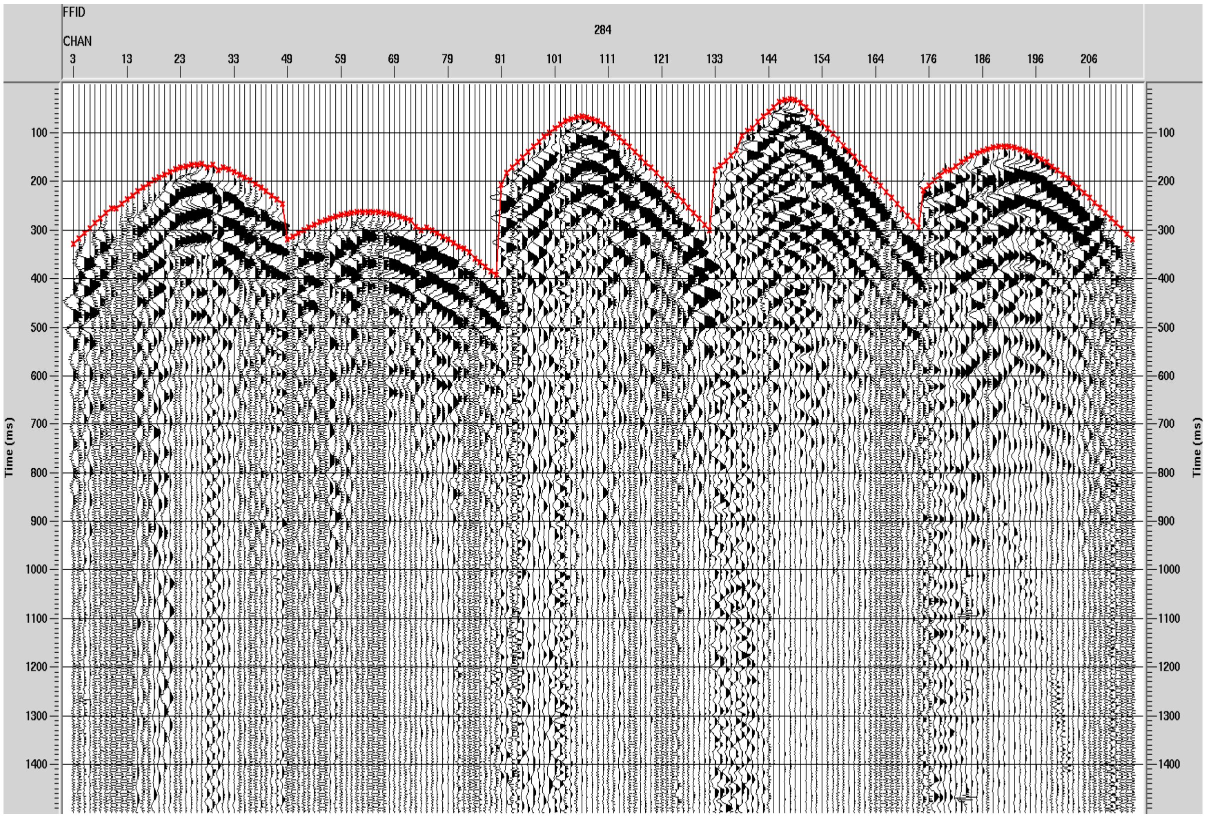
CARBON SEQUESTRATION 3-D PROJECT Processing Overview

1. Reformat field data
2. Geometry Attachment and QC
3. Trace Edits
4. Refraction Model and Statics Corrections
5. Surface Consistent Amplitude Recovery
6. Surface Consistent Deconvolution
7. Air Blast Attenuation
8. Constant Velocity Stacks and Analysis
9. Normal Moveout Corrections
10. Trace Mute
11. Trace balance 1000 ms Agc
12. Brute Stack with refraction statics applied
13. Surface Consistent Residual Statics Pass-1
14. Constant Velocity Stacks and Analysis
15. Cdp Stack
16. Surface Consistent Residual Statics Pass-2
17. Cdp Stack
18. Trim Statics
19. Trace Balance
20. Cdp Stack
21. FX-Y Decon
22. Post-Stack Kirchhoff Migration
23. Inverse Normal Moveout Corrections
24. Pre-Stack Time Migration
25. Residual Velocity Analysis
26. Normal Moveout Corrections
27. Trace Mute
28. Trace balance 400 ms Agc
29. FX-Y noise reduction
30. CDP Stack
31. Band Pass Filter
32. Trace Balance 500 ms Window
33. Output Pre-stack Migration Stack Volume in Segy Format
34. 3D data loading information

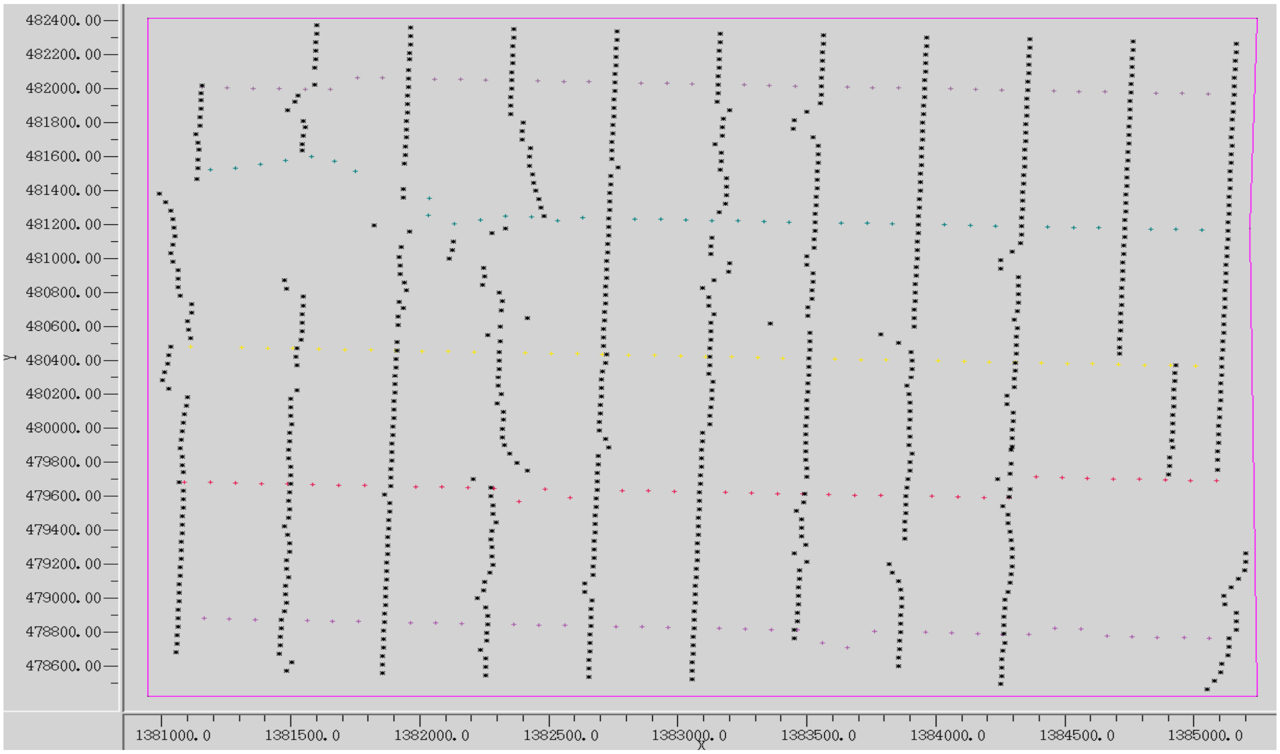
1. Geometry

Geometry was extracted from the headers of field data supplied by the Client. QC of the geometry applied was done by visual display of the shot records.

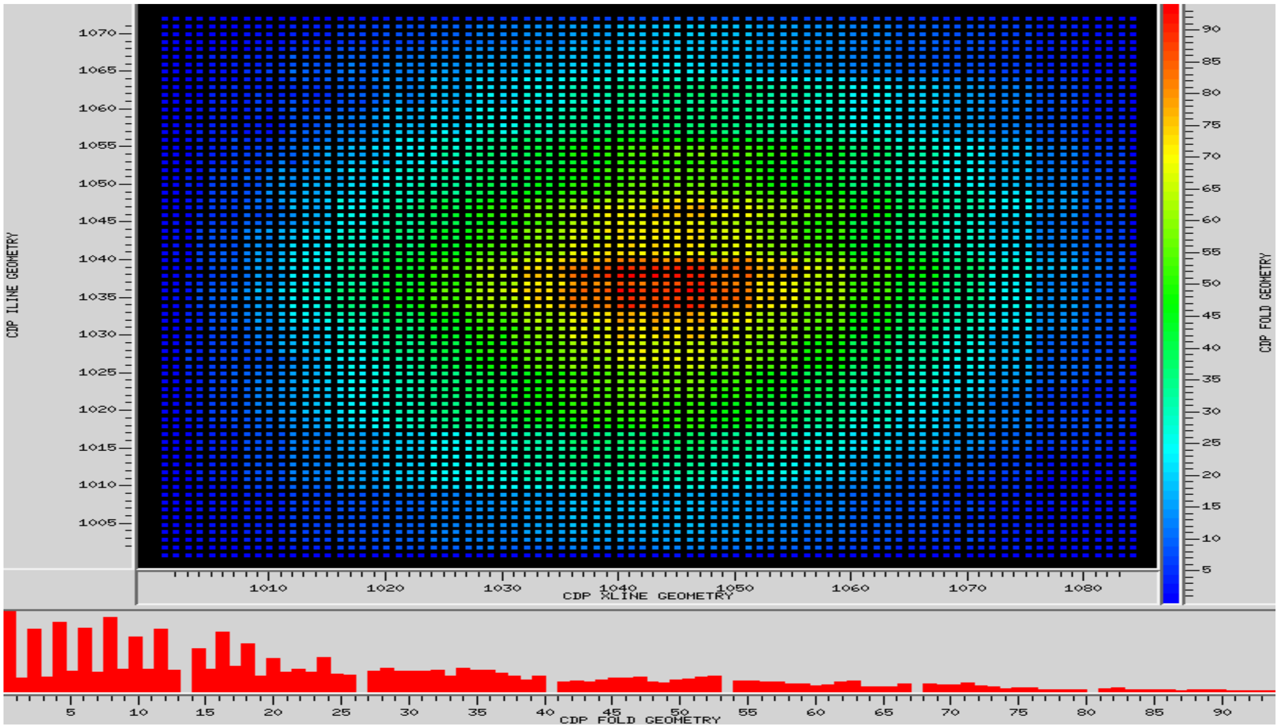
Input Data Sort : Field File
Total Shots : 768
Total Traces : 152,832
CDP Bin Size : 50 x 50 Ft
Number of Inlines : 72 (1001-1072)
Number of Xlines : 84 (1001-1084)
CDP Bin Fold : 90(avg.)



FIELD RECORD WITH GEOMETRY APPLIED



CARBON SEQUESTRATION 3D BASE MAP SHOT AND RECEIVERS

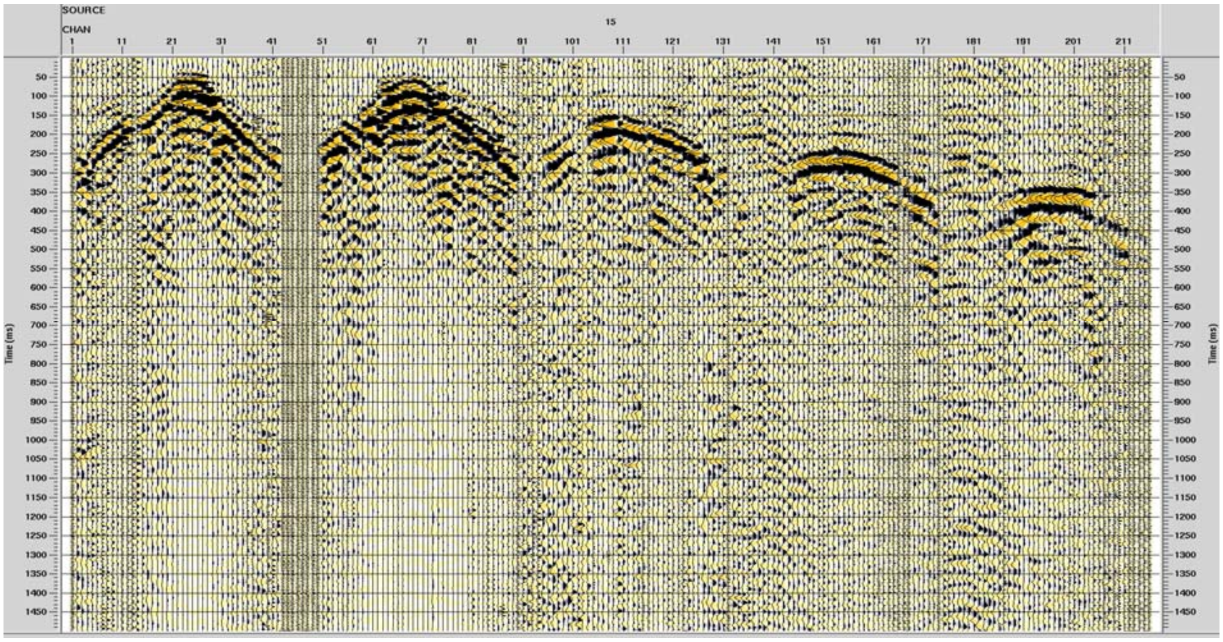


CARBON SEQUESTRATION 3D CDP FOLD MAP

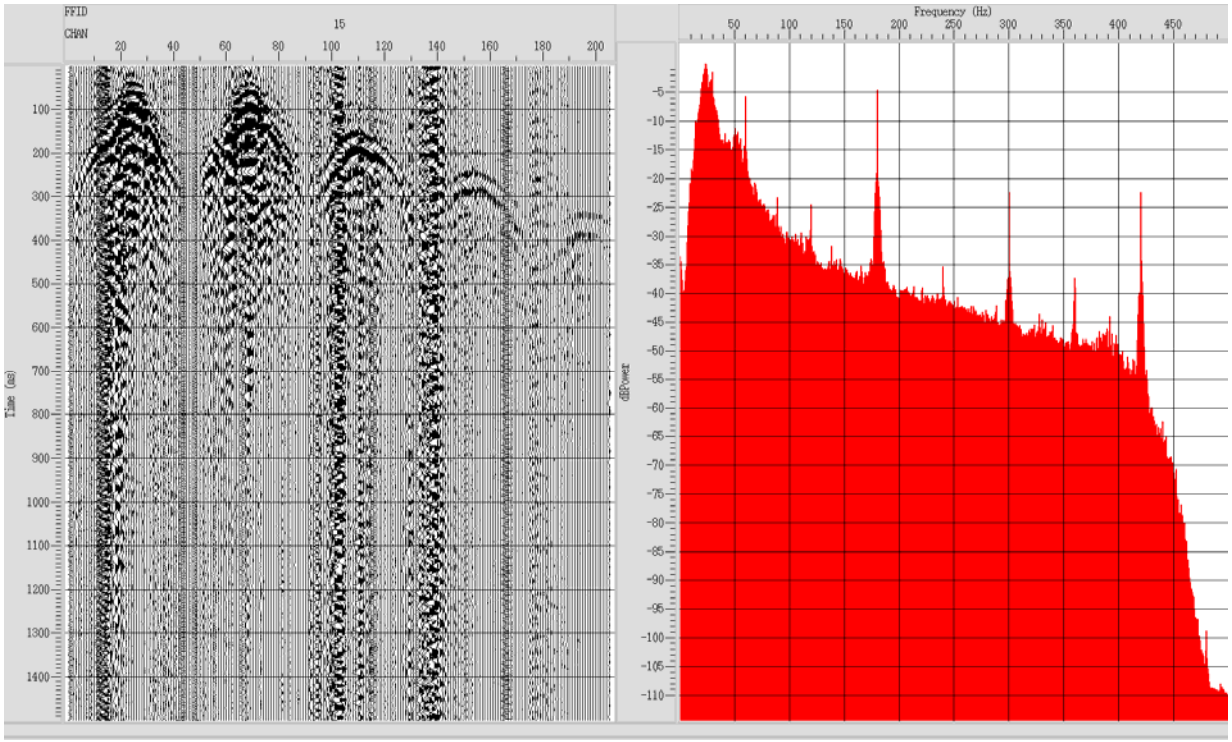
2. Trace Edit

Initial trace editing was done through visual QC of each record. Traces appearing to be bad or dead were killed at this time.

RAW FIELD RECORD



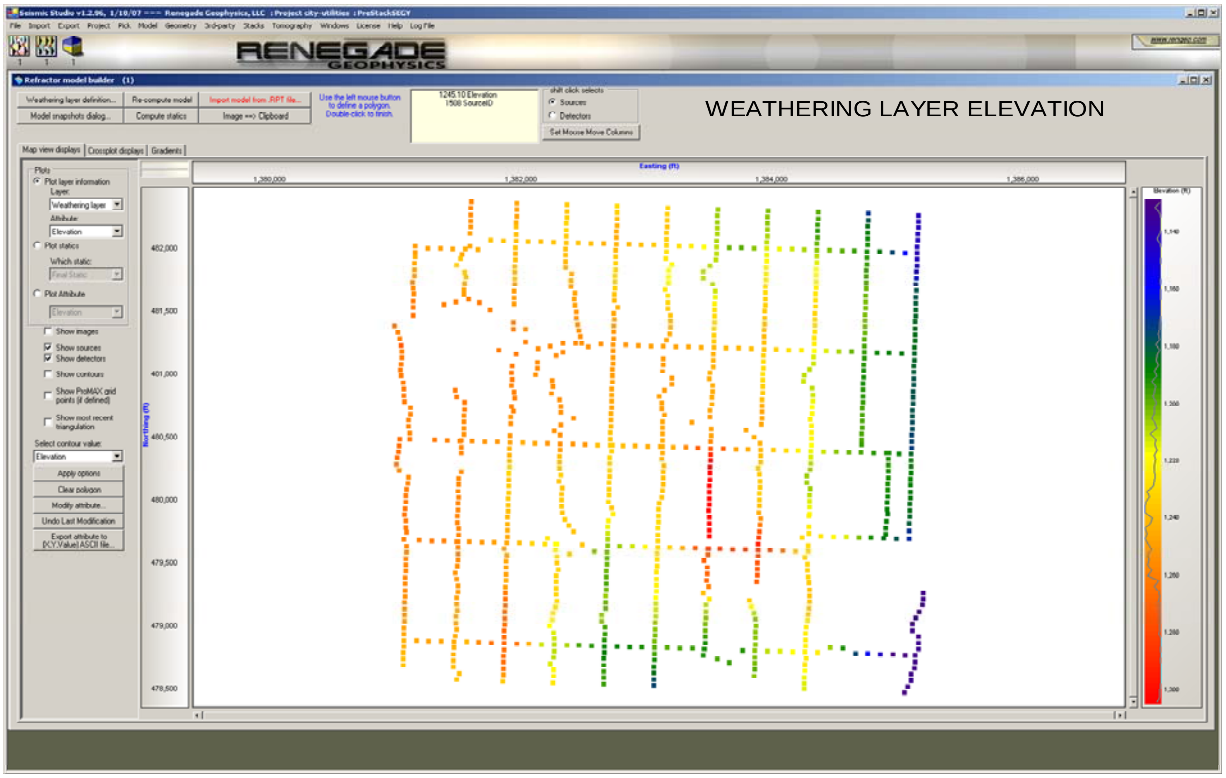
RAW FIELD RECORD & POWER SPECTRUM



3. Refraction Model Building and Statics Corrections

```
Datum                  :  1200
Replacement velocity   :  8400 Feet/sec
```

GEO-ENGINEERING CITY UTILITIES – CARBON SEQUESTRATION PROJECT GREENE CO. MISSOURI



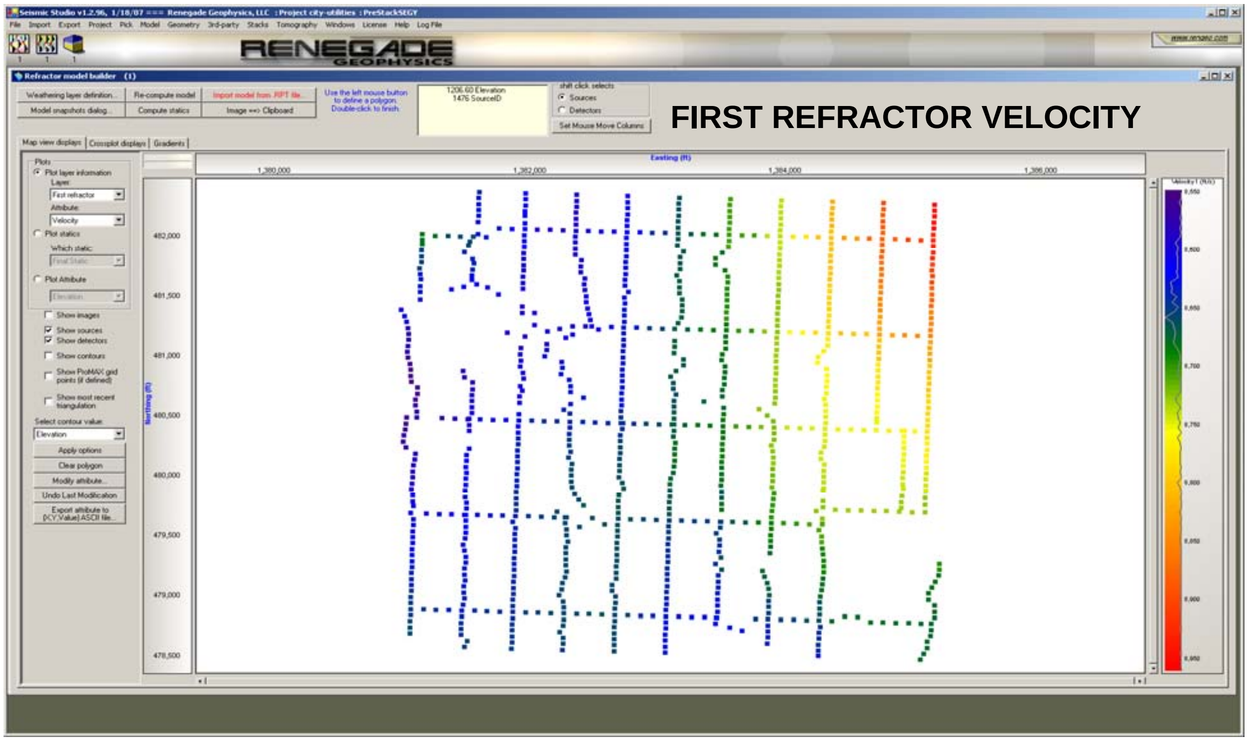
WEATHERING LAYER ELEVATION

Seismic Studio v1.2.96, 1/18/07 === Renegade Geophysics, LLC :Project city-utilities :PreStackSEGY

Refractor model builder (1)

1245.10 Elevation
1508 SourceID

Layer: Weathering layer
Attribute: Elevation
Select contour value: Elevation



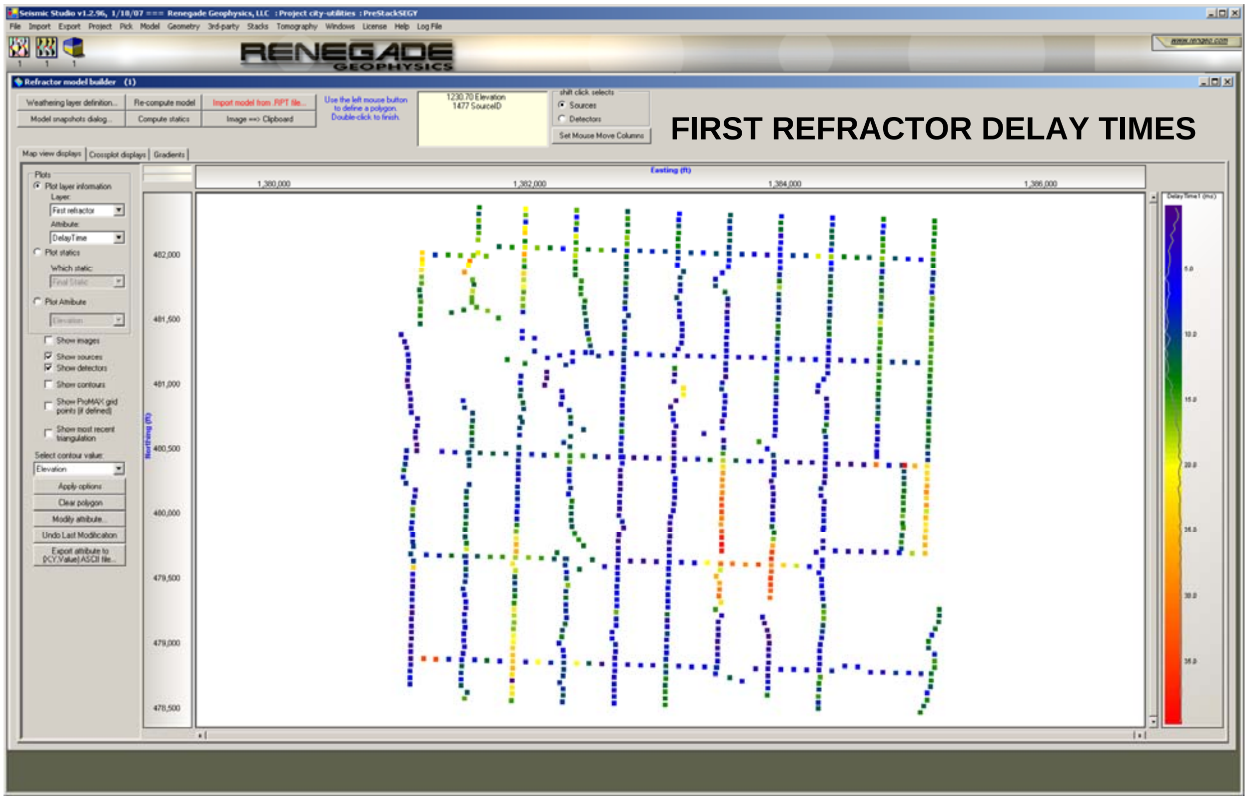
FIRST REFRACTOR VELOCITY

Seismic Studio v1.2.96, 1/18/07 === Renegade Geophysics, LLC :Project city-utilities :PreStackSEGY

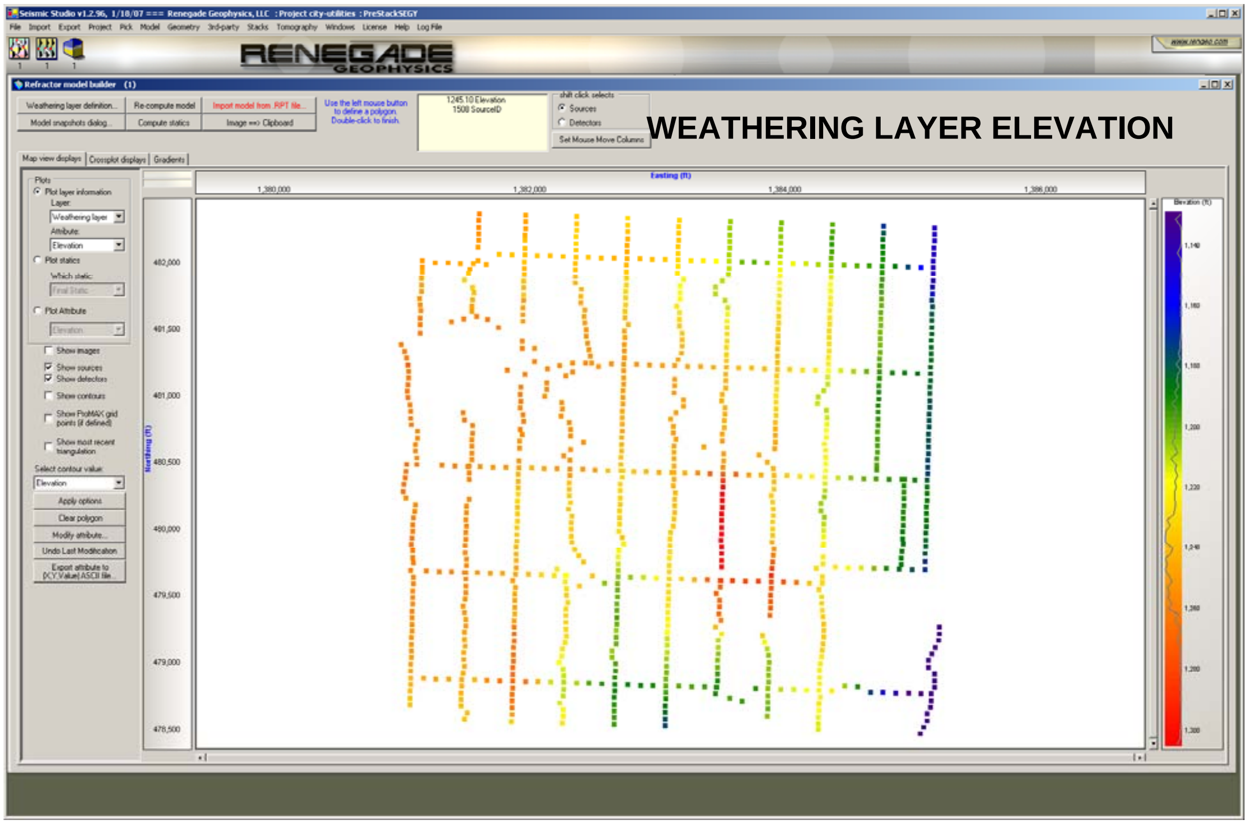
Refractor model builder (1)

1206.60 Elevation
1476 SourceID

Layer: First refractor
Attribute: Velocity
Select contour value: Elevation

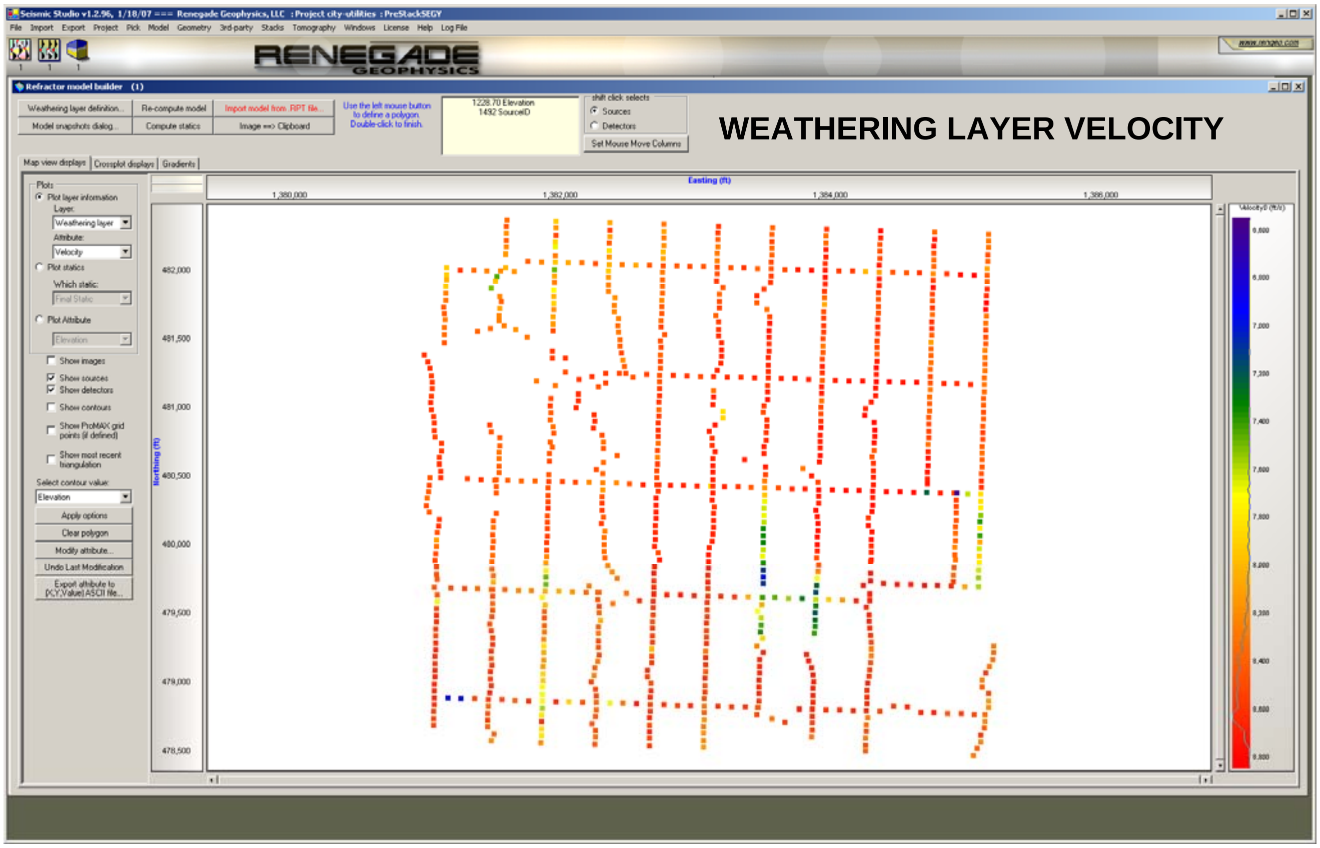


FIRST REFRACTOR DELAY TIMES



WEATHERING LAYER ELEVATION

WEATHERING LAYER VELOCITY

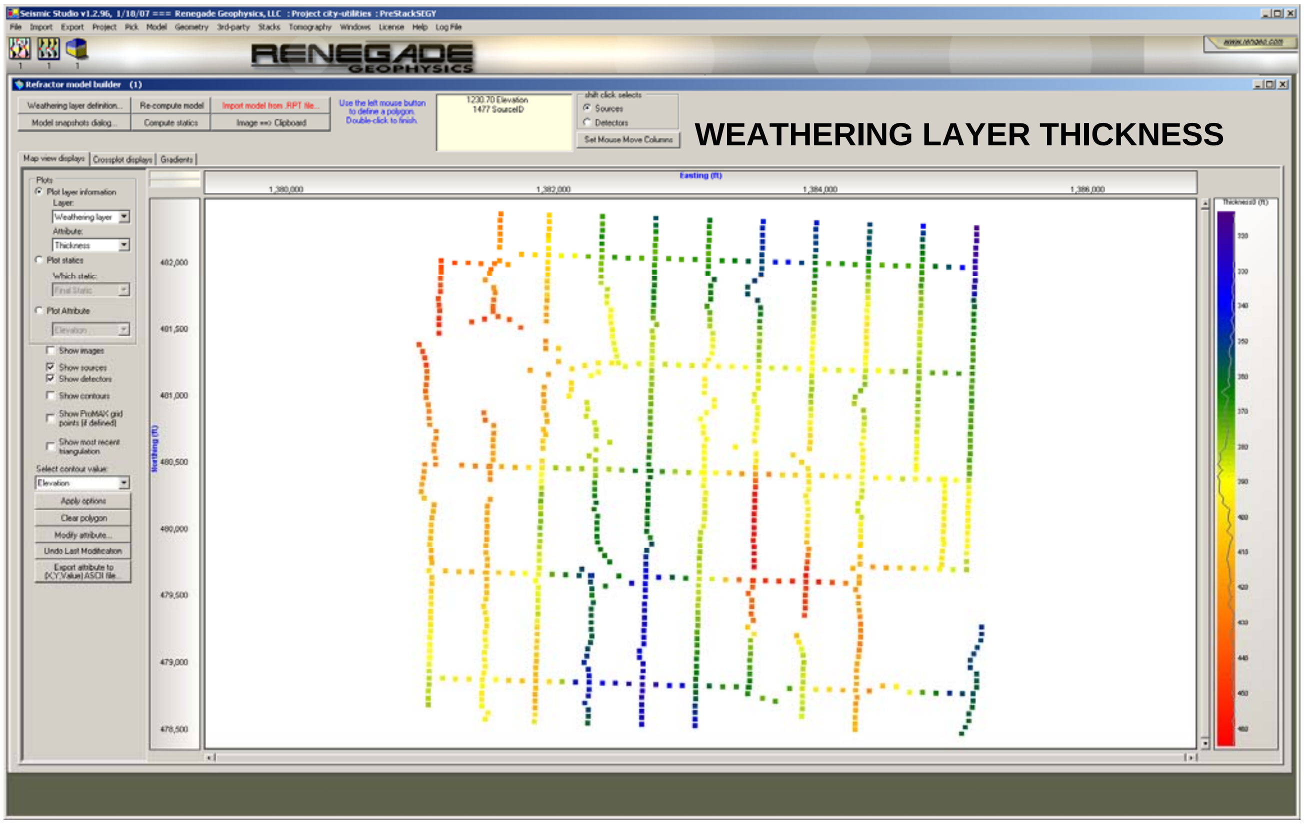


1228.70 Elevation
1492 SourceID

● Sources
○ Detectors

● Plot layer information
Layer: Weathering layer
Attribute: Velocity
○ Plot statics
Which static: Final Static
○ Plot Attribute
Elevation
☐ Show images
☑ Show sources
☑ Show detectors
☐ Show contours
Select contour value: Elevation

WEATHERING LAYER THICKNESS



1230.70 Elevation
1477 SourceID

● Sources
○ Detectors

● Plot layer information
Layer: Weathering layer
Attribute: Thickness
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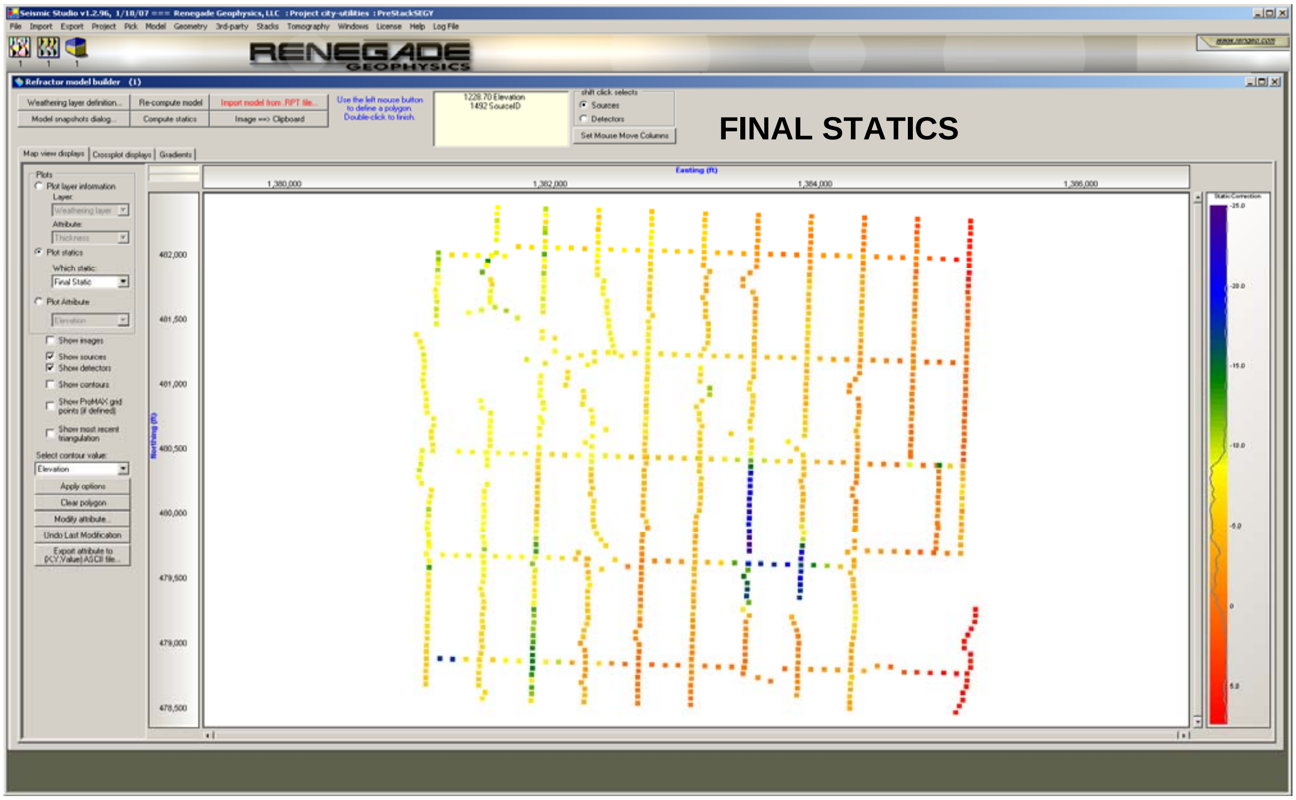
Which static: Final Static
○ Plot Attribute
Elevation
☐ Show images
☑ Show sources
☑ Show detectors
☐ Show contours
Select contour value: Elevation



FINAL STATICS

Seismic Studio v1.2.96, 1/18/07 === Renegade Geophysics, LLC : Project city-utilities : PreStackSEGY

Refractor model builder (1)

Use the left mouse button to define a polygon. Double-click to finish.

1228.70 Elevation
1492 SourceID

shift click selects: ● Sources ○ Detectors

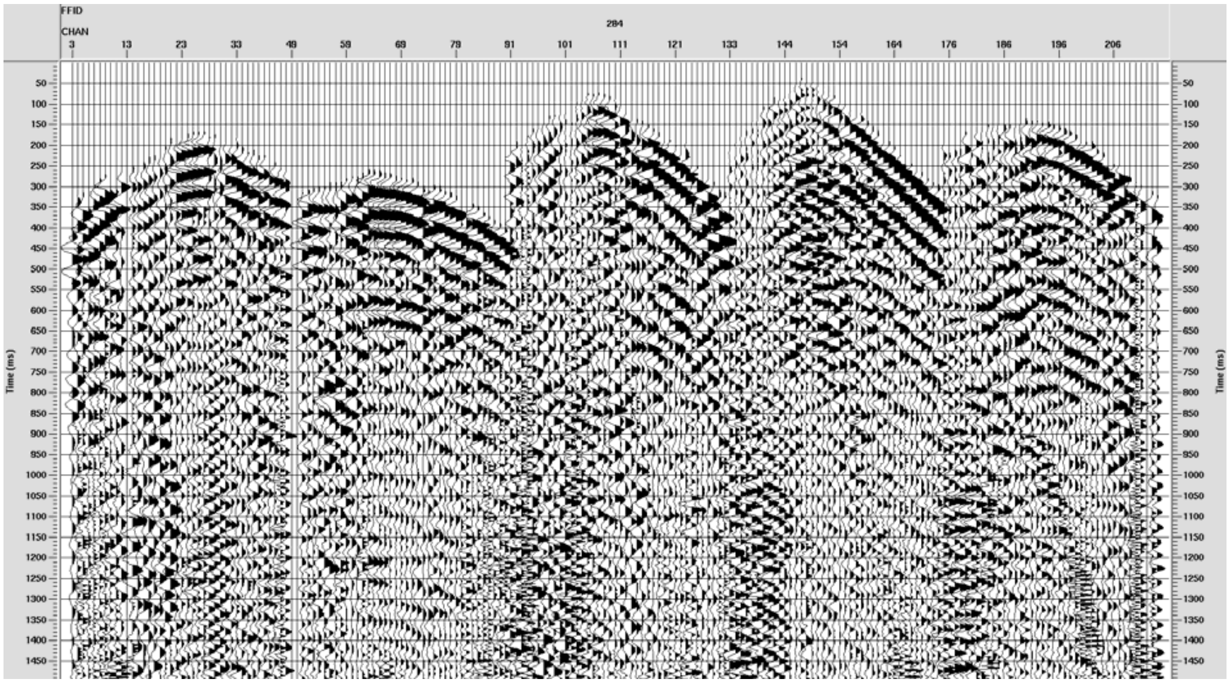
Plots: ○ Plot layer information; Layer: Weathering layer; Attribute: Thickness; ● Plot statics; Which static: Final Static; ○ Plot Attribute: Elevation

☐ Show images
☑ Show sources
☑ Show detectors
☐ Show contours
☐ Show ProMAX grid points (if defined)
☐ Show most recent triangulation

Select contour value: Elevation

4. Amplitude Recovery

A gain curve was applied to the dataset with a 2.0 *time. A surface consistent amplitude was calculated and applied. The shot and receiver component were applied to the dataset.



SHOT RECORD WITH SURFACE CONSISTENT AMPLITUDE

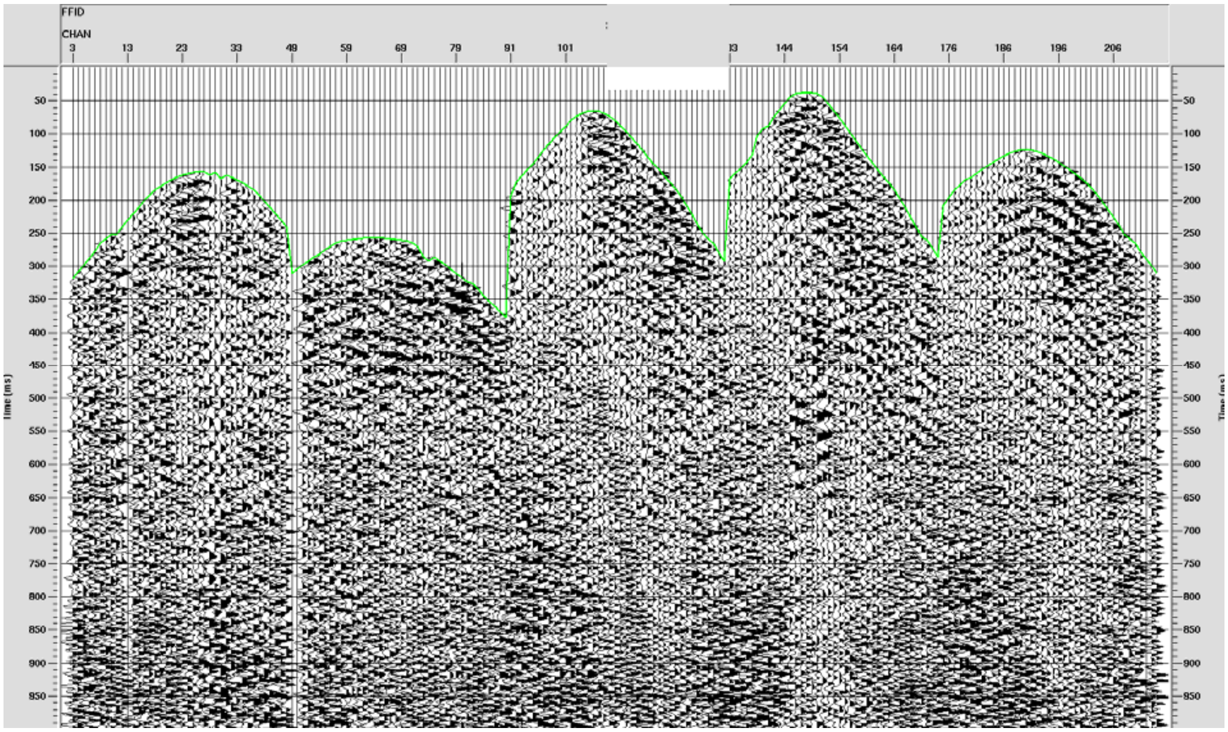
5. Deconvolution

Data Input Sort : Cdp Gathers
Decon Type : Minimum phase Surface Consistent Spiking
Decon Operator : 80 ms.
White Noise : 0.1

Decon Window:

Offset	Start Time	End Time
250’	50 ms.	850 ms.
1820’	225 ms.	975 ms.

2665’	350 ms.	1050 ms.
3500’	450 ms.	1150 ms.

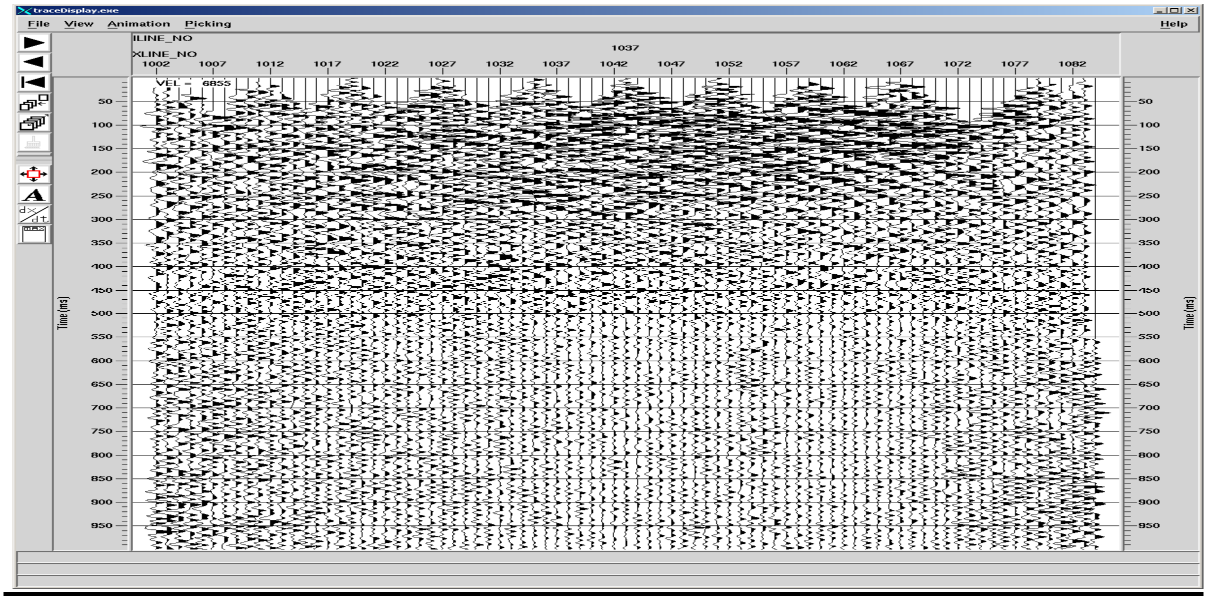


SHOT RECORD WITH SURFACE CONSISTENT DECONVOLUTION

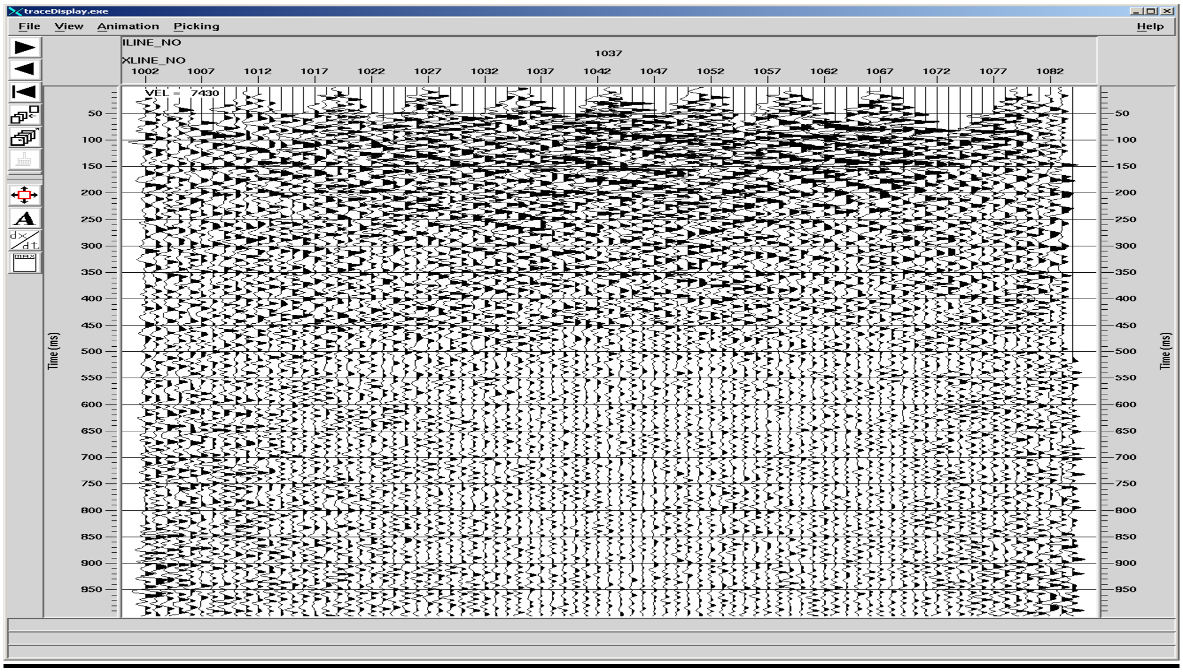
6. Velocity Analysis

After surface consistent decon the dataset was
input to a Constant Velocity Stacks analysis.
Data Input Sort : CDP
Velocity Grid : Every 10th Inline
Velocity Range : 5000 feet/sec. - 15000 feet/sec.
Total of 50 panels.

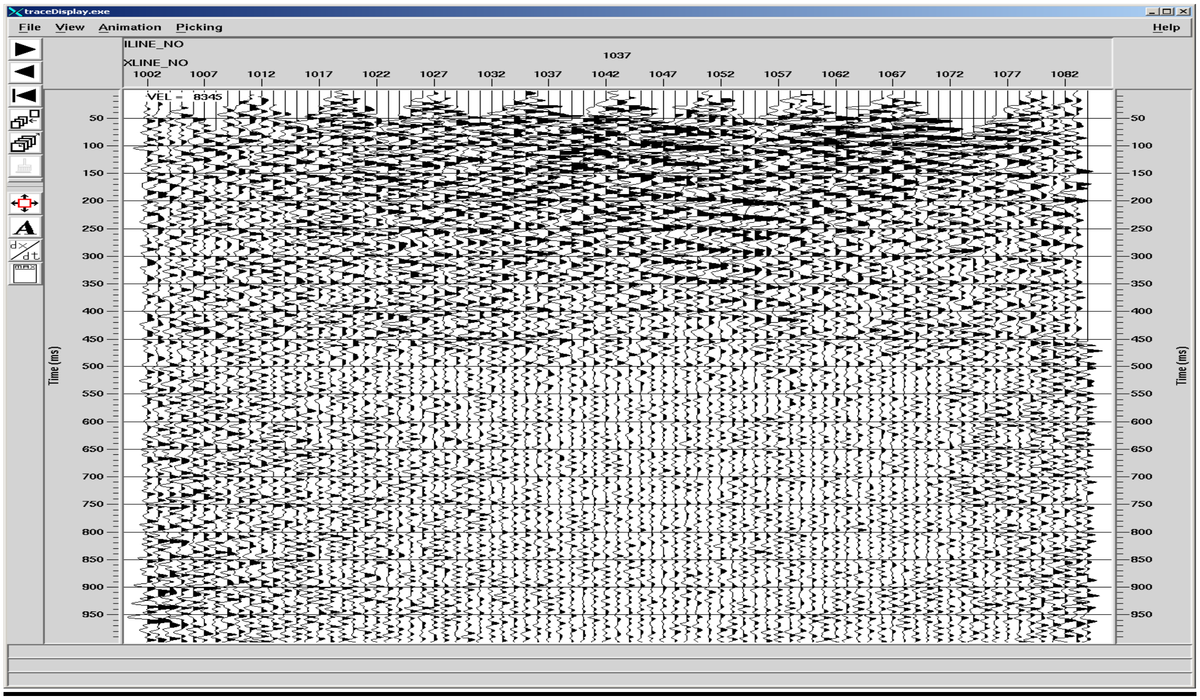
INLINE 1037 CVS PANEL / VELOCITY=6855



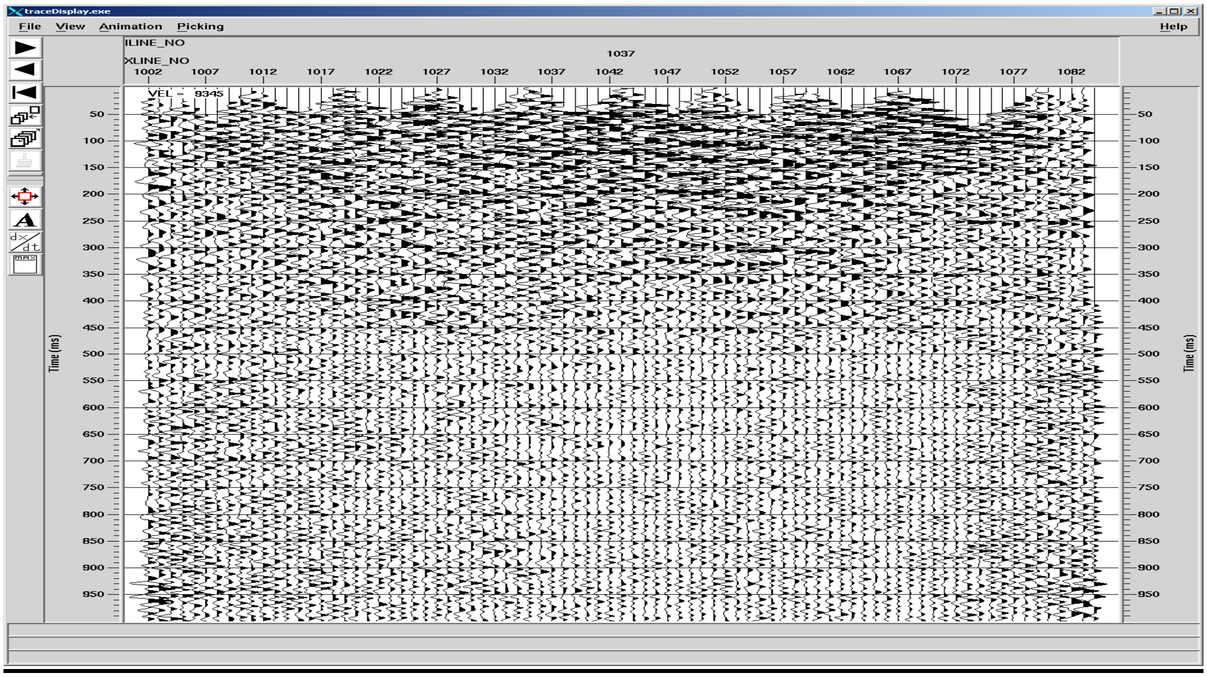
INLINE 1037   CVS PANEL / VELOCITY=7490



INLINE 1037   CVS PANEL / VELOCITY=8345



INLINE 1037   CVS PANEL / VELOCITY=9345



7. Normal Moveout Corrections

Normal moveout corrections were applied to the dataset using velocities picked from the constant velocity stacks.

8. Trace Muting

After the Normal Moveout Correction was applied a Trace Mute was applied.

Offset-Feet	Time-ms.
0’	0 ms.
824’	30 ms.
1940’	100 ms.
2600’	350 ms.
3160’	600 ms.
4189’	850 ms.

9. Surface Consistent Statics

The first pass of Surface Consistent Statics were run on the dataset and applied. Normal Moveout Corrections with the cvs grid velocities were applied to the dataset followed by a trace mute.

Parameters for Statics:
Scaling : 500ms agc
Window : 0 ms. - 900 ms.
Statics : +/- 30ms.
The static solution was checked with CDP Stacks, Common Shot Stacks, Common Receiver Stacks.

10. Velocity Analysis

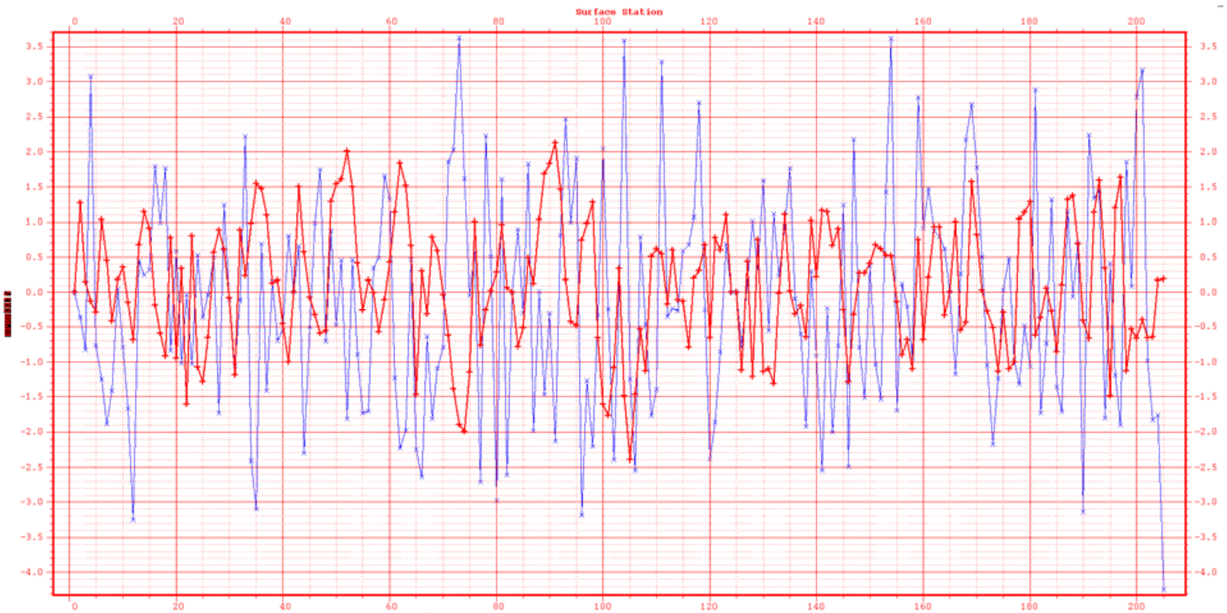
After the first pass of surface consistent statics the dataset Was input to a Constant Velocity Stacks analysis.

Data Input Sort : CDP
Velocity Grid : Every 10th Inline
Velocity Range : 5000 feet/sec. - 15000 feet/sec.
Total of 50 panels

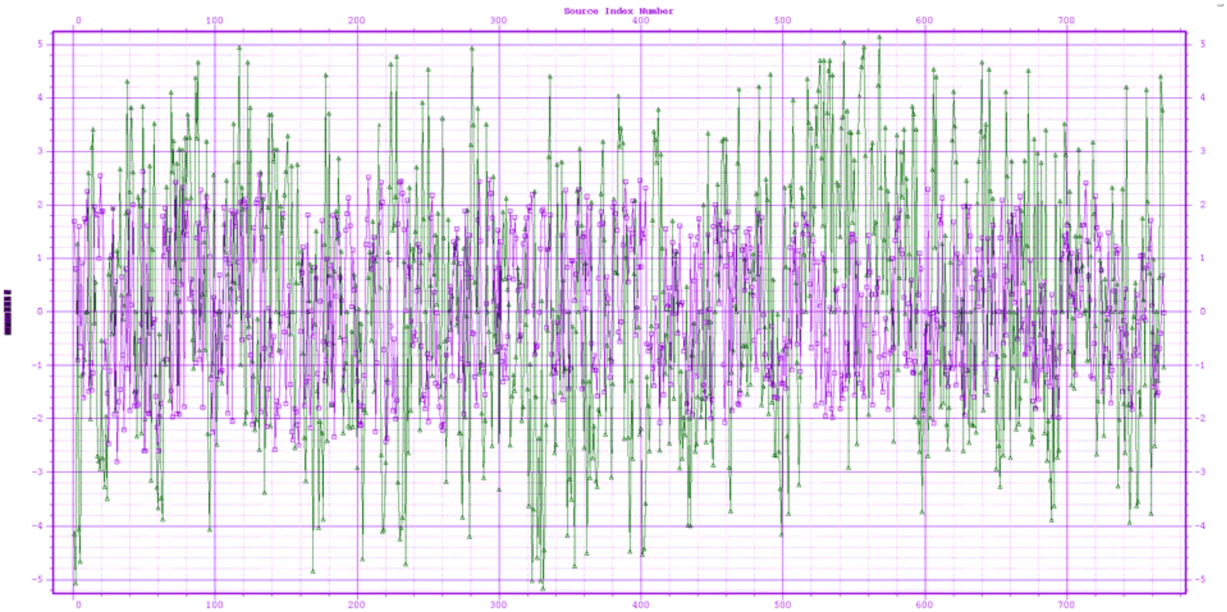
11. Surface Consistent Statics

After the initial pass of surface consistent statics followed by velocity analysis the dataset was input to a second iteration of surface consistent statics.

Parameters for Statics:
Scaling : 500ms agc
Window : 0 ms. - 900ms.
Statics : +/- 20ms.



BLUE=1st Pass residual receivers statics
RED =2nd Pass residual receivers statics



Green=1st Pass residual shot statics
Purple=2nd Pass residual shot statics

12. Trim Statics

Parameters for Statics:
Scaling : 500ms agc

Window : 0ms. - 9000ms.
Statics : +/- 6ms.

13. Normal moveout Correction and Trace mutw

14. Trace Balance ,400 ms Agc

15. Band Pass filter 10-16-120-130 HZ

16. Cdp Stack

17. Very Strong Noise reduction using FX-Y Decon

18. Band Pass Filter 12-16-85-95

19. Post-Stack Kirchhoff Migration

20. Pre-Condition data for input to Pre-stack Migration

21. Trace Balance
Following the all statics applications a 400 ms agc was applied to the pre-stack dataset.
Input Data Sort : Offset Planes (24 offset planes / 0-5280 feet
With increment of 220 feet)

22. FX-Y Decon run on individual offset planes for noise reduction

23. Inverse Normal moveout Corrections

24. **Pre-Stack Time Migration**
The entire pre-stack volume was input to Pre-stack Kirchhoff Time migration and migrated gathers were output.

25. **Residual Velocity Analysis**
The migrated pre-stack volume was input for a final residual velocity analysis and normal moveout corrections were applied.

23. **3-D Stack**
The complete pre-stack dataset was sorted into cdp bins and Stacked. Raw and filtered dataset were output.
The final filter used was:12-16-85-95 Hz.
Trace Balance : 400 ms Agc
Inline Bins : 72 (1001-1072)
Xline Bins : 84 (1001-1084)

24. 3-D Loading Sheet

3D Data Loading Worksheet

Client: **CITY UTILITIES**
Survey: **CARBON SEQUESTRATION 3D**
Area: **GREENE CO. MISSOURI** **Date:** **9/16/2009**

Upper Left Corner

Line#:	1072
Trace #:	1001
X:	1381072
Y:	482243

Upper Right Corner

Line #:	1072
Trace #:	1084
X:	1385220
Y:	482118

Lower Left Corner

Line#:	1001
Trace #:	1001
X:	1380965
Y:	478695

Lower Right Corner

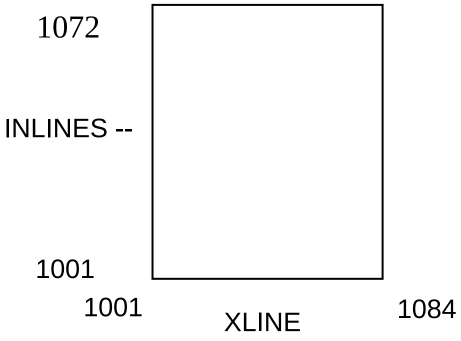
Line #:	1001
Trace #:	1084
X:	1385113
Y:	478569

Line (Bin) Spacing:	50
Trace (Bin) Spacing:	50

Format- SEGY 32 Bit Floating Point

Header Information

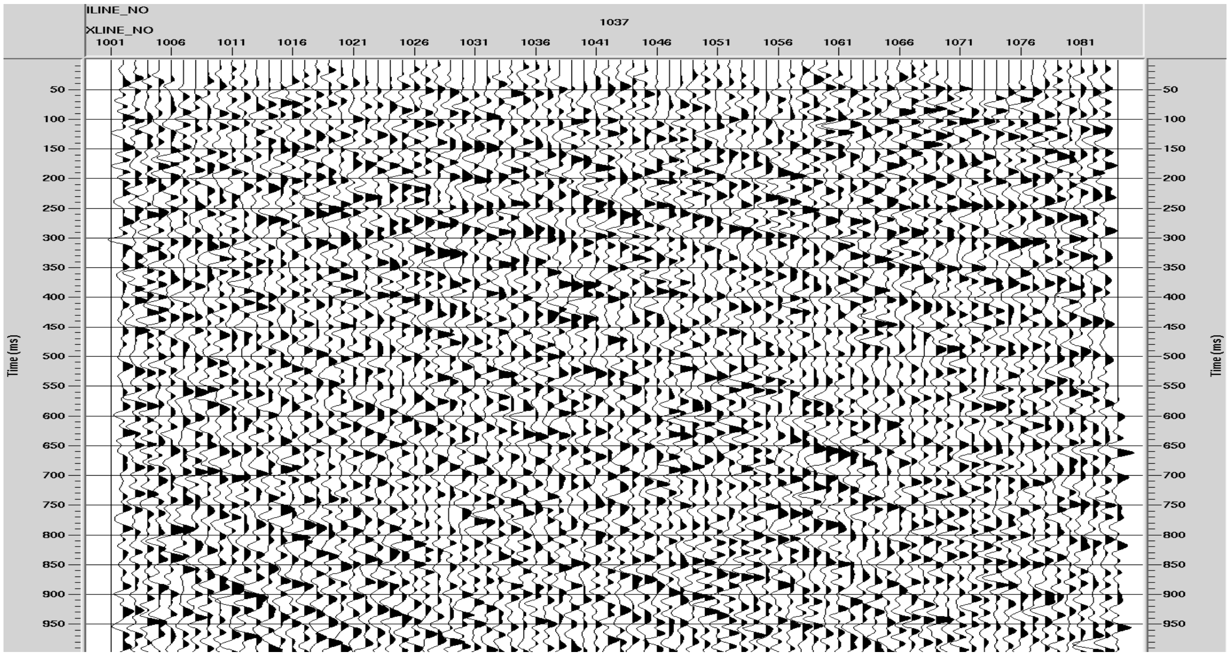
Line Number Starts in Byte:	17-20
Trace Number Starts in Byte:	21-24
CDP X Coordinate Starts in Byte:	181-184
CDP Y Coordinate Starts in Byte:	185-188



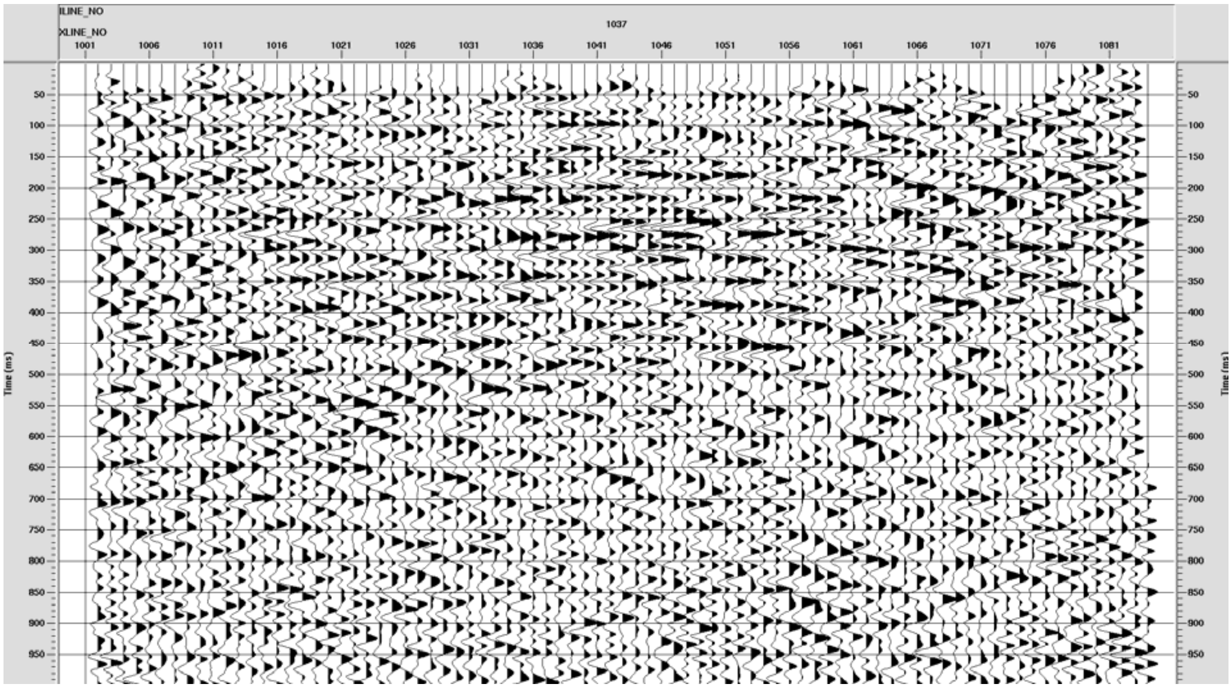
Sample Rate:	1 ms.	Record Length:	1.5sec
Datum:	1200	Datum Velocity	8400

Your Personal Processor

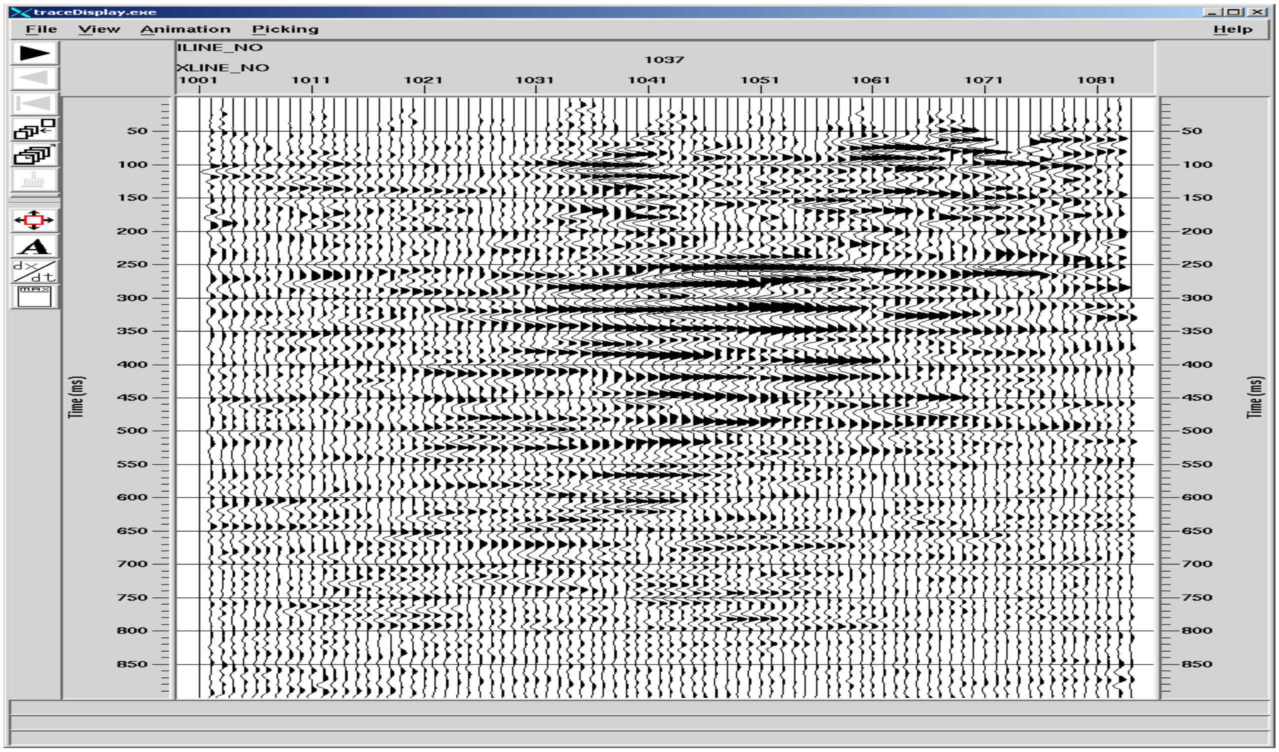
HARDIN



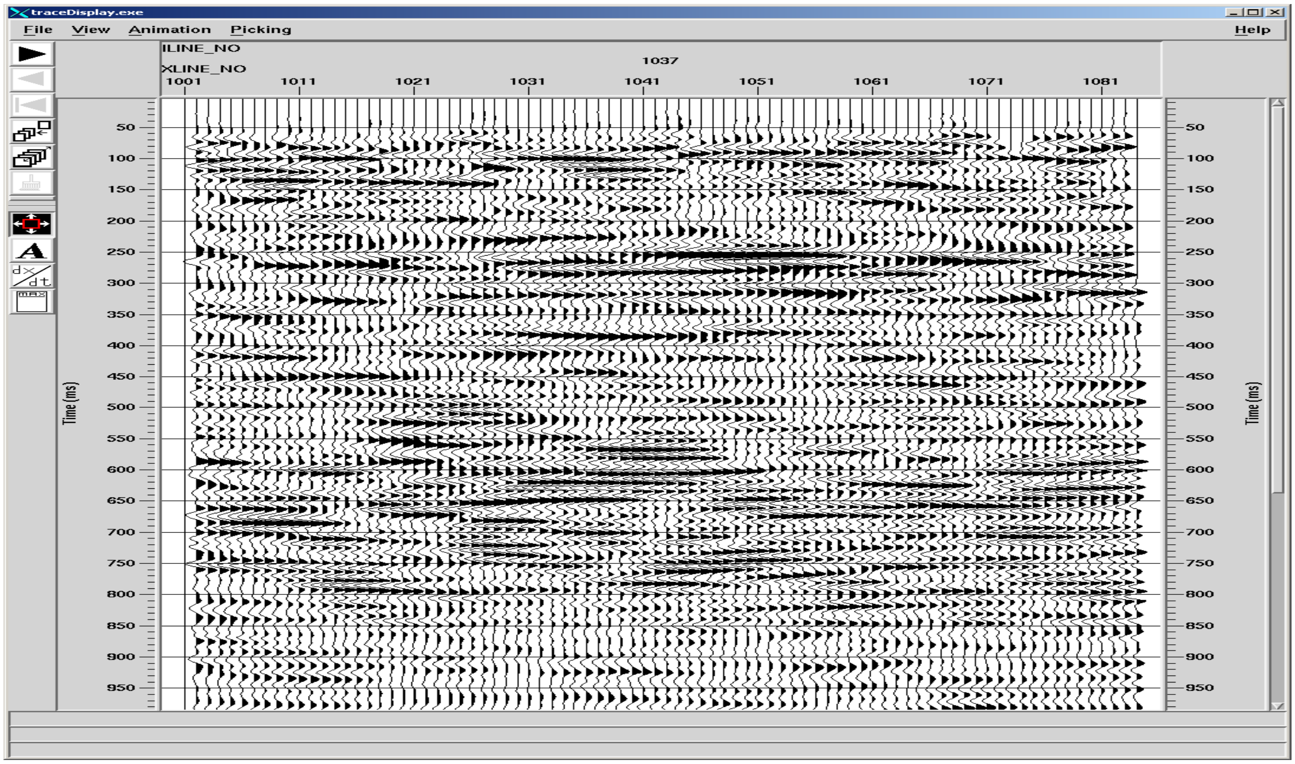
INLINE 1037 - BRUTE STACK WITH REFRACTION STATICS



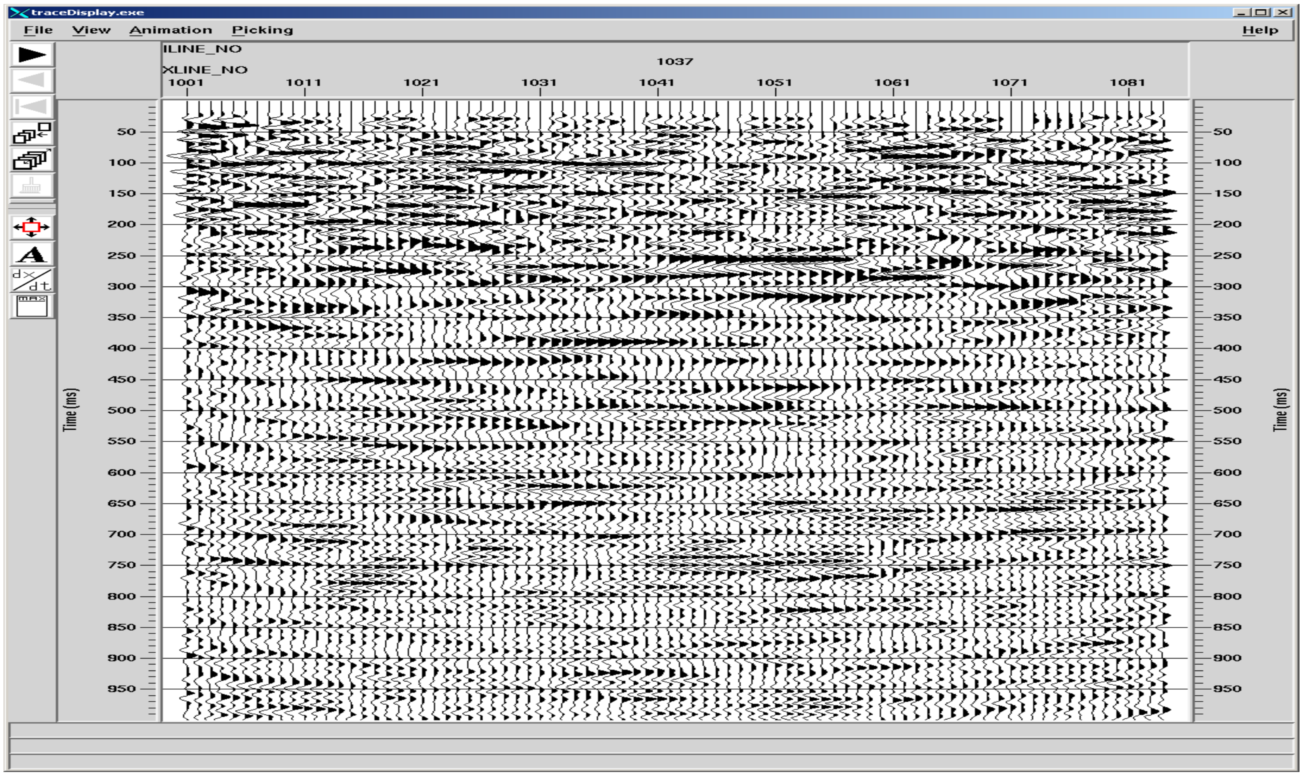
INLINE 1037 - DECON STACK



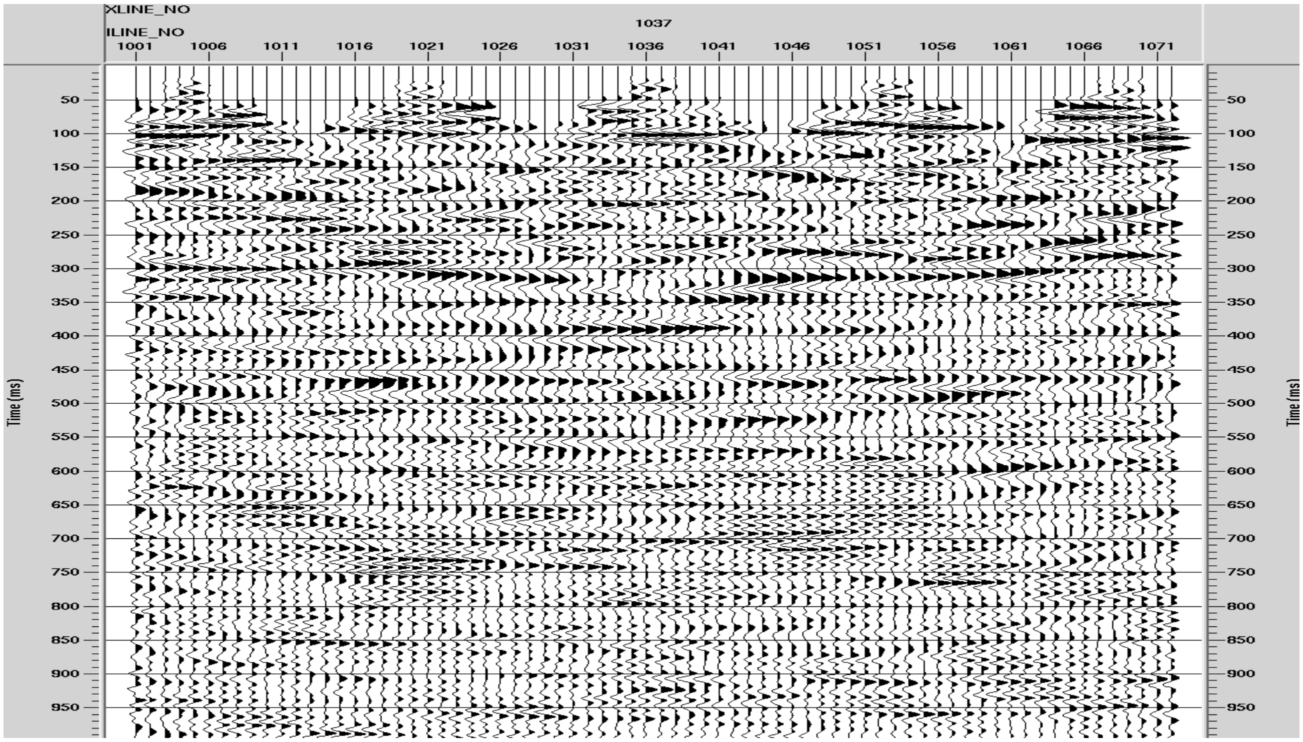
INLINE 1037 – FINAL STACK WITH STRONG NOISE REDUCTION



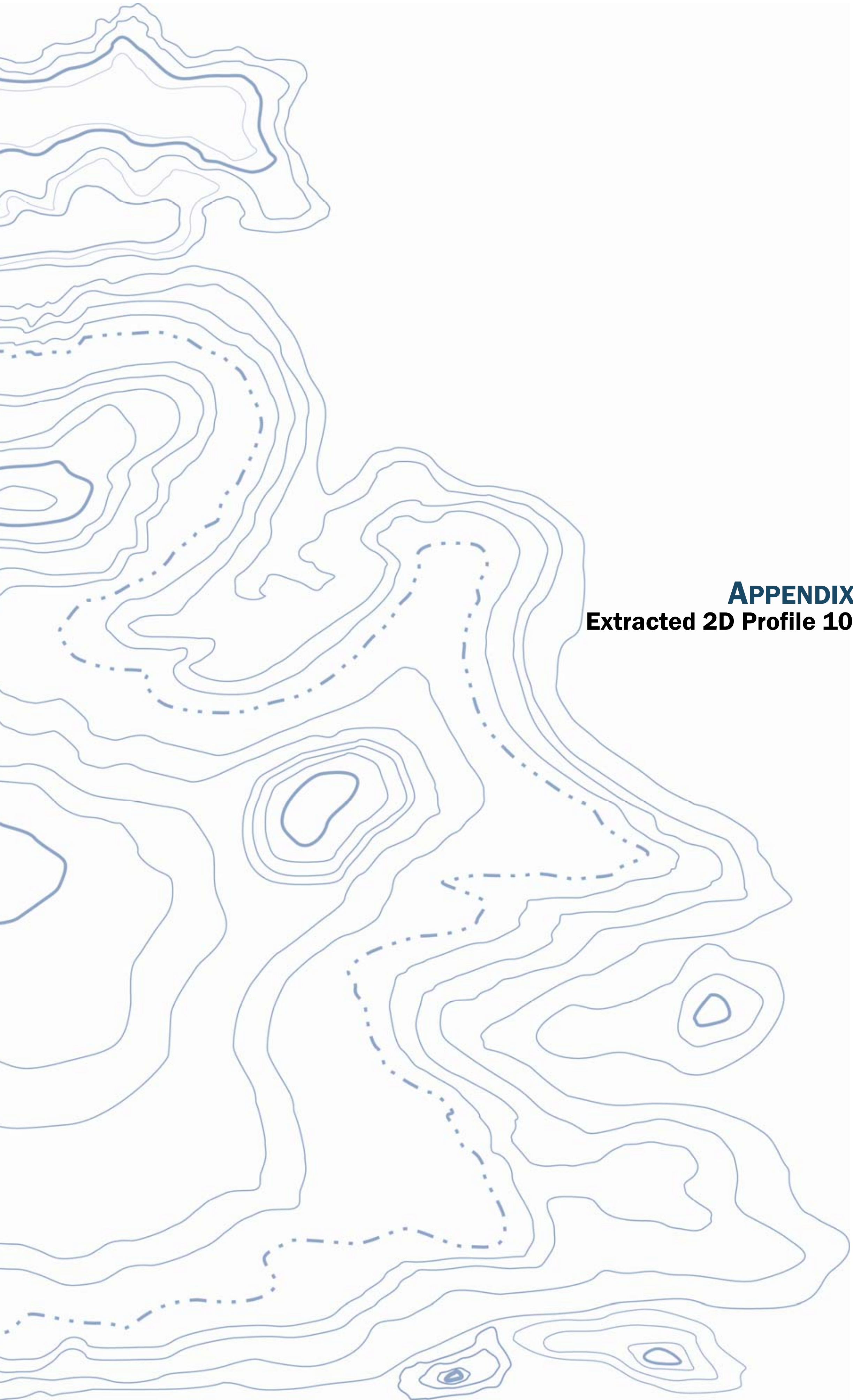
INLINE 1037 -POST-STACK MIGRATION WITH STRONG NOISE REDUCTION



INLINE 1037 – PRE-STACK MIGRATION WITH STRONG NOISE REDUCTION

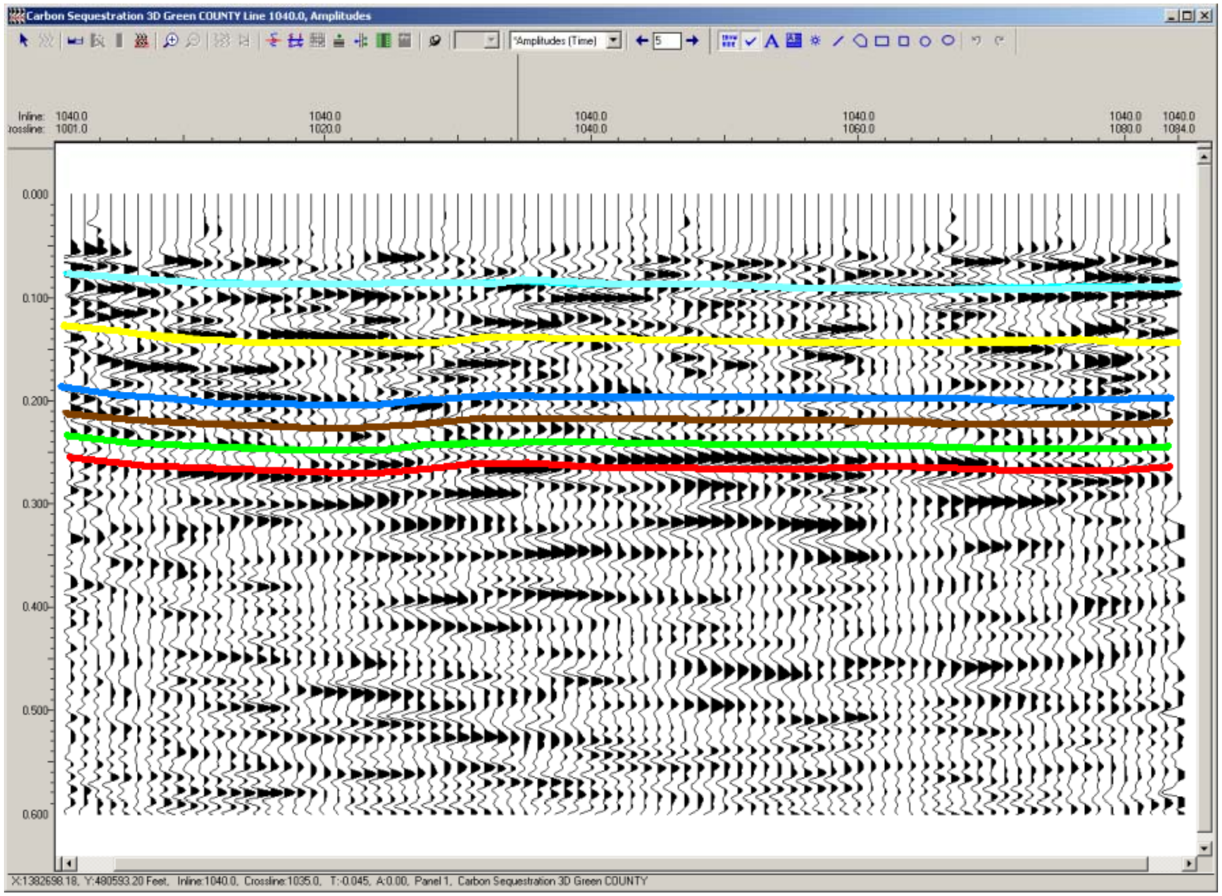


XLINE 1037 – PRE-STACK MIGRATION WITH STRONG NOISE REDUCTION



Appendix B

Extracted 2D Profile 1040



Carbon Sequestration 3D Green COUNTY Line 1040.0, Amplitudes

X:1382698.18, Y:480593.20 Feet, Inline:1040.0, Crossline:1035.0, T:-0.045, A:0.00, Panel 1, Carbon Sequestration 3D Green COUNTY

Interpreted 2-D in-line seismic profile 1040. This 2-D profile was extracted from the 3-D data set to illustrate data quality and interpretations. Seismic correlation is approximate and represents an interpretation only.

Symbol	Interpreted Structure
🟦	Top Lower Gasconade
🟨	Top Eminence
🟦	Top Davis
🟫	Top Bonneterre
🟩	Top Lamotte
🟥	Top Precambrian

Extracted 2D Profile 1040

City Utilities of Springfield
Carbon Sequestration Geophysical
Investigation

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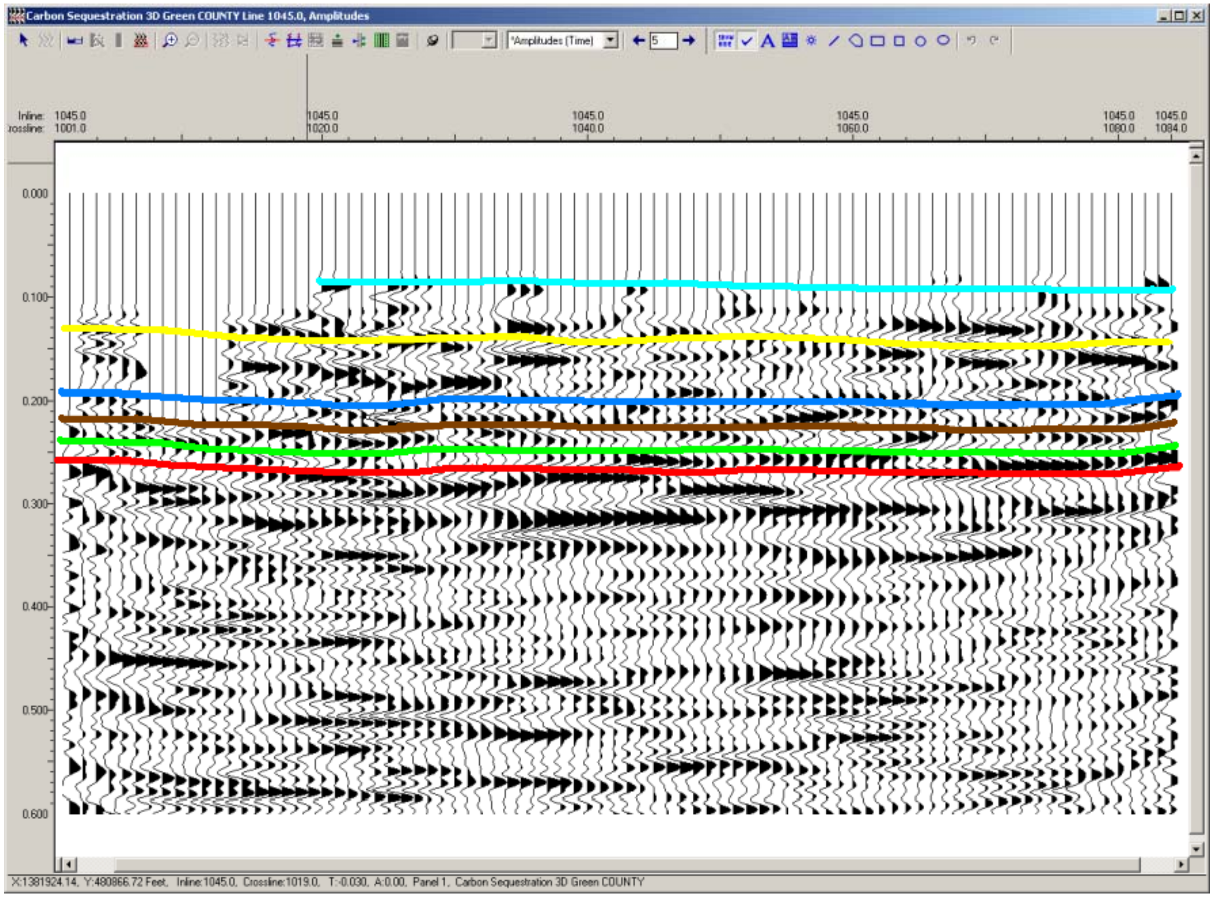
Figure B-1


Carbon Sequestration 3D Green COUNTY Line 1045.0, Amplitudes

X:1381924.14, Y:480866.72 Feet, Inline:1045.0, Crossline:1019.0, T:-0.030, A:0.00, Panel 1, Carbon Sequestration 3D Green COUNTY

Interpreted 2-D in-line seismic profile 1045. This 2-D profile was extracted from the 3-D data set to illustrate data quality and interpretations. Seismic correlation is approximate and represents an interpretation only.

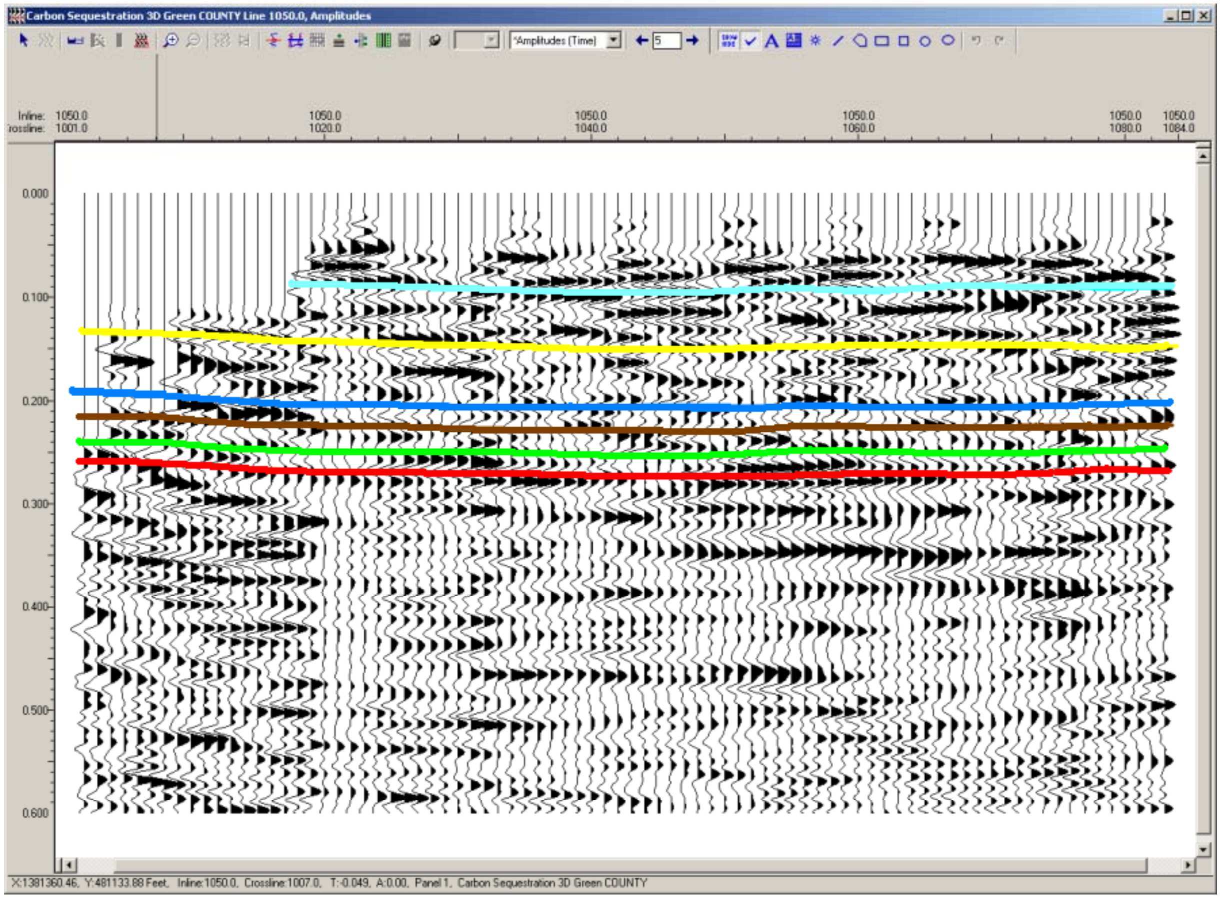
Symbol	Interpreted Structure
▬	Top Lower Gasconade
▬	Top Eminence
▬	Top Davis
▬	Top Bonneterre
▬	Top Lamotte
▬	Top Precambrian

Extracted 2D Profile 1045

City Utilities of Springfield
Carbon Sequestration Geophysical
Investigation

GEOENGINEERS

Figure B-2



X:1381360.46, Y:481133.88 Feet, Inline:1050.0, Crossline:1007.0, T:-0.049, A:0.00, Panel 1, Carbon Sequestration 3D Green COUNTY

Interpreted 2-D in-line seismic profile 1050. This 2-D profile was extracted from the 3-D data set to illustrate data quality and interpretations. Seismic correlation is approximate and represents an interpretation only.

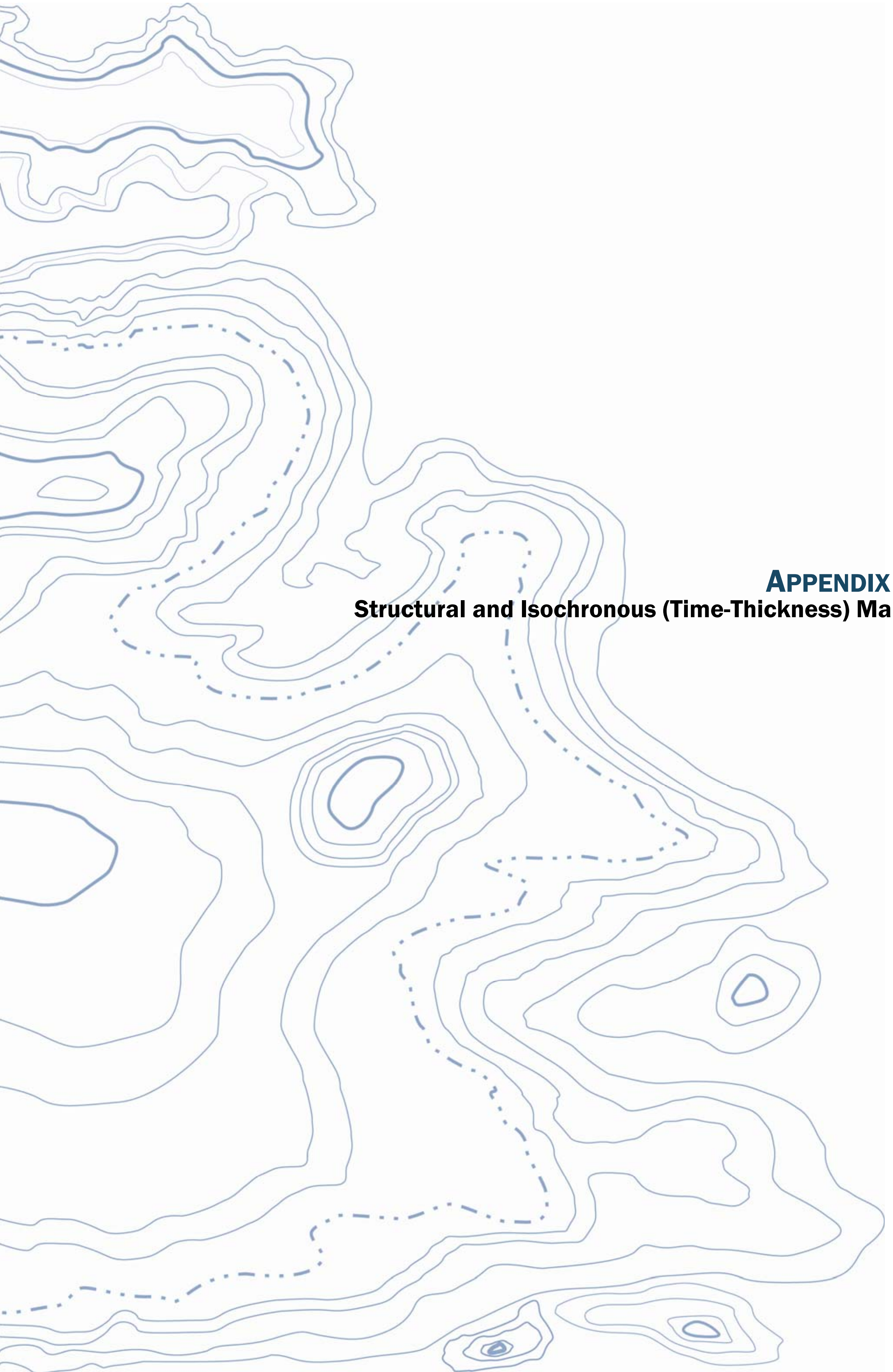
Symbol	Interpreted Structure
—	Top Lower Gasconade
—	Top Eminence
—	Top Davis
—	Top Bonneterre
—	Top Lamotte
—	Top Precambrian

Extracted 2D Profile 1050

City Utilities of Springfield
Carbon Sequestration Geophysical
Investigation

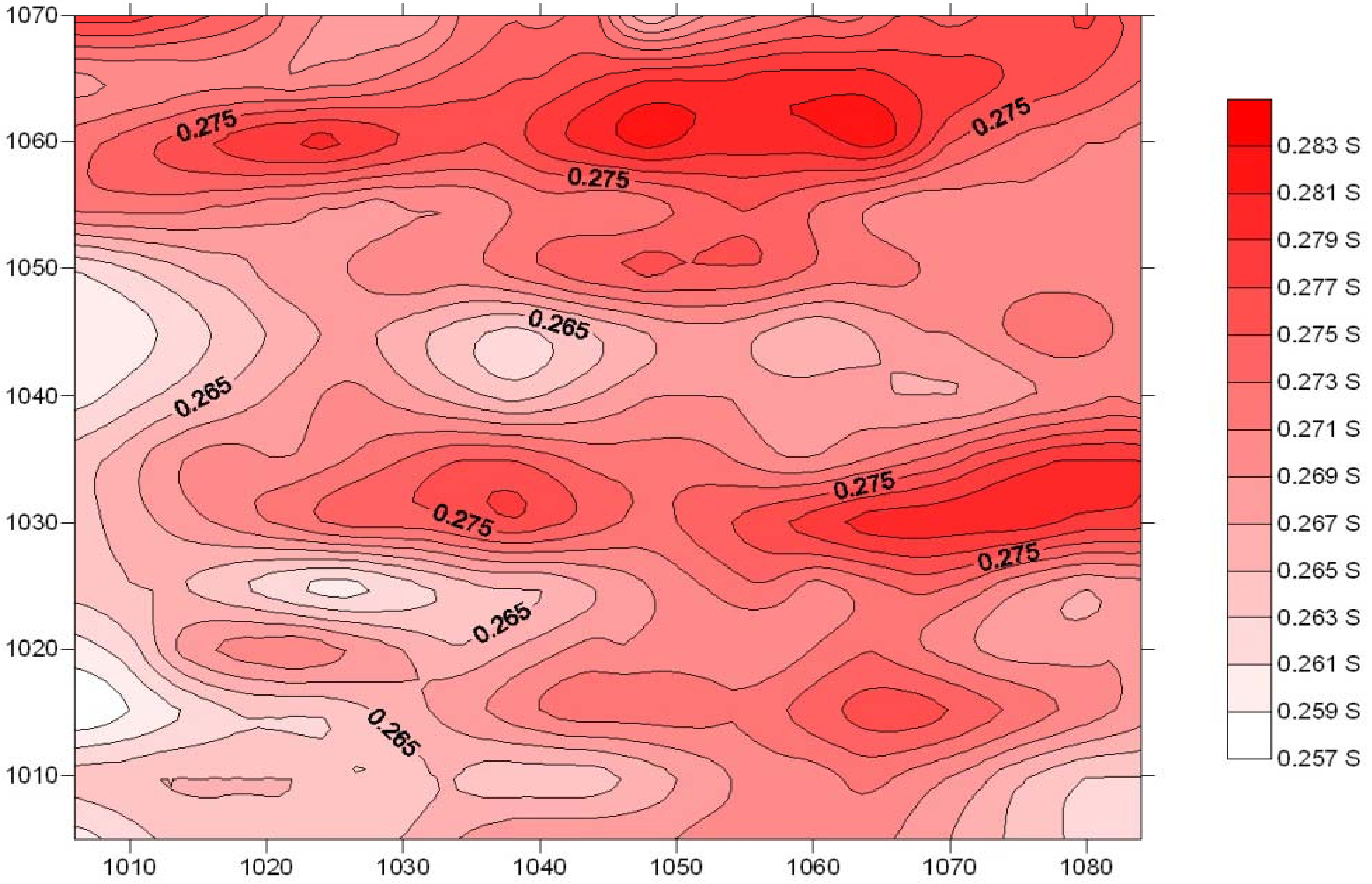
GEOENGINEERS

Figure B-3



APPENDIX C

Structural and Isochronous (Time-Thickness) Maps



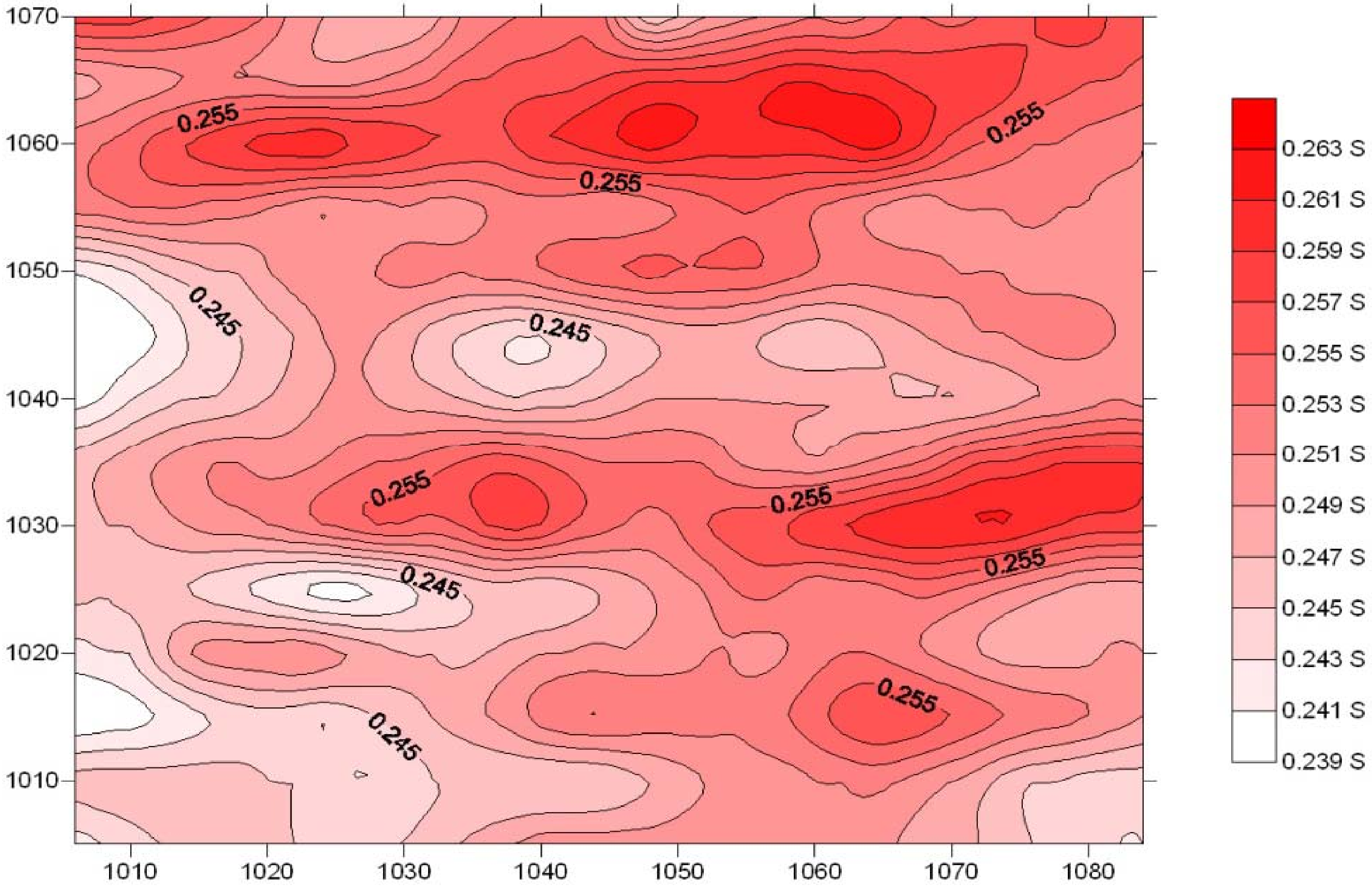
Top Precambrian time-structure map in seconds. Each millisecond (0.001 s) of time structural relief could represent up to 8 ft of structural relief (assuming an average velocity of 16000 ft/s). However, the observed time structural relief may not be attributable to "real" structure. Rather, it is likely mostly attributable to karst-related velocity variations within the shallow subsurface.

Top Pre-Cambrian Time-Structure Map

City Utilities of Springfield
Carbon Sequestration Geophysical Investigation

GEOENGINEERS

Figure C-1



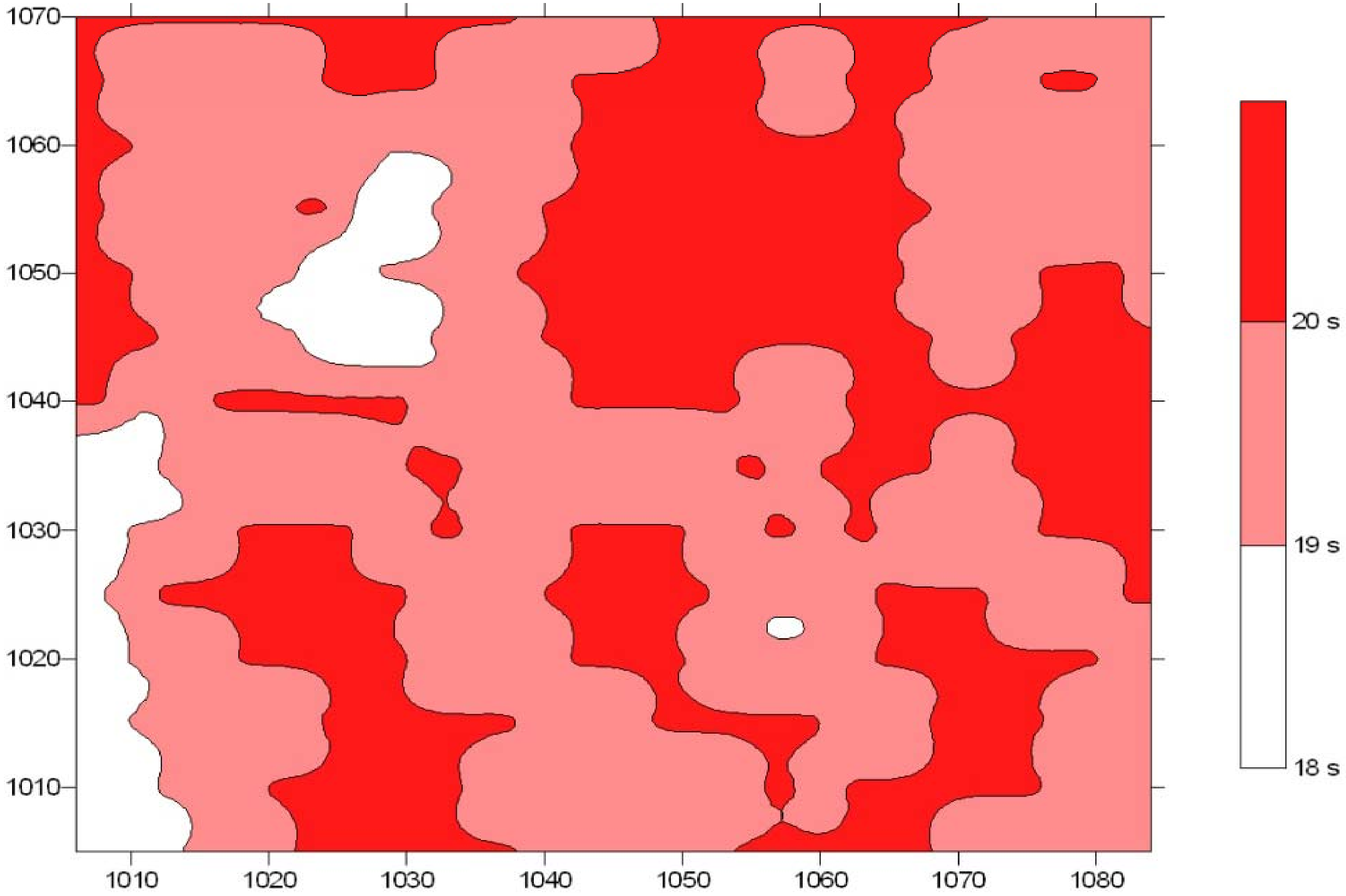
Top Lamotte time-structure map in seconds. Each millisecond (0.001 s) of time structural relief could represent up to 8 ft of structural relief (assuming an interval velocity of 16000 ft/s). However, the observed time structural relief may not be attributable to “real” structure. Rather, it is likely mostly attributable to karst-related velocity variations within the shallow subsurface.

Top Lamotte Time-Structure Map

City Utilities of Springfield
Carbon Sequestration Geophysical Investigation

GEOENGINEERS

Figure C-2



Top Lamotte/Top Precambrian isochronous (time-thickness) map in milliseconds (0.001 s). Each millisecond of additional time thickness could represent up to 8 ft of structural relief (assuming an average velocity of 16000 ft/s).

Top Lamotte/Top Pre-Cambrian Time-Thickness Map

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Carbon Sequestration Geophysical Investigation

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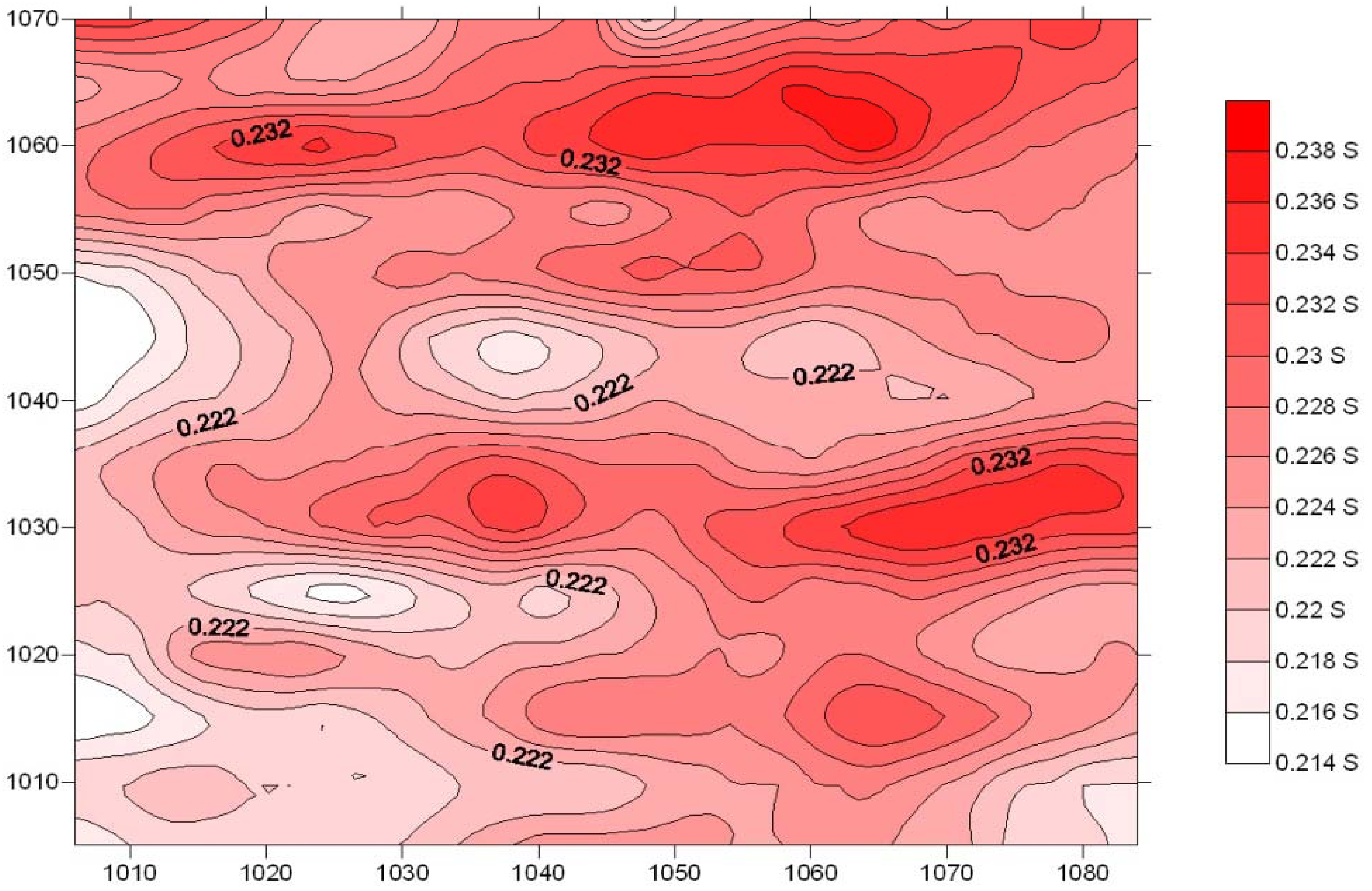
Figure C-3



Top Bonneterre time-structure map in seconds. The interpreter believes the interpreted time-structural relief is mostly attributable to velocity variations within shallow bedrock.

Top Bonneterre Time-Structure Map

City Utilities of Springfield
Carbon Sequestration Geophysical Investigation

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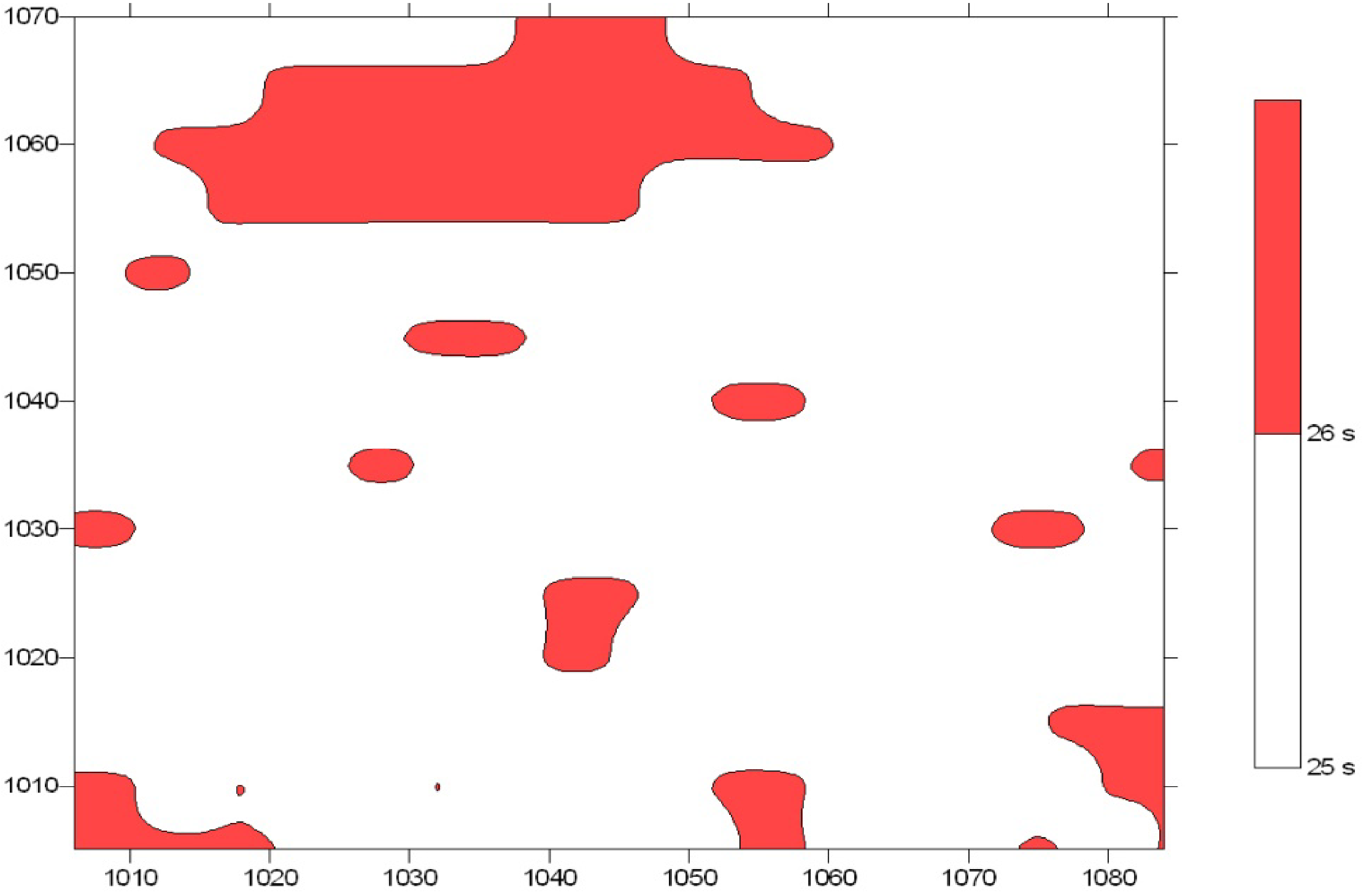
Figure C-4



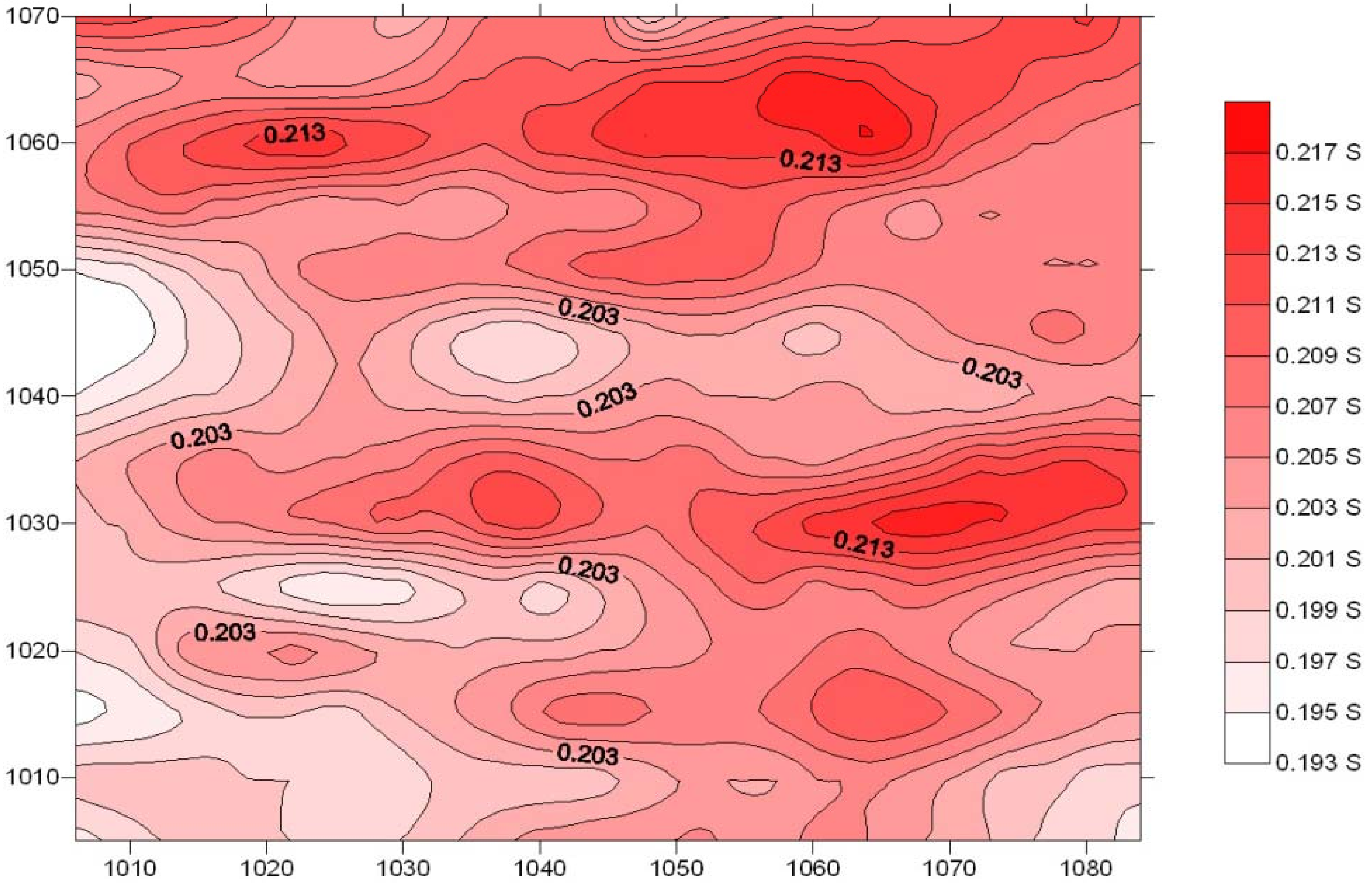
Top Bonneterre/Top Lamotte isochronous (time-thickness) map in milliseconds (0.001 s). Each millisecond of additional time thickness could represent up to 8 ft of structural relief (assuming an average velocity of 16000 ft/s).

Top Bonneterre/Top Lamotte Time-Thickness Map

City Utilities of Springfield
Carbon Sequestration Geophysical Investigation

GEOENGINEERS

Figure C-5



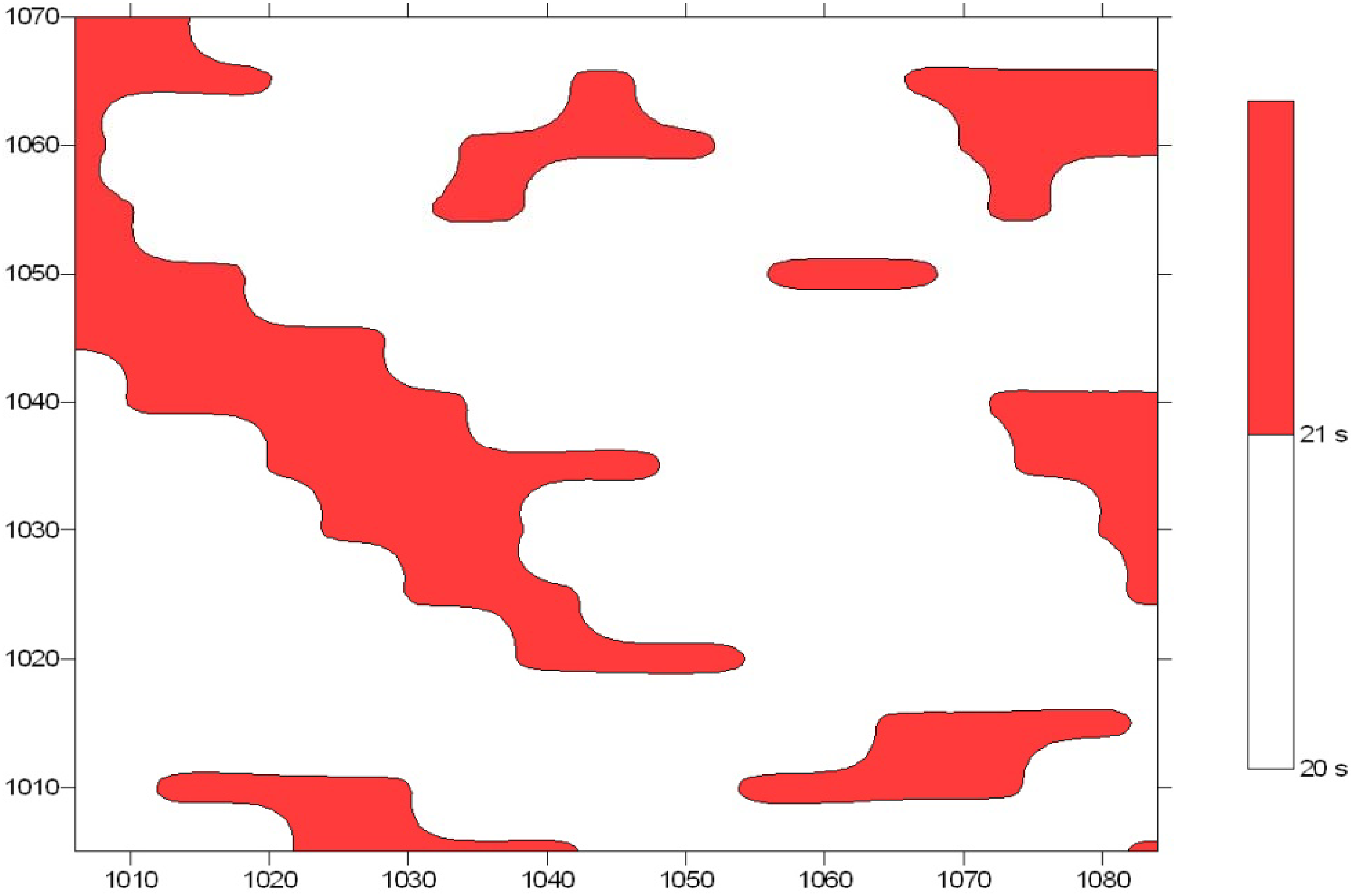
Top Davis time-structure map in seconds. The interpreter believes the interpreted time-structural relief is mostly attributable to velocity variations within shallow bedrock.

Top Davis Time-Structure Map

City Utilities of Springfield
Carbon Sequestration Geophysical Investigation

GeoEngineers

Figure C-6



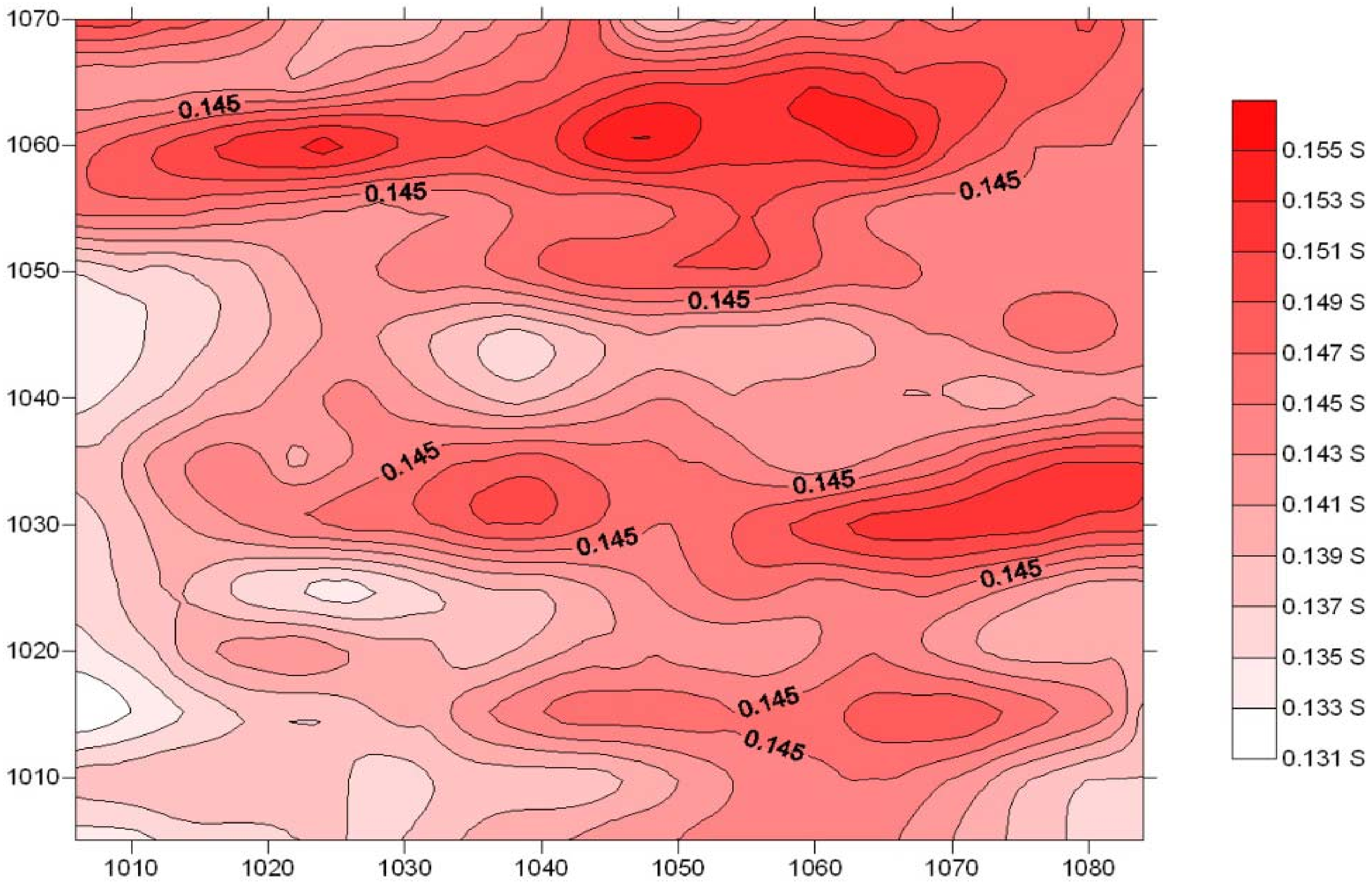
Top Davis /Top Bonneterre isochronous (time-thickness) map in milliseconds (0.001 s). Each millisecond of additional time thickness could represent up to 8 ft of structural relief (assuming an average velocity of 16000 ft/s).

Top Davis/Top Bonneterre Time-Thickness Map

City Utilities of Springfield
Carbon Sequestration Geophysical Investigation

GEOENGINEERS

Figure C-7



Top Eminence time-structure map in seconds. The interpreted time-structural relief is likely mostly attributable to velocity variations within shallow bedrock.

Top Eminence Time-Structure Map

City Utilities of Springfield
Carbon Sequestration Geophysical Investigation

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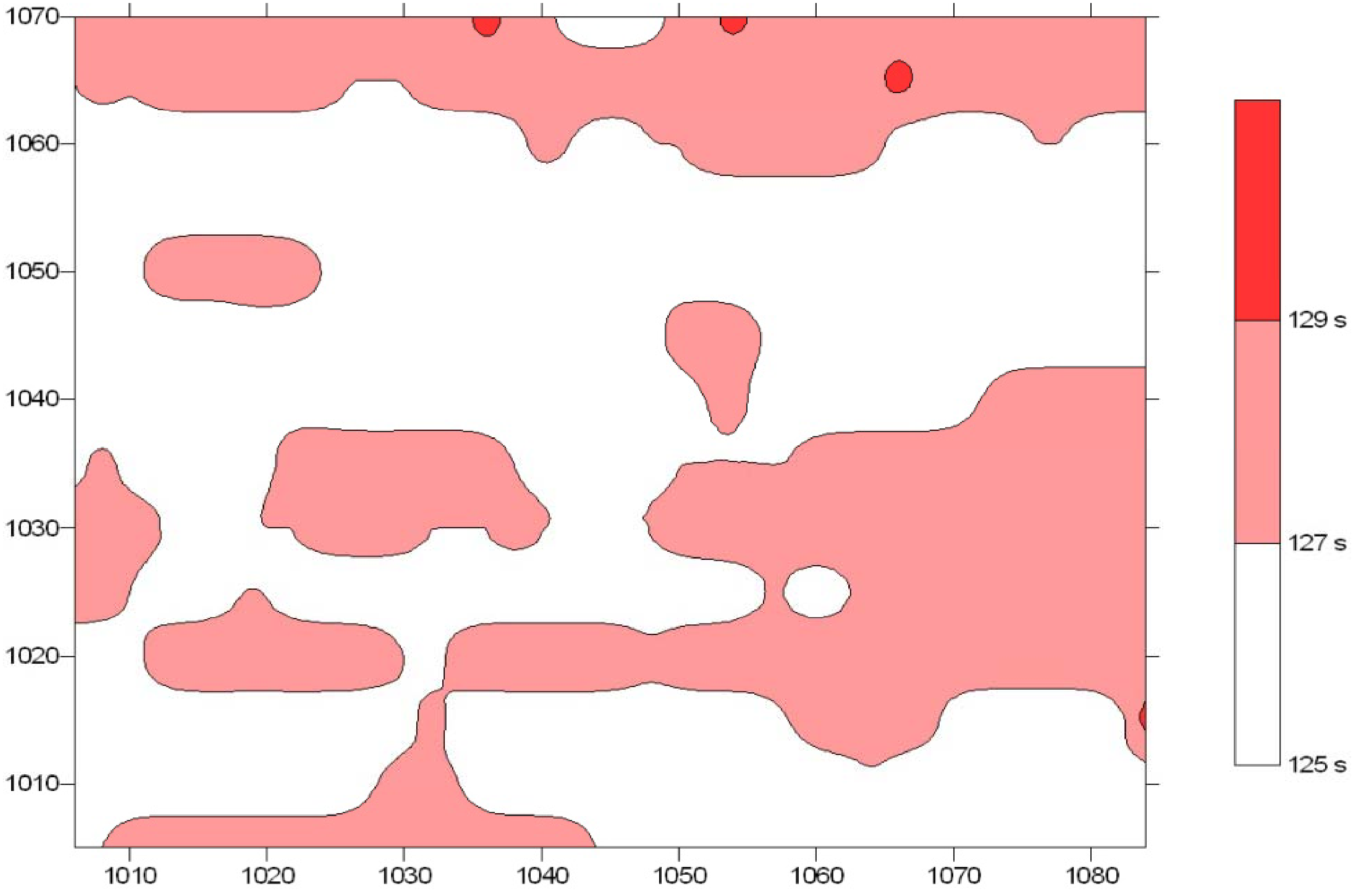
Figure C-8



Top Eminence/Top Davis isochronous (time-thickness) map in milliseconds (0.001 s). Each millisecond of additional time thickness could represent up to 8 ft of structural relief (assuming an average velocity of 16000 ft/s).

Top Eminence/Top Davis Time-Thickness Map

City Utilities of Springfield
Carbon Sequestration Geophysical Investigation

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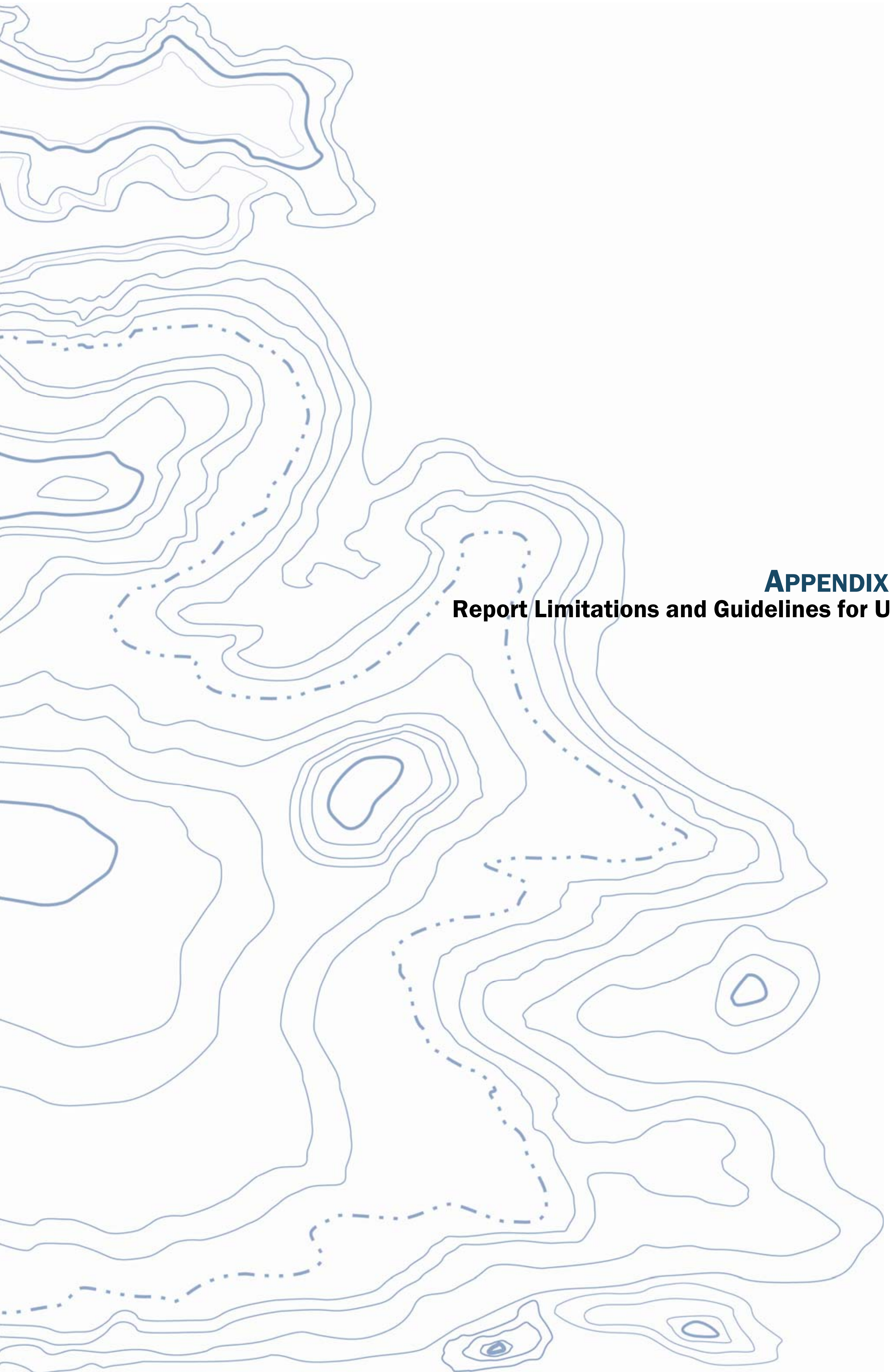
Figure C-9



APPENDIX D

Report Limitations and Guidelines for Use

APPENDIX D
REPORT LIMITATIONS AND GUIDELINES FOR USE[1]

This Appendix provides information to help you manage your risks with respect to the use of this report.

Geotechnical Services Are Performed for Specific Purposes, Persons and Projects

This report has been prepared for the exclusive use of City Utilities of Springfield, and their authorized agents for the Carbon Sequestration Geophysical Investigation. This report is not intended for use by others, and the information contained herein is not applicable to other sites.

GeoEngineers structures our services to meet the specific needs of our clients. For example, a geotechnical or geologic study conducted for a civil engineer or architect may not fulfill the needs of a construction contractor or even another civil engineer or architect that are involved in the same project. Because each geotechnical or geologic study is unique, each geotechnical engineering or geologic report is unique, prepared solely for the specific client and project site. Our report is prepared for the exclusive use of our Client. No other party may rely on the product of our services unless we agree in advance to such reliance in writing. This is to provide our firm with reasonable protection against open-ended liability claims by third parties with whom there would otherwise be no contractual limits to their actions. Within the limitations of scope, schedule and budget, our services have been executed in accordance with our Agreement with the Client and generally accepted geotechnical practices in this area at the time this report was prepared. This report should not be applied for any purpose or project except the one originally contemplated.

A Geotechnical Engineering or Geologic Report Is Based on a Unique Set of Project-Specific Factors

GeoEngineers considered a number of unique, project-specific factors when establishing the scope of services for this project and report. Unless GeoEngineers specifically indicates otherwise, do not rely on this report if it was:

- not prepared for you,
- not prepared for your project,
- not prepared for the specific site explored, or
- completed before important project changes were made.

For example, changes that can affect the applicability of this report include those that affect:

- the function of the proposed structure;
- elevation, configuration, location, orientation or weight of the proposed structure;

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[1] Developed based on material provided by ASFE/The Best People on Earth, Professional Firms Practicing in the Geosciences; www.asfe.org.

- composition of the design team; or
- project ownership.

If important changes are made after the date of this report, should be given the opportunity to review our interpretations and recommendations and provide written modifications or confirmation, as appropriate.

Subsurface Conditions Can Change

This geotechnical or geologic report is based on conditions that existed at the time the study was performed. The findings and conclusions of this report may be affected by the passage of time, by manmade events such as construction on or adjacent to the site, or by natural events such as floods, earthquakes, slope instability or ground water fluctuations. Always contact GeoEngineers before applying a report to determine if it remains applicable.

Topsoil

For the purposes of this report, we consider topsoil to consist of generally fine-grained soil with an appreciable amount of organic matter, based on visual examination, and to be unsuitable for direct support of the proposed improvements. However, the organic content and other mineralogical and gradational characteristics used to evaluate the suitability of soil for use in landscaping and agricultural purposes were not determined, nor were they considered in our analyses. Therefore, the information and recommendations in this report, and our logs and descriptions, should not be used as a basis for estimating the volume of topsoil available for such purposes.

Most Geotechnical and Geologic Findings Are Professional Opinions

Our interpretations of subsurface conditions are based on field observations from widely spaced sampling locations at the site. Site exploration identifies subsurface conditions only at those points where subsurface tests are conducted or samples are taken. GeoEngineers reviewed field and laboratory data and then applied our professional judgment to render an opinion about subsurface conditions throughout the site. Actual subsurface conditions may differ, sometimes significantly, from those indicated in this report. Our report, conclusions and interpretations should not be construed as a warranty of the subsurface conditions.

Geotechnical Engineering Report Recommendations Are Not Final

Do not over-rely on the preliminary construction recommendations included in this report. These recommendations are not final, because they were developed principally from GeoEngineers' professional judgment and opinion. GeoEngineers' recommendations can be finalized only by observing actual subsurface conditions revealed during construction. GeoEngineers cannot assume responsibility or liability for this report's recommendations if we do not perform construction observation.

Sufficient monitoring, testing and consultation by GeoEngineers should be provided during construction to confirm that the conditions encountered are consistent with those indicated by the explorations, to provide recommendations for design changes should the conditions revealed during the work differ from those expected, and to evaluate whether or not earthwork activities are completed in accordance with our recommendations. Retaining GeoEngineers for construction observation for this project is the most effective method of managing the risks associated with unexpected conditions.

A Geotechnical Engineering or Geologic Report Could Be Subject to Misinterpretation

Misinterpretation of this report by other design team members can result in costly problems. You could lower that risk by having GeoEngineers confer with appropriate members of the design team after submitting the report. Also retain GeoEngineers to review pertinent elements of the design team's plans and specifications. If important changes are made after the date of this report, GeoEngineers should be given the opportunity to review our interpretations and recommendations and provide written modifications or confirmation, as appropriate.

Subsurface Conditions Can Change

This report is based on conditions that existed at the time the study was performed. The findings and conclusions of this report may be affected by the passage of time, by manmade events such as construction on or adjacent to the site, by new releases of hazardous substances, or by natural events such as floods, earthquakes, slope instability or groundwater fluctuations. Always contact GeoEngineers before applying a report to determine if it remains applicable.

Most Geotechnical and Environmental Findings Are Professional Opinions

Our interpretations of subsurface conditions are based on field observations and laboratory test results from widely spaced sampling locations at the site. Site exploration identifies subsurface conditions only at those points where subsurface tests are conducted or samples are taken. GeoEngineers reviewed field and laboratory data and then applied our professional judgment to render an opinion about subsurface conditions throughout the site. Actual subsurface conditions may differ, sometimes significantly, from those indicated in this report. Our report, conclusions and interpretations should not be construed as a warranty of the subsurface conditions.

Geotechnical Engineering Report Recommendations Are Not Final

Do not over-rely on the preliminary construction recommendations included in this report. These recommendations are not final, because they were developed principally from GeoEngineers' professional judgment and opinion. GeoEngineers' recommendations can be finalized only by observing actual subsurface conditions revealed during construction. GeoEngineers cannot assume responsibility or liability for this report's recommendations if we do not perform construction observation.

Sufficient monitoring and consultation by GeoEngineers should be provided during construction to confirm that the conditions encountered are consistent with those indicated by the explorations, to provide recommendations for design changes should the conditions revealed during the work differ from those anticipated, and to evaluate whether or not construction activities are completed in accordance with our recommendations. Retaining GeoEngineers for construction observation for this project is the most effective method of managing the risks associated with unanticipated conditions.

A Geotechnical Engineering or Geologic Report Could Be Subject to Misinterpretation

Misinterpretation of this report by other design team members can result in costly problems. You could lower that risk by having GeoEngineers confer with appropriate members of the design team after submitting the report. Also retain GeoEngineers to review pertinent elements of the design team's plans and specifications. Contractors can also misinterpret a geotechnical engineering or geologic report. Reduce that risk by having GeoEngineers participate in pre-bid and preconstruction conferences, and by providing construction observation.

Do Not Redraw the Exploration Logs

Geotechnical engineers and geologists prepare final boring and testing logs based upon their interpretation of field logs and laboratory data. To prevent errors or omissions, the logs included in a geotechnical engineering or geologic report should never be redrawn for inclusion in architectural or other design drawings. Only photographic or electronic reproduction is acceptable, but recognize that separating logs from the report can elevate risk.

Give Contractors a Complete Report and Guidance

Some owners and design professionals believe they can make contractors liable for unanticipated subsurface conditions by limiting what they provide for bid preparation. To help prevent costly problems, give contractors the complete geotechnical engineering or geologic report, but preface it with a clearly written letter of transmittal. In that letter, advise contractors that the report was not prepared for purposes of bid development and that the report's accuracy is limited; encourage them to confer with GeoEngineers and/or to conduct additional study to obtain the specific types of information they need or prefer. A pre-bid conference can also be valuable. Be sure contractors have sufficient time to perform additional study. Only then might an owner be in a position to give contractors the best information available, while requiring them to at least share the financial responsibilities stemming from unanticipated conditions. Further, a contingency for unanticipated conditions should be included in your project budget and schedule.

Contractors Are Responsible for Site Safety on Their Own Construction Projects

Our geotechnical recommendations are not intended to direct the contractor's procedures, methods, schedule or management of the work site. The contractor is solely responsible for job site safety and for managing construction operations to minimize risks to on-site personnel and to adjacent properties.

Read These Provisions Closely

Some clients, design professionals and contractors may not recognize that the geoscience practices (geotechnical engineering or geology) are far less exact than other engineering and natural science disciplines. This lack of understanding can create unrealistic expectations that could lead to disappointments, claims and disputes. GeoEngineers includes these explanatory "limitations" provisions in our reports to help reduce such risks. Please confer with GeoEngineers if you are unclear how these "Report Limitations and Guidelines for Use" apply to your project or site.

Biological Pollutants

GeoEngineers' Scope of Work specifically excludes the investigation, detection, prevention or assessment of the presence of Biological Pollutants. Accordingly, this report does not include any interpretations, recommendations, findings, or conclusions regarding the detecting, assessing, preventing or abating of Biological Pollutants and no conclusions or inferences should be drawn regarding Biological Pollutants, as they may relate to this project. The term "Biological Pollutants" includes, but is not limited to, molds, fungi, spores, bacteria, and viruses, and/or any of their byproducts.

If Client desires these specialized services, they should be obtained from a consultant who offers services in this specialized field.

Have we delivered World Class Client Service?

Please let us know by visiting **www. geoengineers.com/feedback**.

GeoEngineers

Shallow Carbon Sequestration Demonstration Project

DOE NT0006642

Missouri Department of Natural Resources

Final Project Report

Reporting Period Start Date

10/01/2008

Reporting Period End Date

9/30/2013

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Rolla, Missouri

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Missouri Geological Survey

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Missouri Geological Survey

Rolla, MO

CHAPTER III. - MISSOURI GEOLOGICAL SURVEY

EXECUTIVE SUMMARY

The Shallow Carbon Sequestration Demonstration Project investigated the technical feasibility of carbon sequestration at four energy producing sites in Missouri. As part of the investigation the Missouri Geological Survey Program (GSP) described drill cuttings and core, identified rock units, estimated porosity and permeability of rock units, formulated the local structural setting of each site, and collected water samples to determine water quality of target aquifers.

The first borehole was extended to Precambrian basement rock at the John Twitty Energy Center (JTEC). The regional hydrogeology of the site consists of three aquifer systems separated by two regional confining units. The St. Francois confining unit isolates the targeted St. Francois aquifer from overlying aquifers. Water samples collected from the St. Francois aquifer at JTEC contained Total Dissolved Solids (TDS) concentrations of 153 milligrams per Liter (mg\L). The regional dip, measured at the top of the Elvins Group (Derby-Doerun Dolomite and Davis Formation) is approximately 20 feet per mile to the northeast. Based on surrounding well logs, a small local anticline may be present in the subsurface. The site is located between two northwest-southeast trending structural features, the Sac River-Battlefield Graben and the Fassnight Fault.

Precambrian basement rock also was encountered in the second borehole at the Thomas Hill Energy Center (THEC). The regional hydrogeology of this site consists of four regional aquifer systems separated by a regional confining unit. The lower Cambrian-Ordovician aquifer approximately correlates to the St. Francois aquifer and is separated from the upper Cambrian-Ordovician aquifer, equivalent to the Ozark aquifer, by a confining unit equivalent to the St. Francois confining unit. Water samples collected from the lower Cambrian–Ordovician aquifer at THEC contained TDS concentrations of 50,800 mg/L. The regional dip of the top of the Derby–Doerun Dolomite is approximately 11 feet per mile to the northwest. The site is located between two northwest-southeast trending regional structural features, the College Mound–Bucklin and Salisbury–Quitman anticlines. Numerous small faults also have been mapped in the between these structural features.

Drilling at the Iatan Generating Station (IGS) was halted due to caving of the borehole before reaching the targeted aquifer or potential confining units of interest. The hydrogeology of the site consists of three regional aquifer systems. A nearby cuttings log was used to estimate target aquifer thicknesses characteristics. Water samples were not collected from the site; however, TDS of the target aquifer is expected to be over 20,000 mg/L based on water quality data. The regional dip of the Derby–Doerun Dolomite's upper contact is approximately 11 feet per mile to the northwest. The Iatan structure, a possible collapse structure, is located 1.5 mile to the north of the site and is the only mapped structure within five miles of the site.

The targeted St. Francois aquifer was partially penetrated in the borehole located at the Sioux Power Plant (SPP) and potential confining units were identified above this aquifer. The water samples collected from the St. Francois aquifer at SPP contain TDS values with at a concentration of 43,800 mg/L. The regional dip of the Derby–Doerun's upper contact is approximately 80 feet per mile to the south. The site is located between two northwest-southeast structural features, the Waterloo–Dupo anticline and the Cheltenham syncline. The site, being located in proximity to these structural features, may have resulted in a local dip towards the southwest.

In addition to the description of drill core and cuttings, the Geological Survey Program also constructed several geologic cross-sections to illustrate stratigraphic intervals, general orientations and show relationships between bedrock units.

A. EXPERIMENTAL METHODS

A. Missouri Geological Survey Program Field Studies

As part of the Shallow Carbon Sequestration Demonstration Project, (SCSDP) staff from the Missouri Geological Survey Program (GSP) composed detailed geologic descriptions of drill cuttings and core from four borings. These descriptions were formulated through visual observation by hand lenses, testing for mineral hardness, and exposed to dilute 10% hydrochloric acid to determine carbonate minerals. The cuttings and core descriptions predominantly focus on recording mineralogy, fossil content, color, rock texture, grain size, crystal size, fractures and voids, bedding thickness, unit thickness, formational contacts and any other features that may have been deemed as significant lithological information.

Information was considered significant if it would lead to the identification of the rock unit, determination of a unit's porosity, permeability, or derivation of the surrounding hydrologic setting, or assisted with formulating the structural setting. Descriptions of cuttings were conducted on composite samples collected over a five foot interval. Descriptions of the core were conducted continuously as the core was extracted from the borehole.

Water samples were collected and analyzed by the Missouri Department of Natural Resources' Environmental Services Program laboratory after each borehole reached the target aquifer. Sample collection and analysis followed all documented protocols. Samples were analyzed to determine common metals and TDS concentrations. Data generated by GSP water sampling is intended to be compared to analyses derived from Missouri S&T water sampling.

B. Missouri Geological Survey Program Laboratory Studies

The GSP's staff processed the cuttings and core for further observation in the McCracken Core Library and Research Center. This research allowed more detailed study of lithological characteristics, porosity, alteration and mineralization, formational contacts, deformational and structural features, and/or any other characteristics exhibited in the samples. Rock cutting samples were split and washed, followed by a more detailed examination using a binocular microscope to confirm characteristics that had been determined in the field. Photomicrographs were taken of representative cuttings over five foot intervals. Cuttings and cores were visually examined to determine estimates of permeability of strata encountered in the borehole. Cross sections for each individual site were created by plotting the stratigraphic log of the borehole in comparison to DGLS archived well logs. A state-wide cross section was created using data collected from each of the project's exploratory boreholes (Figure 3.1). Regional scale structures of target formations were determined from an unpublished structure contour map created by GSP staff. Local structural features in the vicinity of the boreholes were identified from various geologic and structural maps.

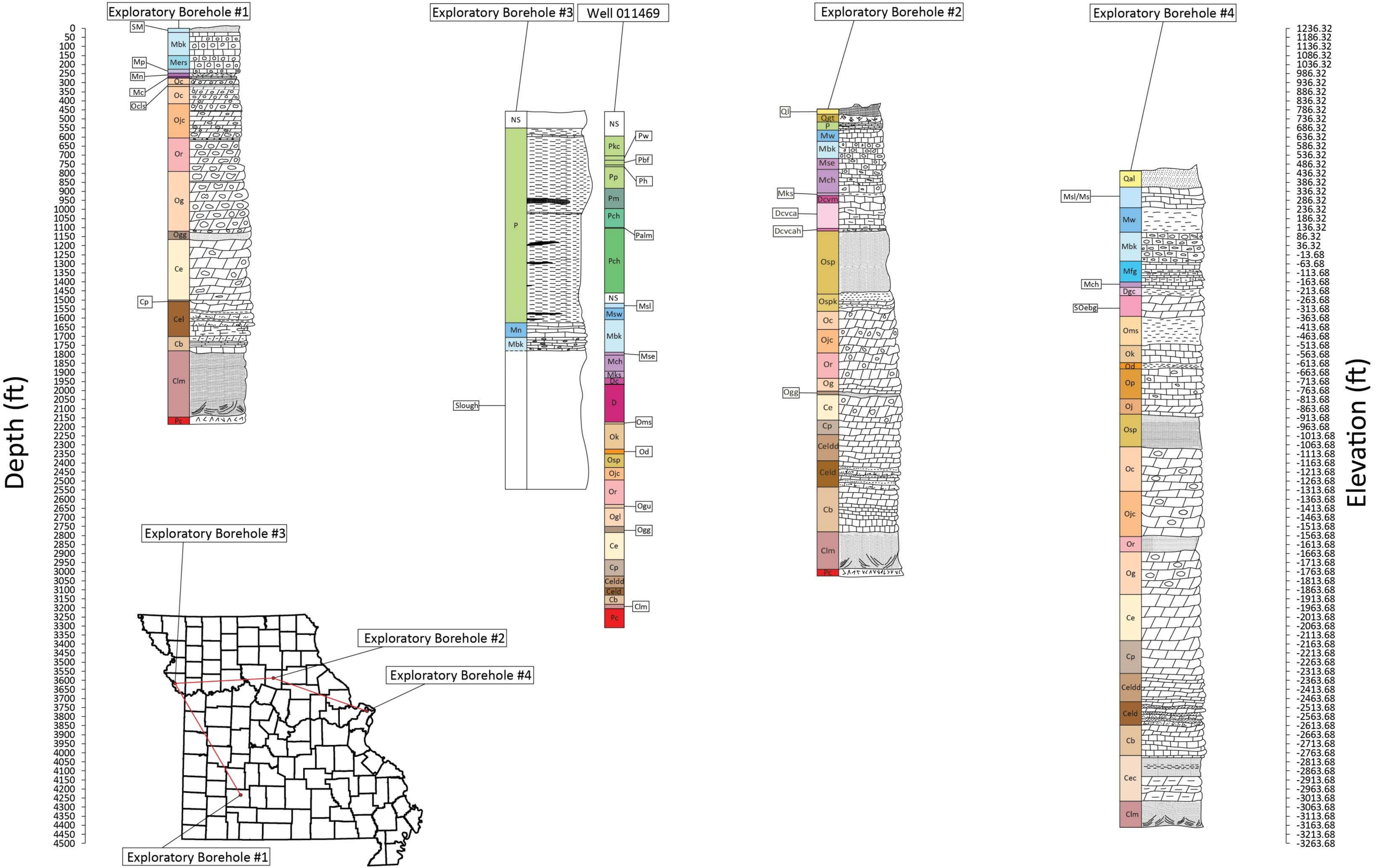


FIGURE 3.1. STATE WIDE CROSS SECTION OF EXPLORATORY BOREHOLES #1-4. STRATIGRAPHIC SYMBOLOGY IS DEFINED IN TABLES 3.2, 3.4, 3.6 AND 3.8.

I. JOHN TWITTY ENERGY CENTER

A. Introduction

This section describes the bedrock and hydrologic units encountered during the drilling of borehole #1 at JTEC. This borehole was drilled over the course of several months. Drilling started in May of 2010 and was completed in November of 2010. The purpose was to determine the hydrologic properties of the St. Francois aquifer and the presence and characteristics of overlying confining units. Water samples for the St. Francois aquifer were collected and analyzed to determine the chemical composition, and primary metals and TDS concentrations of the water.

B. Deviations from Standard Methods

Wire-line geophysical logs and down-hole video of the borehole were compared to cuttings and core descriptions to refine the stratigraphic logs.

C. Site Location

The JTEC Borehole #1 is located in Greene County, Missouri, southwest of Springfield, near the community of Brookline. The site is located in the northwest quarter of section 7, T 28 N, R 22 W approximately 680 feet southwest of the intersection of W. Farm Road 164 and S. Farm Road 11 (Figure 3.1). This borehole is located at 37° 09' 09.71" north latitude 93° 22' 48.51" west longitude, as illustrated on the topographic map in Figure 3.2. Figure 3.3 is an aerial photo of the site and location of the borehole.

D. Geologic Setting

The site is situated on the Springfield Plateau, within the James River Basin. The study area is characterized by an extensive karst plateau dissected by steeply sloped tributaries of the James River.

Surface bedrock is Mississippian-age limestone and chert of the Burlington Limestone. Within the study area and the surrounding region the Burlington Limestone displays extensive solution weathering features such as sinkholes, losing streams, and caves. Previous investigations in the region have shown that surface water moves vertically into the subsurface through solution enlarged conduits, connecting the regional aquifer to the surface in an extremely open system. Surficial materials consist of thick, cherty, clayey residuum overlying bedrock in the uplands, with alluvial chert cobbles and gravels intermixed with sand being found in the low-lying elevations adjacent to the streambeds. Elevation at the top of the surface casing for this borehole was 1,236.32 feet above mean sea level.

E. Geologic Structure

At the JTEC site the regional dip of the top of the Elvins Group is approximately 20 feet per mile to the northeast (Crews & Bone, 2010). Locally a small anticline may be present in the subsurface however deep stratigraphic control is not sufficient to determine this definitively. The site is located between two structural features. The Sac River–Battle Field Graben is located 2.25 miles to the southwest of the site (Robertson, 1990). This northwest-southeast trending structural feature is a localized expression of the extensive Sac River–Battle Field Fault. The Fassnight Fault is located three miles to the northeast of the site and consists of a northwest–southeast trending fault downthrown to the southwest (Thomson, 1978).

F. Hydrology

The JTEC site is located within the Springfield Plateau Groundwater Province (Miller & Vandike, 1997). The regional hydrogeology of the site consists of three aquifer systems separated by two regional confining units. The upper most aquifer, the Springfield aquifer, is separated from the underlying Ozark aquifer by the Ozark confining unit. The Ozark aquifer is utilized throughout the region as a primary source of drinking water by municipalities and individuals. The Ozark aquifer is separated from the underlying St. Francois aquifer by the St. Francois confining unit. Figure 3.5 is a topographic map of the area of JTEC and depicts a cross section between two regional groundwater wells as well as the location of Exploratory Borehole #1. Figure 3.6 is illustrates the regional geology and hydrology from the cross section line shown on Figure 3.5.

1. Springfield Aquifer

The Springfield aquifer encountered by the borehole is 247 feet thick. Details of both aquifer thickness and elevation can be seen in Figure 3.6; Table 3.2. This aquifer system consists of residuum derived from weathered Mississippian-age limestone and over 225 feet of Mississippian-age bedrock formations. The uppermost formation is the Burlington Limestone. The Burlington Limestone is a medium to coarsely crystalline, medium to coarsely grained, crinoidal, cherty limestone. Voids and solution enlarged joints are present, some containing residual clays. Groundwater movement in this formation is dominated by karst conduit flow. Numerous sinkholes are present at and near the site.

Water tracing suggests that sinkholes direct meteoric water into conduits that discharge via the Rader Spring Karst System (Thomson, 1997). The Burlington Limestone is underlain by the Elsey–Reed Springs Formation. Due to the limitations of analyzing cuttings, distinguishing between the Elsey Formation and Reed Springs Formation is difficult. Local mapping of surface exposures suggest that only the Elsey Formation is present at the site, however the gray color and fine grained nature of the cuttings suggest the Reed Springs facies was encountered (Thompson, 1986). This unit is comprised of low to moderately permeable white to gray, chert nodules with gray to dark gray fine grained limestone.

Below the Elsey–Reed Springs Formation lies the Pierson Limestone. The Pierson Limestone is a low to moderately permeable, light gray to brown, fine grained limestone with white chert nodules containing crinoid fossils.

2. Ozark Confining Unit

The Ozark confining unit encountered by the borehole has a thickness of 27 feet and at a depth of 247 feet below the surface (Figure 3.6; Table 3.2). This confining unit is comprised of the Mississippian-age Northview Formation and Compton Limestone. The Northview Formation is low permeability gray silty shale with light gray fine grained limestone and potentially a small amount of chert. The Northview Formation is 19 feet thick in the borehole and is the primary aquitard of the Ozark confining unit.

Underlying the Northview Formation is the Compton Limestone. The Compton Limestone is a light gray to gray, fine grained limestone with a small amount of chert possibly present.

3. Ozark Aquifer

The Ozark aquifer encountered by the borehole has a thickness of 1,223 feet beginning at a depth of 274 feet below the surface (Figure 3.6; Table 3.2). The aquifer is comprised primarily of Ordovician and Cambrian-age formations. However, the approximately one foot thick Mississippian-age Bachelor Formation is considered as the uppermost unit included in the Ozark aquifer. The Bachelor Formation is calcite cemented, fine grained and well-rounded quartz sandstone. The low to moderately permeable Ordovician-age Cotter Dolomite is immediately below the Bachelor. The Cotter Dolomite is a light gray to light brown, coarse to finely crystalline dolomite. The Cotter Dolomite contains a chert free and cherty dolomite zone, interbedded with thin sandstones. The relatively thick "Swan Creek" sandstone is present between 309 to 320 feet below ground surface. Underlying the Cotter Dolomite is the Ordovician-age Jefferson City Dolomite. The low to moderately permeable Jefferson City Dolomite is light brown to gray, fine to medium crystalline, chert free dolomite and cherty dolomite interbedded with thin sandstones. Chert is commonly oolitic, banded or mottled. Permeability in the Cotter Dolomite and Jefferson City Dolomite is typically associated with fractures, bedding planes and discrete sandstone beds. The highly permeable Ordovician-age Roubidoux Formation underlies the Jefferson City Dolomite. The Roubidoux Formation is approximately 185 feet thick and comprised of light gray to gray medium crystalline dolomite, interbedded with carbonate and silica cemented sandstones and chert. The chert is commonly oolitic or banded. Voids were encountered within the Roubidoux Formation. The Roubidoux Formation is functioning as a prolific aquifer. The Roubidoux Formation is underlain by the moderate to highly permeable Ordovician-age Gasconade Dolomite. The Gasconade Dolomite is a light gray to dark gray, fine to medium crystalline, vuggy dolomite and cherty dolomite.

The chert is commonly oolitic, banded, or opaque. At the base of the Gasconade Dolomite the Gunter Sandstone Member is present between 1,120 and 1,165 feet below ground surface. The Gunter Sandstone is primarily clean quartz sandstone with thin interbeds of friable dolomite. Voids were encountered within the Gasconade Dolomite. The moderate to highly permeable Cambrian-age Eminence Dolomite is found below the Gasconade Dolomite. The Eminence Dolomite is comprised of light gray to dark gray, fine to medium crystalline, vuggy dolomite and cherty dolomite. The chert is commonly oolitic, banded, or opaque. Voids were encountered within the Eminence Dolomite. The final unit comprising the base of the Ozark aquifer is the Potosi Dolomite. The highly permeable Potosi Dolomite is comprised of gray, fine to coarse crystalline, vuggy dolomite and with dolomite and druse quartz lined vugs.

4. St. Francois Confining Unit

The St. Francois confining unit encountered by the borehole has a thickness of 194 feet at a depth of 1,507 feet below ground surface (Figure 3.6; Table 3.2). This confining unit is comprised of the Cambrian-age Elvins Group. The Elvins Group is comprised of interbedded dolomite and limestone exhibiting moderate to low permeability transitioning from a shallow marine silty limestone facies at the base to a deep water shaly carbonate in the center and back to a shallow marine facies at the top. The deep water facies consists of laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules. Interbedded within the entire sequence are debris flow beds represented by edgewise flat pebble conglomerates, carbonate sands and mud derived from locally mobilized limestone nodules, distal carbonate sands and local carbonate mud. The uppermost bed is a fining upwards sequence of pebble to flat pebble conglomerate to cross-bedded carbonate sand. The shallower facies are dolomitized and the deeper shaly facies are limestone.

In addition to the low permeability zones of the Elvins Group, low permeability units in the upper Bonneterre Formation also were evaluated to determine if these units are functionally part of the St. Francois confining unit. This evaluation is presented in the Missouri State University (MSU) portion of this report.

5. St. Francois Aquifer

The St. Francois aquifer encountered by the borehole is 484 feet thick beginning at a depth of 1,701 feet below ground surface (Figure 3.6; Table 3.2). This aquifer system consists of Cambrian-age dolomite, limestone, siltstone and sandstone. The uppermost unit is the Bonneterre Formation. The Bonneterre Formation consists of gray to greenish gray, fine crystalline, brecciated dolomite, gray mottled dolomite interbedded with grainstone and shaly dolomite, as well as laminated limestone and limey mud. The Bonneterre Formation is underlain by the Lamotte Sandstone. The Lamotte Sandstone is comprised of two sand bodies separated by a burrowed shale and siltstone facies and a deeper water glauconitic sand and carbonate facies. The carbonate facies may be interpreted as Bonneterre Formation interbedded with the Lamotte Sandstone. The upper sand body consists of medium to coarse grained, marine sand containing numerous brachiopod shells and other shell fragments interbedded with thin marine shale.

The lower sand body consists of a marine facies similar to the upper sand body and transactions to a lower fluvial facies consisting of medium to coarse grained arkosic sands containing quartz and feldspar pebbles. The fluvial facies also contains a zone with hematite cements.

A fractured and weathered/altered Precambrian basement rock was encountered at the base of the borehole at a depth of 2,147 feet below ground surface. A confining unit was not encountered by this borehole, although it is surmised that one exists at depth within the Precambrian rocks. These rock units would not typically be considered part of the St. Francois aquifer, however, the rock is heavily fractured and functionally part of the aquifer. Packer testing showed this unit had a higher hydraulic conductivity than portions of the overlying St. Francois aquifer. The results of the packer testing are included in the MSU portion of this report.

The igneous rock encountered appears pegmatitic in character. It consists of quartz, plagioclase, orthoclase, muscovite, and biotite, with feldspar crystals larger than 10 centimeter (cm) veined with quartz. The fractures dip at approximately 30 degrees with striations on fractures. Ductile deformation is likely in some zones. Extensive weathering/alteration along fractures has occurred with micas and possibly epidote altered to chlorite. A water sample collected by GSP staff yielded a TDS value of 154 mg/L for the upper portion of the aquifer and 153 mg/L for sampling of the entire aquifer.

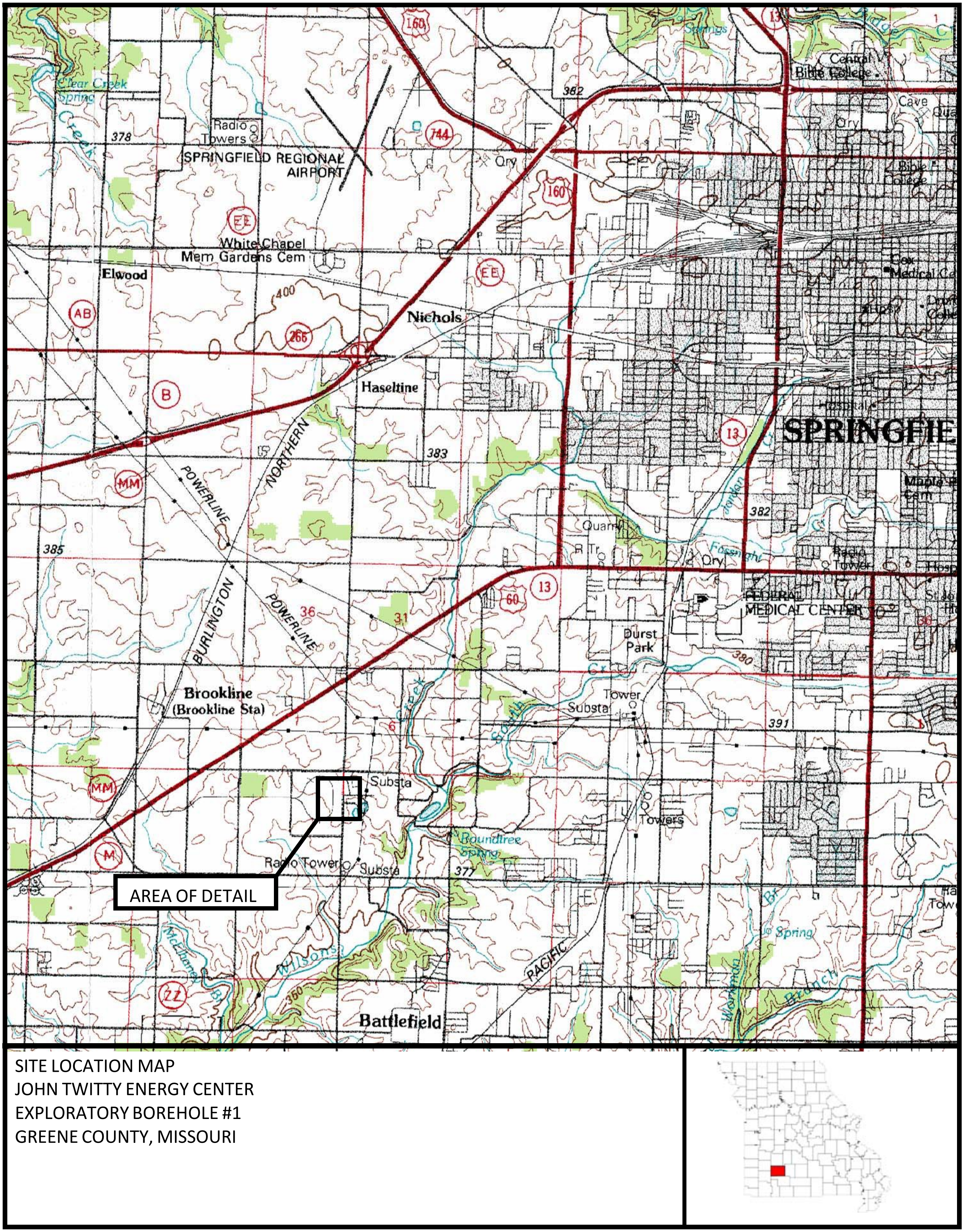


FIGURE 3.2. TOPOGRAPHIC MAP SHOWING THE LOCATION OF THE JOHN TWITTY ENERGY CENTER SITE WHICH CONTAINS EXPLORATORY BOREHOLE #1.

FIGURE 3.3. AERIAL PHOTO SHOWING THE LOCATION OF THE JOHN TWITTY ENERGY CENTER AND EXPLORATORY BOREHOLE #1.

FIGURE 3.4. EXPLORATORY BOREHOLE #1 STRATIGRAPHIC COLUMN. STRATIGRAPHIC SYMBOLOGY DEFINED IN TABLE 3.1.

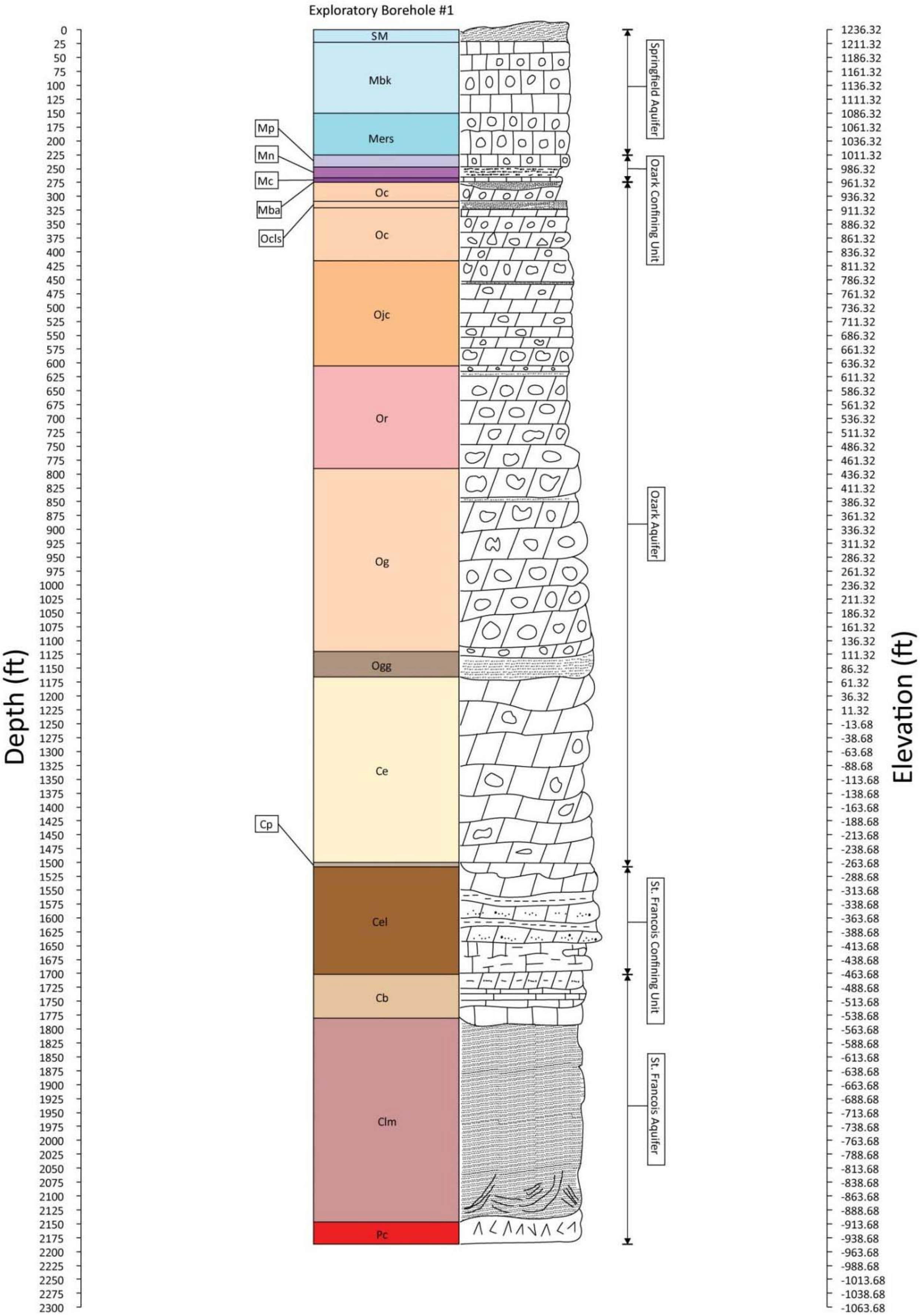
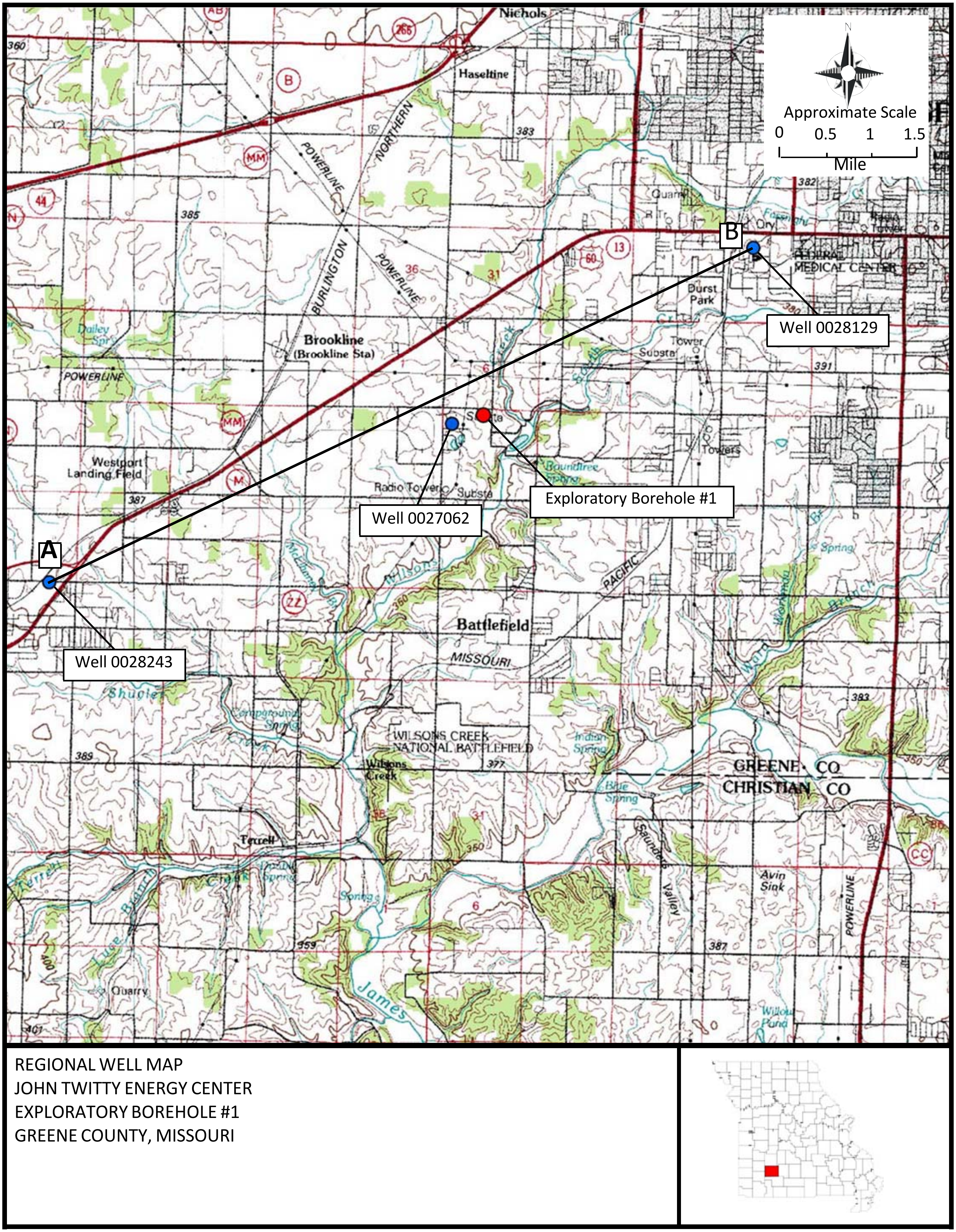


TABLE 3.1. TOPS OF FORMATION AND HYDROLOGIC UNITS IN EXPLORATORY BOREHOLE #1.

Formation	Symbol	Formation Top	Depth (Feet)	Elevation (Feet)	Hydrologic Unit
Surficial Material	SM	0’	0-22	1236.32 to 1214.32	Springfield Aquifer
Burlington Limestone	Mbk	22’	22-150	1214.32 to 1086.32	
Elsey-Reed Springs Formation	Mers	150’	150-225	1086.32 to 1011.32	
Pierson Limestone	Mp	225’	225-247	1011.32 to 989.32	
Northview Formation	Mn	247’	247-266	989.32 to 970.32	Ozark Confining Unit
Compton Limestone	Mc	266’	266-274	970.32 to 962.32	
Bachelor Formation	Mba	274’	274-275	962.2 to 961.32	Ozark Aquifer
Cotter Dolomite	Oj	275’	275-416	961.32 to 820.32	
-“Swan Creek” sandstone	Ocls	309’	309-320	927.32 to 916.32	
Jefferson City Dolomite	Ojc	416’	416-605	820.32 to 631.32	
Roubidoux Formation	Or	605’	605-790	631.32 to 446.32	
Gasconade Dolomite	Og	790’	790-1165	446.32 to 71.32	
-Gunter Sandstone Member	Ogg	1120’	1120-1165	116.32 to 71.32	
Eminence Dolomite	Ce	1165’	1165-1500	71.32 to -263.68	
Potosi Dolomite	Cp	1500’	1500-1507.5	-263.68 to -271.18	
Elvins Group *	Cel	1507.5’	1507.5-1701.9	-271.18 to -465.58	St. Francois Confining Unit
Bonneterre Formation	Cb	1701.9’	1701.9-1780.3	-465.58 to -543.98	
Lamotte Sandstone	Clm	1780.3’	1780.3-2147	-543.98 to -910.68	St. Francois Aquifer
Precambrian Basement	Pc	2147’	2147-2186.6	-910.68 to -950.28	

*Elvins Group (Cel) is comprised of Derby-Doerun Dolomite (Celdd) and Davis Formation (Celd)



REGIONAL WELL MAP
JOHN TWITTY ENERGY CENTER
EXPLORATORY BOREHOLE #1
GREENE COUNTY, MISSOURI

FIGURE 3.5. MAP OF REGIONAL WELLS AND CROSS SECTION LINE OF AREA AROUND THE JOHN TWITTY ENERGY CENTER.

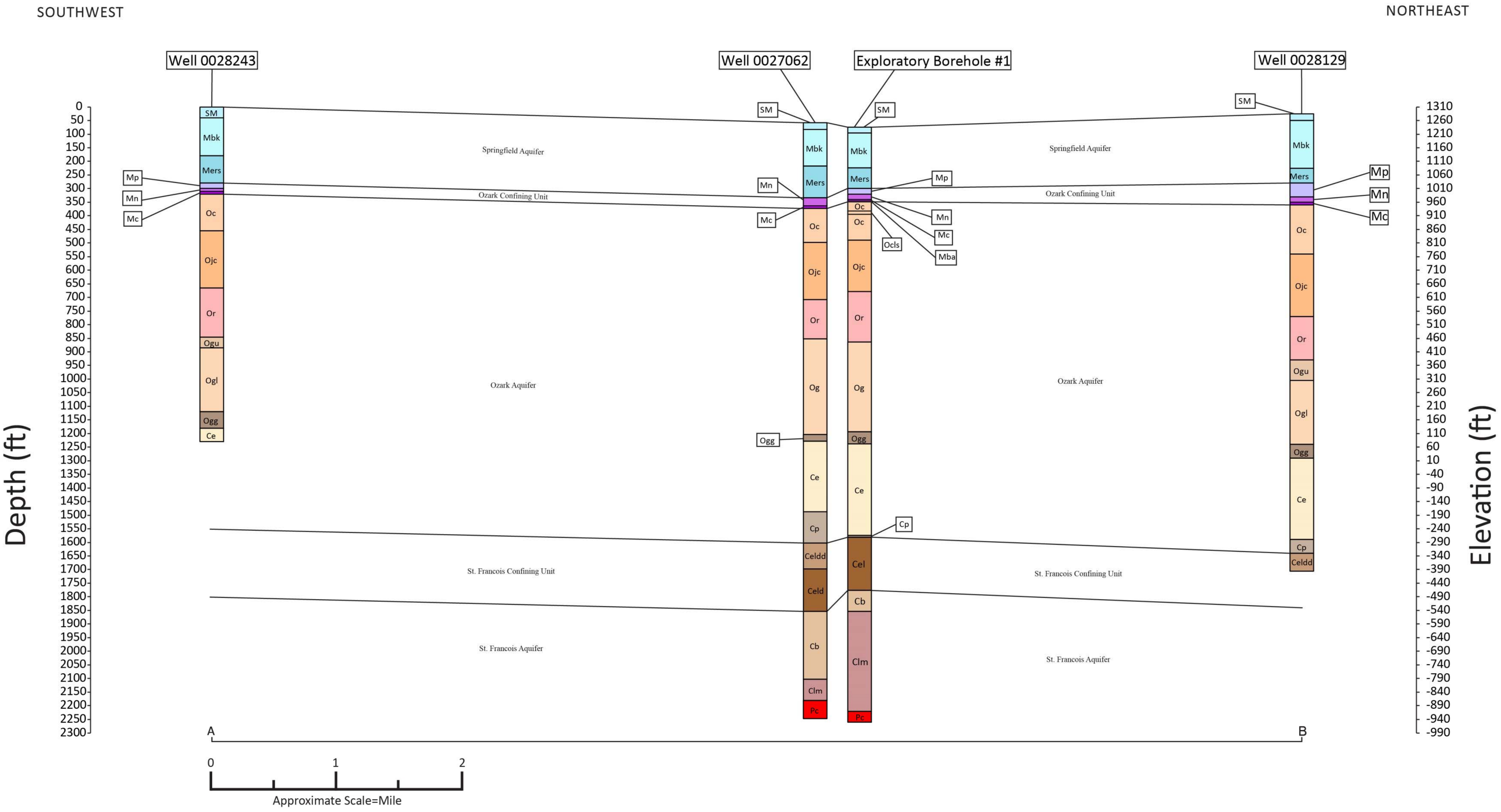


FIGURE 3.6. REGIONAL GEOLOGY AND HYDROLOGY CROSS SECTION OF THE JOHN TWITTY ENERGY CENTER AREA. STRATIGRAPHIC SYMBOLOGY IS DEFINED IN TABLE 3 .2.

TABLE 3.2. FORMATION LIST FOR REGIONAL SECTION IN THE VICINITY OF THE JOHN TWITTY ENERGY CENTER.

Formation	Symbol
Surficial Material	SM
Burlington Limestone	Mbk
Elsey-Reed Springs Formation	Mers
Pierson Limestone	Mp
Northview Formation	Mn
Compton Limestone	Mc
Bachelor Formation	Mba
Cotter Dolomite	Oc
Swan Creek sandstone	Ocls
Jefferson City Dolomite	Ojc
Roubidoux Formation	Or
Gasconade Dolomite	Og
Upper Gasconade Dolomite	Ogu
Lower Gasconade Dolomite	Ogl
Gunter Sandstone Member	Ogg
Eminence Dolomite	Ce
Potosi Dolomite	Cp
Elvins Group	Cel
Derby-Doerun Dolomite	Celdd
Davis Formation	Celd
Bonneterre Formation	Cb
Lamotte Sandstone	Clm
Precambrian Basement	Pc

II. THOMAS HILL ENERGY CENTER

A. Introduction

This section describes in detail the bedrock and hydrologic units encountered while drilling borehole #2 at THEC. This borehole was drilled over the course of several months, with drilling beginning on February 2, 2012 and completed on June 23, 2012. The objective of the project was to analyze the characteristics of the lower Cambrian-Ordovician aquifer and the overlying confining units in order to determine the potential for carbon dioxide sequestration in and around THEC.

B. Deviations from Standard Methods

Wire line geophysical logs were used to measure conductivity of water in the borehole. These values were compared to other conductivity readings in the Ozark Aquifer.

C. Site Location

THEC is located approximately 0.5 miles west of State Hwy 3.9 (Figure 3.7). The site is located in Randolph County, Missouri in the southeast quarter of section 19, T 55 N, R 15 W. The borehole is located at 39° 32'

57.9” north latitude 92° 37’32.5”west longitude, as illustrated on the topographic map in Figure 3.7. Figure 3.8 is an aerial photo of the site and the drilling location of the borehole.

D. Geologic Setting

Exploratory Borehole #2 is located in the Dissected Till Plains physiographic province. This province consists of loess and glacial tills deposited on Pennsylvanian-age sedimentary rocks. Elevation at the top of the surface casing for this borehole was 790.41 feet above mean sea level. The surficial materials at the site consist mainly of glacial deposits, primarily silty clays, sands and gravels. Geological maps indicate that the uppermost bedrock is the Pennsylvanian-age Cabaniss Subgroup. This subgroup consists of cycles of sandstone, siltstone, shale, underclay, limestone, and coal beds.

E. Geologic Structure

At THEC the regional dip of the top of the Derby–Doerun Dolomite is approximately 11 feet per mile to the Northwest (Crews & Bone, 2010). The site is located between two regional structural features (McCracken, 1971). The axis of the College Mound–Bucklin anticline is located six miles to the northeast of the site and is a northwest-southeast trending anticline that plunges to the northwest. The axis of the Salisbury–Quitman anticline is located 12 miles to the southwest of the site. This anticline also is gently plunging to the northwest. Between these regional structures are numerous small faults; the Thomas Hill fault, Hubbard fault, Prairie Hill Cemetery fault, Middle Fork Little Chariton River fault, Dark Creek fault.

F. Hydrology

THEC is located within the Northeastern Missouri Groundwater Province (Miller & Vandike, 1997). The regional hydrogeology of the site consists of four regional aquifer systems separated by a regional confining unit. The upper most aquifer consists of the Glacial Drift aquifer which in contact with the underlying Pennsylvanian aquifer. Due to low permeability bedrock units and elevated and variable TDS concentrations, the Pennsylvanian aquifer is generally not considered to be an important water-supply source. The Mississippian aquifer is found below the Pennsylvanian aquifer. The Mississippian aquifer is separated from the Cambrian-Ordovician aquifer by the Mississippian–Devonian–Silurian confining unit. Figure 3.10 is a topographic map of the area of THEC and depicts a cross section between two regional groundwater wells as well as the location of Exploratory Borehole #2. Figure 3.11 is illustrates the regional geology and hydrology from the cross section shown on Figure 3.10.

1. Glacial Drift Aquifer

The Glacial Drift aquifer encountered in the borehole is 73 feet thick (Figure 3.9; Table 3.3). This aquifer system at the site consists of two feet of fill material over 33 feet of Pleistocene-age loess and 38 feet of Pleistocene glacial till. The loess is yellowish brown, silty clay to sandy silty clay. The underlying till is comprised of gray, brown, yellowish silty clays, sandy clays with granite, calcite, chert, quartz, sands, pebbles and gravels. Permeable sand and gravel units within the till are typically hydrologically isolated by the surrounding low-permeability silts and clays.

2. Pennsylvanian Aquifer

The Pennsylvanian aquifer encountered in the borehole is 45 feet thick beginning at a depth of 73 feet below ground surface (Figure 3.9; Table 3.3). This aquifer system consists of the Pennsylvanian-age gray shale, quartz sands, limestone and coal of the Cherokee Group and possibly the lower Marmaton Group.

The Pennsylvanian aquifer generally is considered to be a poor aquifer with low permeability and variable water quality. Water found in the aquifer generally contains excessive sulfate, iron and TDS (Miller & Vandike, 1997). Water quality within the Pennsylvanian aquifer at the site was expected to be between 800 and 1,000 mg/L TDS (Crews, *et al*, 2009a).

3. Mississippian Aquifer

The Mississippian aquifer encountered in the borehole consists of 346 feet of Mississippian-age limestone beginning at a depth of 118 feet below ground (Figure 3.9; Table 3.3). The uppermost formation is the Warsaw Formation, a low to moderately permeable, light gray to buff, fine to medium grained, limestone to cherty limestone with traces of crinoids, gastropods and brachiopod fragments. The moderately permeable Burlington/Keokuk Limestone underlies the Warsaw Formation and is a medium to coarsely crystalline, medium to coarsely grained, crinoidal, cherty limestone. The Burlington Limestone is underlain by limestone of the Chouteau Group. This unit is comprised of low to moderately permeable alternating beds of light gray to buff, medium to coarse grained limestone to buff, fine grained, sandy texture pitted dolomite, with a slight amount of chert over olive gray to light gray, fine grained, sandy textured dolomite to dolomitic limestone with white, milky white, bluish gray, to gray chert.

Water quality within the Mississippian aquifer at the site was expected to be between 1,000 and 10,000 mg/L TDS (Crews, *et al*, 2010a). Some petroleum may be present in the Mississippian aquifer as an oil sheen was noted at a drilling depth of 459 feet.

4. Mississippian-Devonian-Silurian Confining Unit

The Mississippian-Devonian-Silurian Confining Unit encountered in the borehole has a thickness of 195 feet beginning at a depth of 464 feet (Figure 3.9; Table 3.3). This confining unit is comprised of the Mississippian to Devonian-age “Kinderhook Shale” and shaly limestone of the Cedar Valley Limestone. The “Kinderhook Shale” is 15 feet thick and is the primary aquitard of the Mississippian-Devonian- Silurian Unit. The “Kinderhook Shale” is a low permeability, light gray, olive gray, to dark gray, shale.

Underlying the “Kinderhook Shale” is the Cedar Valley Limestone. The upper part of the Cedar Valley Limestone, the Callaway Facies, is low permeability, light gray, gray to buff, fine grained, limestone to microcrystalline, conchoidal fracturing limestone. The lower Cedar Valley Limestone is primarily low to moderately permeable; light gray to gray, fine grained to microcrystalline, limestone, glauconitic limestone, platy limestone, and sandy textured limestone with blue-green limey shale. The lowest member of the Cedar Valley Limestone, the Hoing Sandstone is more permeable and considered a functional part of the Cambrian-Ordovician aquifer in this report.

5. Cambrian-Ordovician Aquifer

The Cambrian-Ordovician aquifer encountered in the borehole has a thickness of 1,880 feet beginning at a depth of 659 feet (Figure 3.9; Table 3.3). The aquifer is comprised primarily of Ordovician and Cambrian-age formations. While these units are typically considered to be a single hydrologic unit in northern Missouri (Miller & Vandike, 1997), visual observations of these units indicate that the upper permeable formations are separated from lower permeable formations by aquitards. These hydrologic units correlate with the Ozark aquifer, St. Francois Confining Unit and St. Francois aquifer identified in southern Missouri.

The Hoing Sandstone Member of the Cedar Valley Limestone is the uppermost unit included in the upper permeable zone of the Cambrian – Ordovician aquifer. The Hoing Sandstone is low to moderately permeable calcite cemented, fine grained and well-rounded quartz sandstone, light gray to gray fine grained limestone, sandy limestone and limey shale. The highly permeable St. Peter Sandstone is immediately below the Hoing Sandstone. The St. Peter Sandstone consists of white, well-sorted, friable, fine grained, rounded, and frosted quartz sandstone over the Kress Member of the St. Peter Sandstone. The Kress Member consists of low permeability light gray, fine grained, dolomite with bluish green to dark gray shale and slight amounts of fine grained, friable, and frosted quartz sand and gray to white chert. The low to moderately permeable Ordovician-age Cotter Dolomite is immediately below the Kress Member. The Cotter Dolomite is a light gray, coarse to finely crystalline dolomite, with bluish green to dark gray shale, slight amounts of fine grained, gray to white oolitic chert to gray to white chert, interbedded with thin sandstones. Underlying the Cotter Dolomite is the Ordovician-age Jefferson City Dolomite. The low to moderately permeable Jefferson City Dolomite is a light gray, fine to medium crystalline, chert free dolomite to cherty dolomite interbedded with thin sandstones. Chert is commonly oolitic, banded or mottled. Secondary minerals present include pyrite, and glauconite.

Permeability in the Cotter and Jefferson City Dolomites is typically associated with fractures, bedding planes and discrete sandstone beds. The highly permeable Ordovician-age Roubidoux Formation underlies the Jefferson City Dolomite. The Roubidoux Formation is approximately 140 feet thick and is comprised of light gray, medium grained, dolomite, interbedded with carbonate and silica cemented sandstones and chert. Chert is commonly oolitic or banded. The Roubidoux Formation is underlain by the moderate to highly permeable Ordovician-age Gasconade Dolomite. The Gasconade Dolomite is a light to dark gray, fine to medium crystalline, vuggy dolomite and cherty dolomite. Chert is commonly oolitic, banded, or opaque. A fracture zone was encountered in the Gasconade Dolomite at a depth of 1,510 feet below ground surface. At the base of the Gasconade Dolomite the Gunter Sandstone Member is present between 1,557 and 1,577 feet below ground surface. The Gunter Sandstone is tan to buff, fine grained, rounded, and calcite cemented quartz sandstone with tan to buff, medium grained dolomite. The moderate to highly permeable Cambrian-age Eminence Dolomite is found below the Gasconade Dolomite. The Eminence Dolomite is comprised of light to brownish to dark gray, fine to medium crystalline, vuggy dolomite and cherty dolomite with rounded, quartz sand and slight amounts of white chert and bluish green shale. The final unit comprising the upper permeable zone in the Cambrian–Ordovician aquifer is the Potosi Dolomite. The highly permeable Potosi Dolomite is comprised of light gray, fine to coarse crystalline, vuggy dolomite with a slight amount of white chert and bluish green to dark gray shale.

Water quality within the upper Cambrian–Ordovician aquifer is highly variable. Conductivity reading taken during drilling had values ranging from 14,450 micro siemen per centimeter (µS/cm) at a depth of 997 feet on March 14th 2012 (Bodenhamer, 2012) to 1,232 µS/cm at a depth of 1,032 feet on April 3rd 2012 (Pate, 2012). Wireline logging of the borehole collected conductivity readings from 1,152 µS/cm at the top of the St. Peter Sandstone to 1,304 µS/cm near the center of the St. Peter Sandstone to 5,300 µS/cm at a depth of 1,018 feet, the top of the Kress Member. Total dissolved solids were expected to range from 8,000 to 10,000 mg/L (Crews, *et al*, 2010c). The wireline log can be found in Appendix E.

Minor amounts of petroleum were encountered in the upper part of the aquifer. Petroleum was encountered at depths of 659 feet and 744 feet.

The upper permeable zone of the Cambrian–Ordovician aquifer is separated from the lower permeable zone of the Cambrian–Ordovician aquifer by units that would make up the St. Francois confining unit. These units are the 290 feet thick Derby–Doerun Dolomite and the Davis Formation. The Derby–Doerun Dolomite is comprised of low permeability light to brownish to dark gray, fine to medium grained dolomite and dolomite peppered with glauconite. Below the Derby–Doerun is the Davis Formation. The low permeability Davis Formation is interbedded variably glauconitic, very fine-grained sandstone, siltstone, and carbonate shale and interbedded carbonate facies ranging from packstone to mudstone.

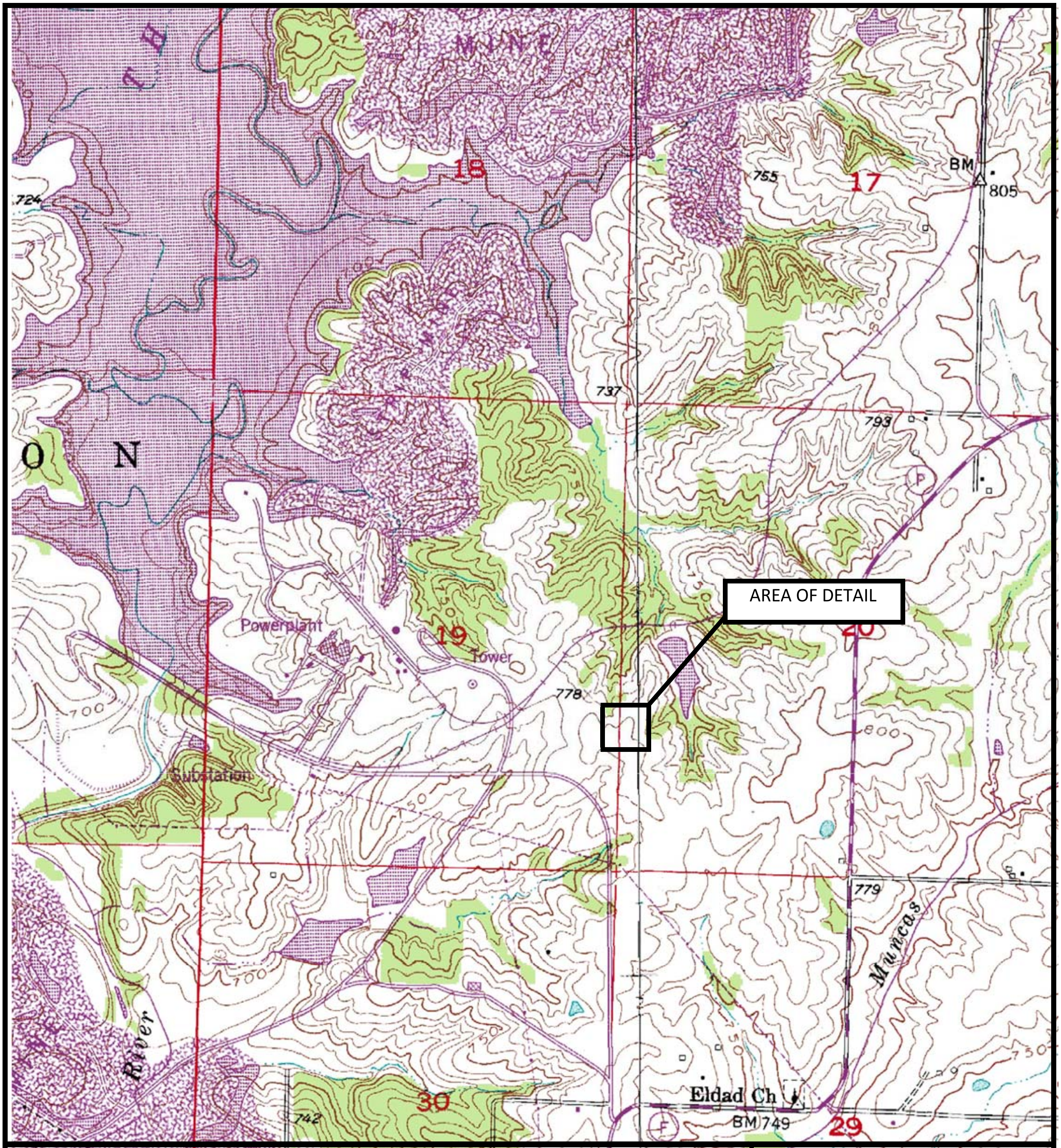
Interbedded within the entire sequence are debris flow beds represented by edgewise flat pebble conglomerates. The Davis Formation is 145 feet thick and is the primary aquitard forming unit.

The lower permeable zone of the Cambrian–Ordovician aquifer is comprised of the Bonneterre Formation and the underlying Lamotte Sandstone. The Bonneterre Formation is low to moderately permeable containing interbedded gray to dark gray, fine to medium grained, oolitic limestone, dolomite with variable glauconite, gray mottled dolomite with grainstones, laminated shaly dolomite, laminated limestone, and dark shale. Lower permeability zones within the Bonneterre would be expected to act as localized confining units within the aquifer. The moderately permeable Lamotte Sandstone is 206 feet thick and is the primary water producing interval of the lower Cambrian– Ordovician aquifer. The Lamotte Sandstone is white to tan, medium to coarse grain, and weakly friable to friable, sub rounded to rounded quartz sandstone. The lower sand body consists of arkosic sand containing quartz pebbles and cross bedding.

A water sample collected by GSP staff yielded a TDS value of 50,800 mg/L. Samples were expected to have TDS values from 35,000 to 40,000 mg/L (Crews, *et al*, 2010b).

6. Precambrian Basement Confining Unit

The deepest unit found at the site consisted of Precambrian igneous rock. A heavily fractured, weathered, low to moderately permeable, red to salmon pink granite with clear to light bluish gray quartz, plagioclase, orthoclase, and biotite granite was encountered. The upper part of this rock unit could be in hydrologic communication with the overlying aquifer, but is expected to be less permeable with depth.



SITE LOCATION MAP THOMAS HILL ENERGY CENTER
EXPLORATORY BOREHOLE #2
RANDOLPH COUNTY, MISSOURI

FIGURE 3.7. TOPOGRAPHIC MAP SHOWING THE LOCATION OF THE THOMAS HILL ENERGY CENTER SITE WHICH CONTAINS EXPLORATORY BOREHOLE #2.

FIGURE 3.8. AERIAL PHOTO SHOWING THE LOCATION OF THE THOMAS HILL ENERGY CENTER AND EXPLORATORY BOREHOLE #2.

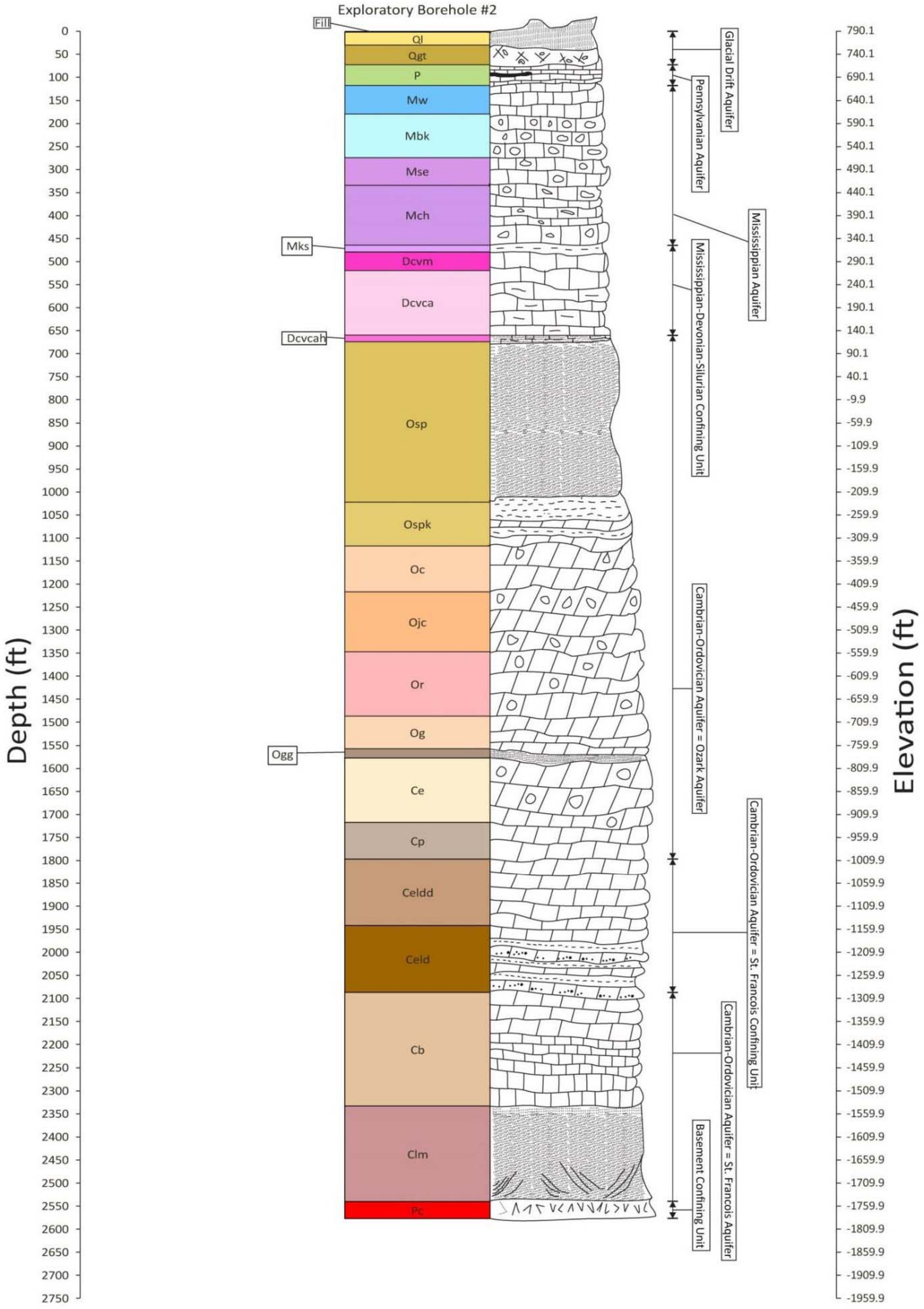
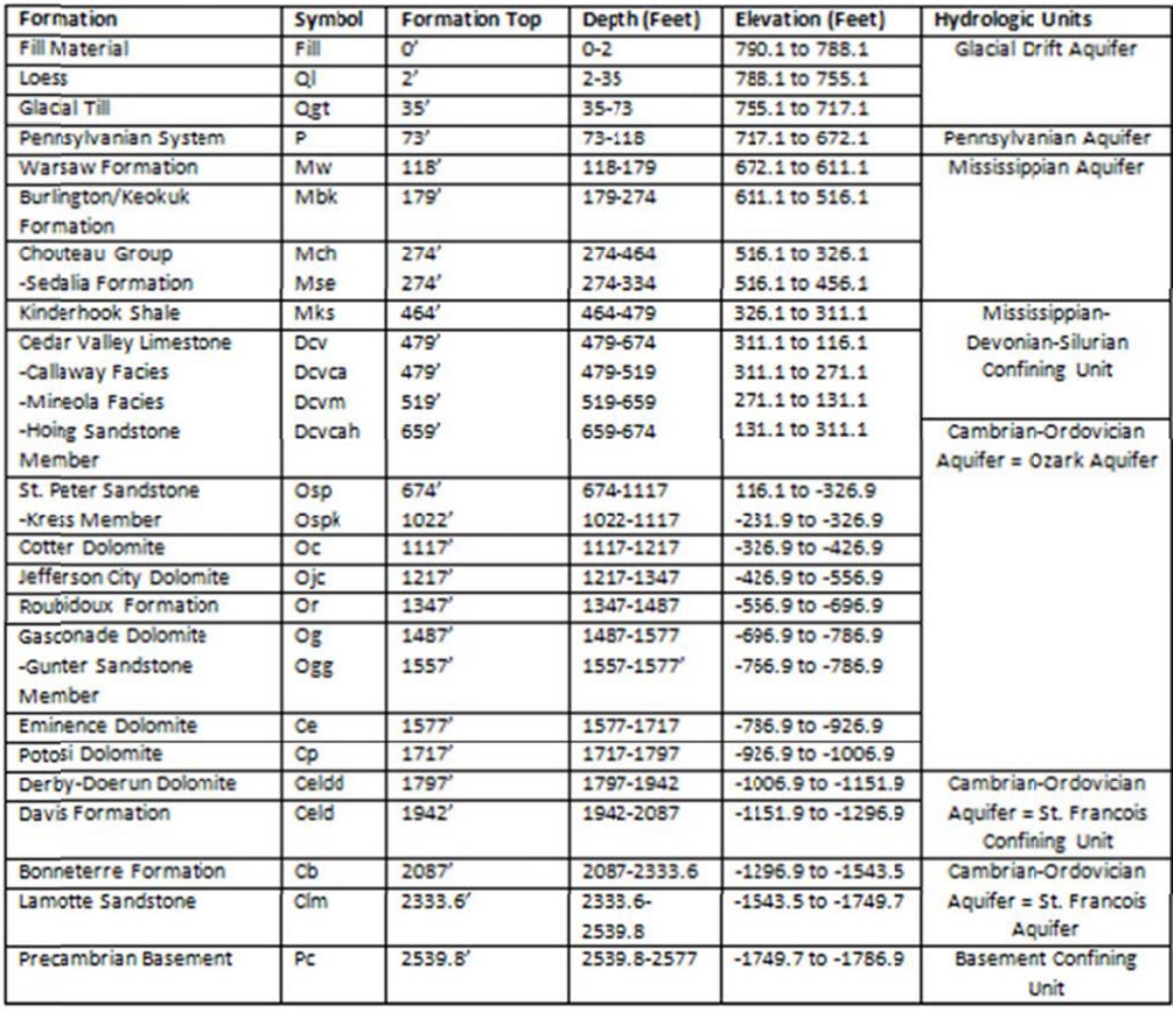


FIGURE 3.9. EXPLORATORY BOREHOLE #2 STRATIGRAPHIC COLUMN. STRATIGRAPHIC SYMBOLOGY DEFINED IN TABLE 3.3.

TABLE 3.3. TOPS OF FORMATION AND HYDROLOGIC UNITS IN EXPLORATORY BOREHOLE #2.



Formation	Symbol	Formation Top	Depth (Feet)	Elevation (Feet)	Hydrologic Units
Fill Material	Fill	0'	0-2	790.1 to 788.1	Glacial Drift Aquifer
Loess	Ql	2'	2-35	788.1 to 755.1	
Glacial Till	Qgt	35'	35-73	755.1 to 717.1	
Pennsylvanian System	P	73'	73-118	717.1 to 672.1	Pennsylvanian Aquifer
Warsaw Formation	Mw	118'	118-179	672.1 to 611.1	Mississippian Aquifer
Burlington/Keokuk Formation	Mbk	179'	179-274	611.1 to 516.1	
Chouteau Group	Mch	274'	274-464	516.1 to 326.1	
-Sedalia Formation	Mse	274'	274-334	516.1 to 456.1	
Kinderhook Shale	Mks	464'	464-479	326.1 to 311.1	Mississippian-Devonian-Silurian Confining Unit
Cedar Valley Limestone	Dcv	479'	479-674	311.1 to 116.1	
-Callaway Facies	Dcvca	479'	479-519	311.1 to 271.1	
-Mineola Facies	Dcvm	519'	519-659	271.1 to 131.1	
-Hoing Sandstone Member	Dcvcah	659'	659-674	131.1 to 311.1	Cambrian-Ordovician Aquifer = Ozark Aquifer
St. Peter Sandstone	Osp	674'	674-1117	116.1 to -326.9	
-Kress Member	Ospk	1022'	1022-1117	-231.9 to -326.9	
Cotter Dolomite	Oc	1117'	1117-1217	-326.9 to -426.9	
Jefferson City Dolomite	Ojc	1217'	1217-1347	-426.9 to -556.9	
Roubidoux Formation	Or	1347'	1347-1487	-556.9 to -696.9	
Gasconade Dolomite	Og	1487'	1487-1577	-696.9 to -786.9	
-Gunter Sandstone Member	Ogg	1557'	1557-1577'	-766.9 to -786.9	
Eminence Dolomite	Ce	1577'	1577-1717	-786.9 to -926.9	
Potosi Dolomite	Cp	1717'	1717-1797	-926.9 to -1006.9	
Derby-Doerun Dolomite	Celdd	1797'	1797-1942	-1006.9 to -1151.9	Cambrian-Ordovician Aquifer = St. Francois Confining Unit
Davis Formation	Celd	1942'	1942-2087	-1151.9 to -1296.9	
Bonneterre Formation	Cb	2087'	2087-2333.6	-1296.9 to -1543.5	Cambrian-Ordovician Aquifer = St. Francois Aquifer
Lamotte Sandstone	Clm	2333.6'	2333.6-2539.8	-1543.5 to -1749.7	
Precambrian Basement	Pc	2539.8'	2539.8-2577	-1749.7 to -1786.9	Basement Confining Unit

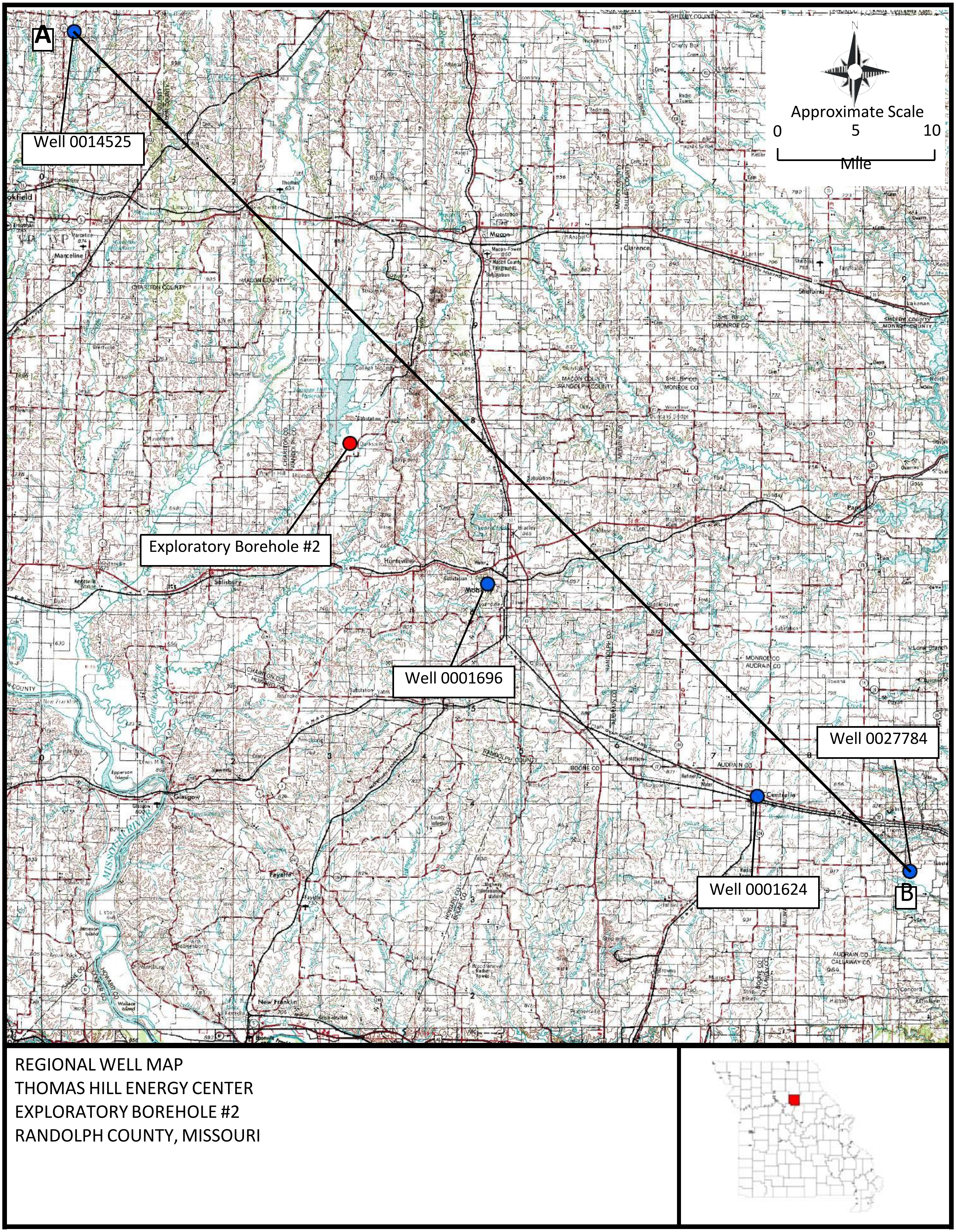


FIGURE 3.10. MAP OF REGIONAL WELLS AND CROSS SECTION LINE OF AREA AROUND THE THOMAS HILL ENERGY CENTER.

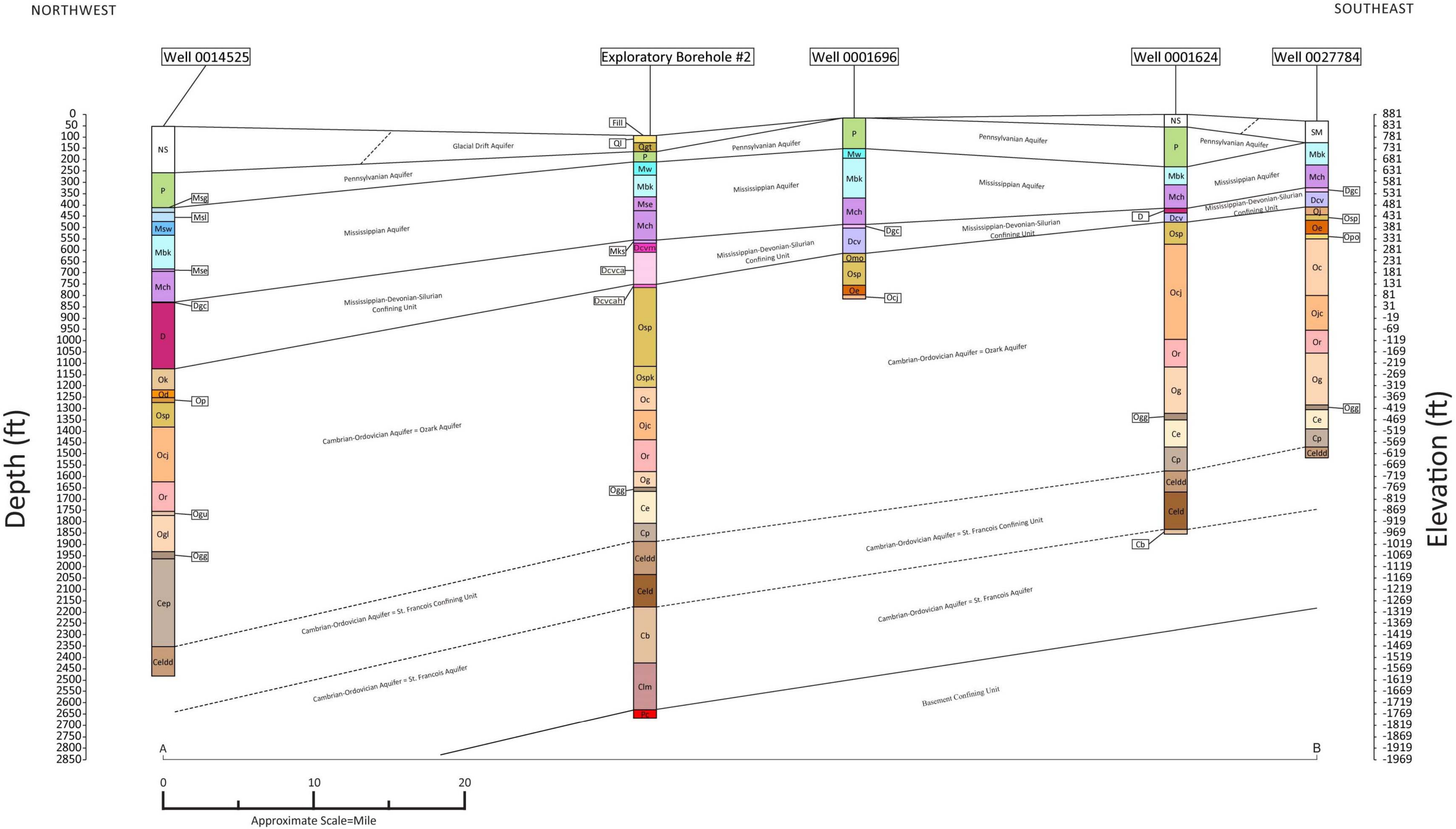


FIGURE 3.11. REGIONAL GEOLOGY AND HYDROLOGY CROSS SECTION OF THE THOMAS HILL ENERGY CENTER AREA. STRATIGRAPHIC SYMBOLOGY IS DEFINED IN TABLE 3.4.

TABLE 3.4. FORMATION LIST FOR REGIONAL SECTION IN THE VICINITY OF THE THOMAS HILL ENERGY CENTER.

Formation	Symbol	Formation	Symbol
No Sample	NS	Kress Member	Ospk
Surficial Material	SM	Everton Formation	Oe
Loess	Ql	Powell Dolomite	Opo
Pennsylvanian System	P	Cotter and Jefferson City Dolomites	Ojc
Ste. Genevieve Limestone	Msg	Cotter Dolomite	Oc
St. Louis Limestone	Msl	Jefferson City Dolomite	Ojc
Warsaw Formation	Mw	Roubidoux Formation	Or
Burlington Limestone	Mbk	Gasconade Dolomite	Og
Sedalia Formation	Mse	Upper Gasconade Dolomite	Ogu
Chouteau Group	Mch	Gasconade Dolomite	Og
Kinderhookian Series	Mkc	Upper Gasconade Dolomite	Ogu
Devonian	D	Lower Gasconade Dolomite	Ogl
Grassy Creek Shale	Dgc	Gunter Sandstone Member	Ogg
Cedar Valley Limestone	Dcv	Eminence and Potosi formations	Cep
Callaway Facies	Dcvca	Eminence Dolomite	Ce
Mineola Facies	Dcvm	Potosi Dolomite	Cp
Hoing Sandstone Member	Dcvcah	Elvins Group	Cel
Kimmswick Limestone	Ok	Derby-Doerun Dolomite	Celdd
Decorah Group	Od	Davis Formation	Celd
Plattin Group	Op	Bonneterre Formation	Cb
Joachim Dolomite	Oj	Lamotte Sandstone	Clm
Mohawkian Series	Omo	Precambrian Basement	Pc
St. Peter Sandstone	Osp		

III. IATAN GENERATING STATION

A. Introduction

This section describes in detail the bedrock and hydrologic units encountered while drilling borehole #3 at the Iatan Generation Station (IGS). This borehole was drilled over the course of several months, with drilling beginning January 8, 2013 and completed on March 1, 2013. The objective of the project was to analyze the characteristics of the St. Francois Aquifer and the overlying confining units in order to determine the potential for carbon dioxide sequestration in and around IGS.

B. Site location

The IGS site is located approximately 1.3 miles southeast of the intersection of the IGS private road and Hwy 45 (figure 3.12). The site is located in Platte County, Missouri in section 32 T 54, R 36 W the borehole is located at 39° 26’ 25.39” north latitude 94°57’ 27.23” west longitude, as illustrated on the topographic map in Figure 3.12. Figure 3.13 is an aerial photo of the site and the location of the borehole.

C. Geologic Setting

The IGS site is located in the Dissected Till Plains physiographic province. This province consists of loess and glacial tills deposited on Pennsylvanian-age sedimentary rocks. Elevation at the top of the surface casing for this borehole was 779.49 feet above mean sea level.

The surficial materials at the site consist mainly of Missouri River alluvium deposits consisting of silty clay, sand and gravel. Geological maps indicate that the uppermost bedrock series is of Pennsylvanian- age. This series consists of thin to thick layers of shale, limestone and sand with coal seams.

D. Geologic Structure

At the IGS site the regional dip of the top of the Derby–Doerun Dolomite is approximately 11 feet per mile to the northwest (Crews & Bone, 2010). The Iatan structure, a possible collapse structure, is located 1.5 mile to the north of the site and is the only mapped structure within five miles of the site (McCracken, 1971).

E. Hydrology

The IGS site is located in the Northwestern Missouri Groundwater Province (Miller & Vandike, 1997). The hydrogeology of the site consists of three regional aquifer systems. The upper most aquifer consists of the Missouri River alluvial aquifer. This aquifer is in contact with the underlying Pennsylvanian aquifer. Below the Pennsylvanian aquifer is, for lack of a better definition, the Pre–Pennsylvanian aquifer. The Pre-Pennsylvanian aquifer within the province is not typically subdivided as the water quality is too highly mineralized for most uses. Problems with drilling Exploratory Borehole #3 made characterization of this aquifer difficult. This report will refer to confining units and aquifers within Pre– Pennsylvanian strata as needed. Figure 3.15 is a topographic map of the area of IGS and depicts a cross section between two regional groundwater wells as well as the location of Exploratory Borehole #3.

Figure 3.16 is illustrates the regional geology and hydrology from the cross section shown on Figure 3.15.

1. Missouri River Alluvial Aquifer

The Missouri River alluvial aquifer encountered in the borehole is 93 feet thick (Figure 3.14; Table 3.5). This aquifer at the site was not logged and samples were not collected or described. The Missouri River alluvial aquifer is utilized regionally for irrigation, industrial and drinking water purposes (Miller & Vandike, 1997).

2. Pennsylvanian Aquifer

The Pennsylvanian aquifer encountered in the borehole is 1,073 feet thick beginning at a depth of 93 feet (Figure 3.14; Table 3.5). This aquifer system consists of the Pennsylvanian-age gray shale, quartz sandstone, limestone and coal of the Lansing, Kansas City, Pleasanton, Marmaton and Cherokee Groups. The Pennsylvanian aquifer generally has low permeability and poor water quality. Water found in this aquifer generally contains excessive sulfate, iron, hydrocarbon and TDS (Miller & Vandike, 1997). Water quality within the Pennsylvanian aquifer at the site was expected to be between 8,000 and 40,000 mg/L TDS (Crews, *et al*, 2009a-c).

3. Pre-Pennsylvanian Aquifer

The Pre-Pennsylvanian aquifer at the site was not fully penetrated by the borehole. Complications with drilling made interpretations of strata from cuttings collected below 1,325 feet impractical. A nearby cuttings log (see Appendix H) was used to estimate formation thicknesses and rock characteristics for deeper strata at the site. This aquifer system can be further subdivided by aquitards into at least three separate zones (Figure 3.14; Table 3.5).

Below the Pennsylvanian strata, approximately 365 feet of low to moderately permeable Mississippian age cherty limestone and dolomite are present. The water quality of this unit was expected to be over 20,000 mg/L TDS (Crews, *et al*, 2010a). This hydrologic unit is separated from lower permeable units by approximately 170 feet of low permeability Mississippian–Devonian-age, Kinderhook/Chattanooga Shale.

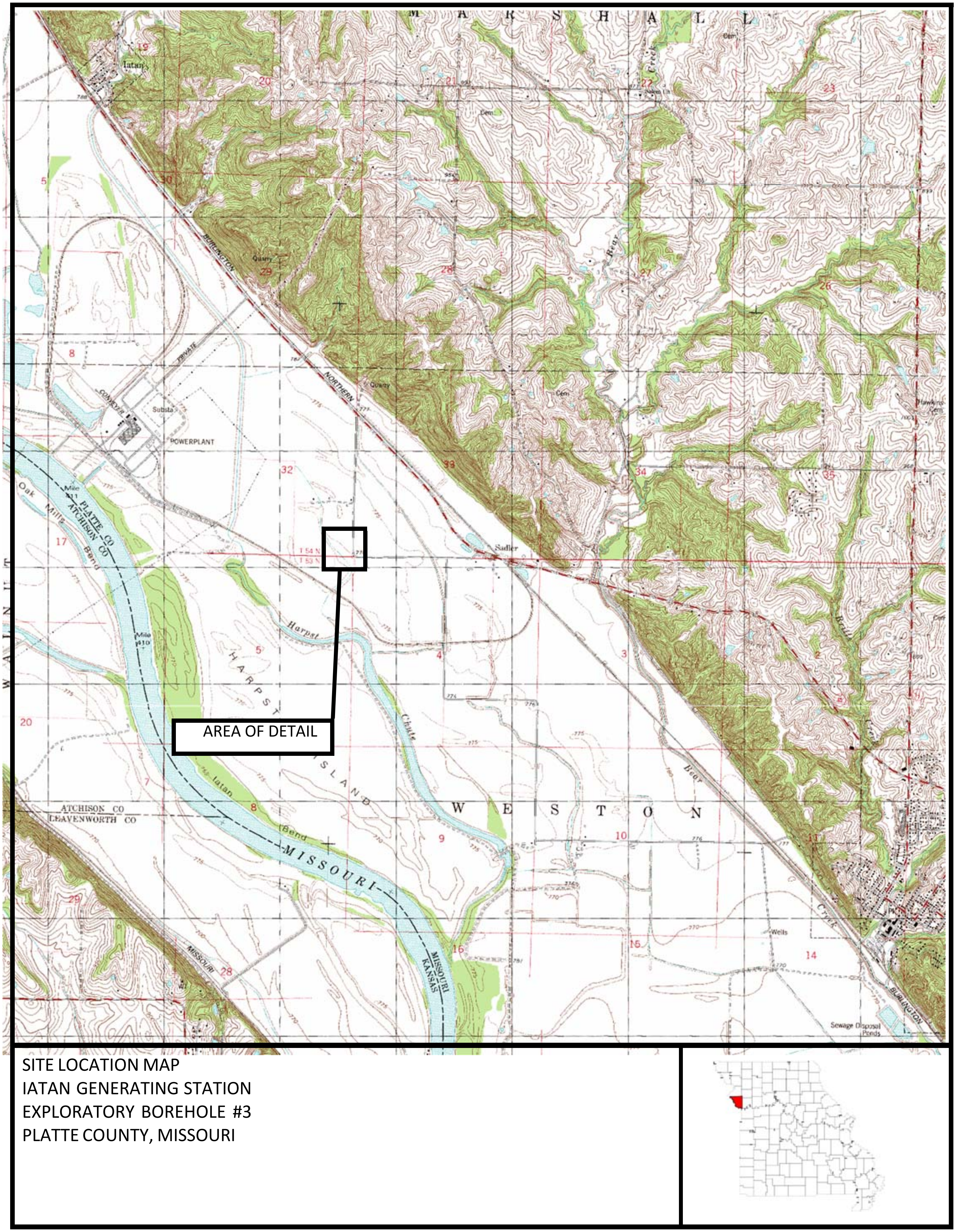
The aquifer unit that most closely corresponds with the Ozark aquifer in southern Missouri extends vertically from the base of the Devonian-age Chattanooga Shale to the base of the Cambrian-age Potosi Dolomite. In the northwest corner of Missouri, the Maquoketa Group was expected to isolate this portion of the aquifer from overlying permeable units. The Maquoketa Group is either lacking shale near the site or the shale was eroded prior to deposition of Devonian strata. As such, Devonian carbonates are included in this aquifer unit. The total thickness of this zone is approximately 1,060 feet. Water quality was expected to be between 25,000 to 30,000 mg/L (Crews, *et al*, 2010c).

The low to moderately permeable Cambrian-age Derby–Doerun Dolomite and Davis Formation is approximately 105 feet thick. These units have been logged as predominately dolomite with a small percentage of shale present in the Davis Formation.

The deepest permeable units expected below the site consist of the Bonneterre Dolomite and the Lamotte Sandstone. These low to moderately permeable units have a total thickness of approximately 75 feet. No water quality data is available for units at these depths within 50 miles of the site; however the water quality was expected to be over 20,000 mg/L (Crews, *et al*, 2010b).

4. Precambrian Basement Confining Unit

Basement rock encountered below these units consists of Precambrian granite and is expected to have low permeability.



SITE LOCATION MAP
IATAN GENERATING STATION
EXPLORATORY BOREHOLE #3
PLATTE COUNTY, MISSOURI

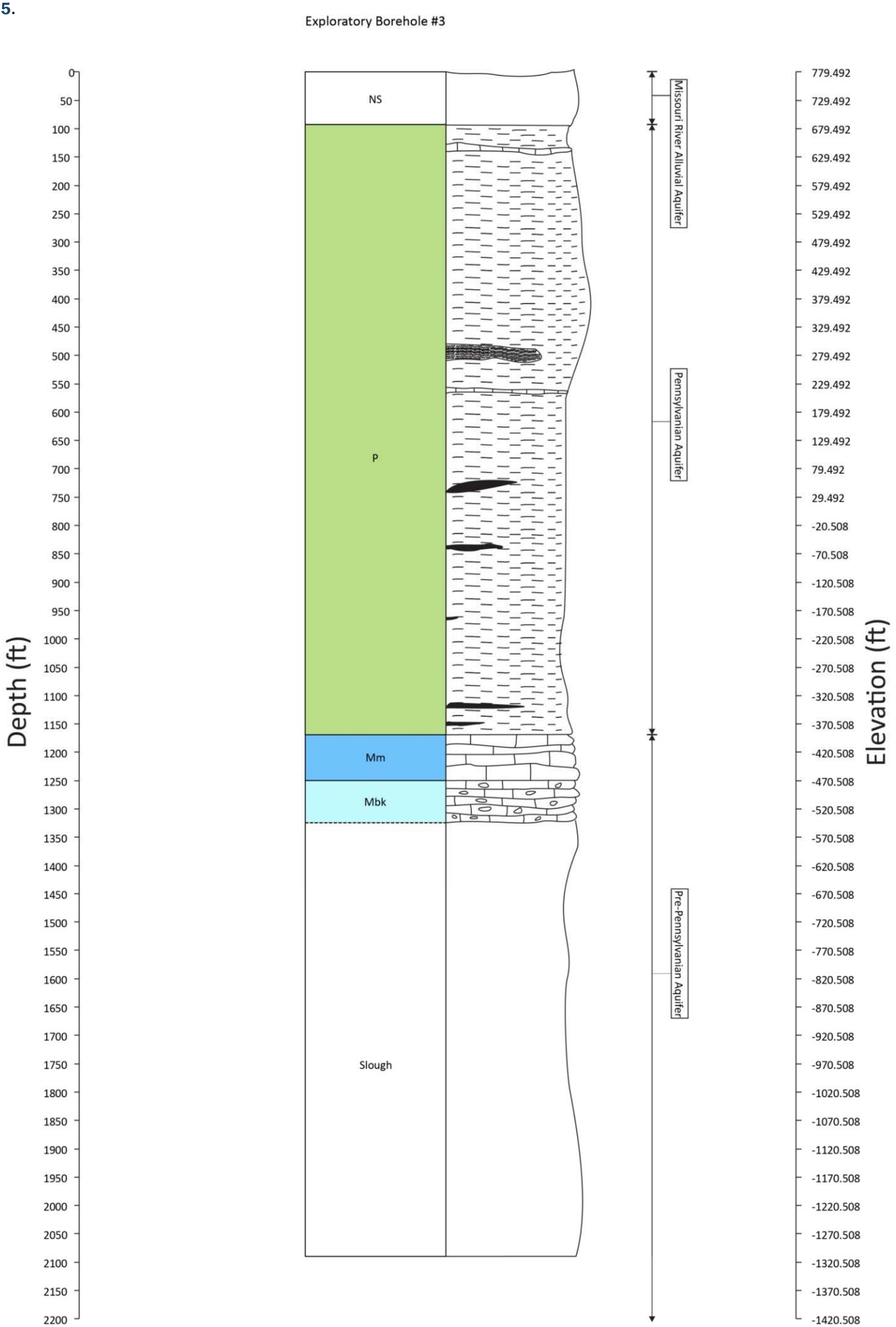
FIGURE 3.12. TOPOGRAPHIC MAP SHOWING THE LOCATION OF THE IATAN GENERATION STATION SITE WHICH CONTAINS EXPLORATORY BOREHOLE #3.

SITE AND BORING LOCATION MAP
IATAN GENERATING STATION
EXPLORATORY BOREHOLE #3
PLATTE COUNTY, MISSOURI

● Exploratory Borehole #3

FIGURE 3.13. AERIAL PHOTO SHOWING THE LOCATION OF THE IATAN GENERATION STATION AND EXPLORATORY BOREHOLE #3.

FIGURE 3.14. EXPLORATORY BOREHOLE #3 STRATIGRAPHIC COLUMN. STRATIGRAPHIC SYMBOLOGY DEFINED IN TABLE 3.5.



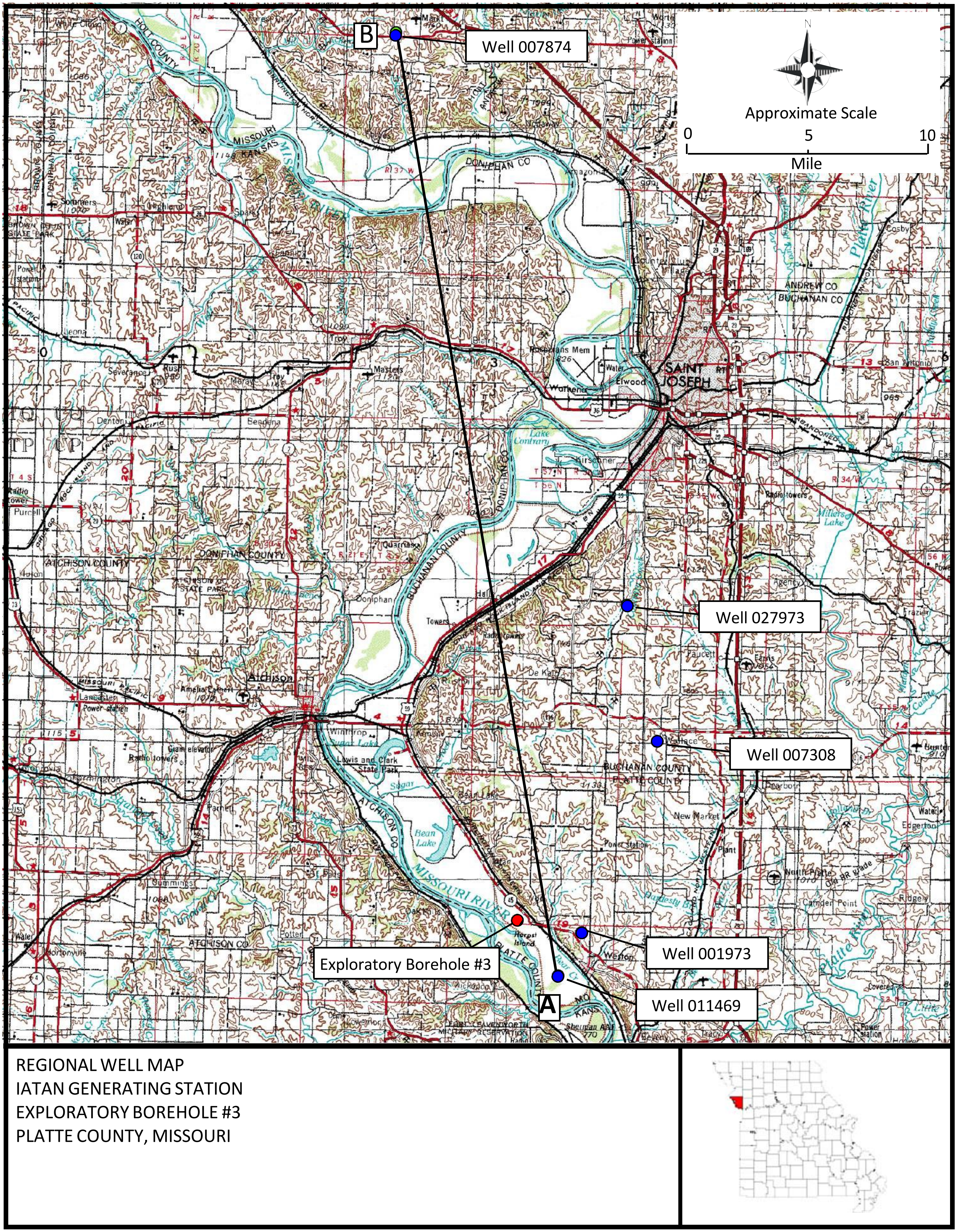


FIGURE 3.15. MAP OF REGIONAL WELLS AND CROSS SECTION LINE OF AREA AROUND THE IATAN GENERATION STATION.

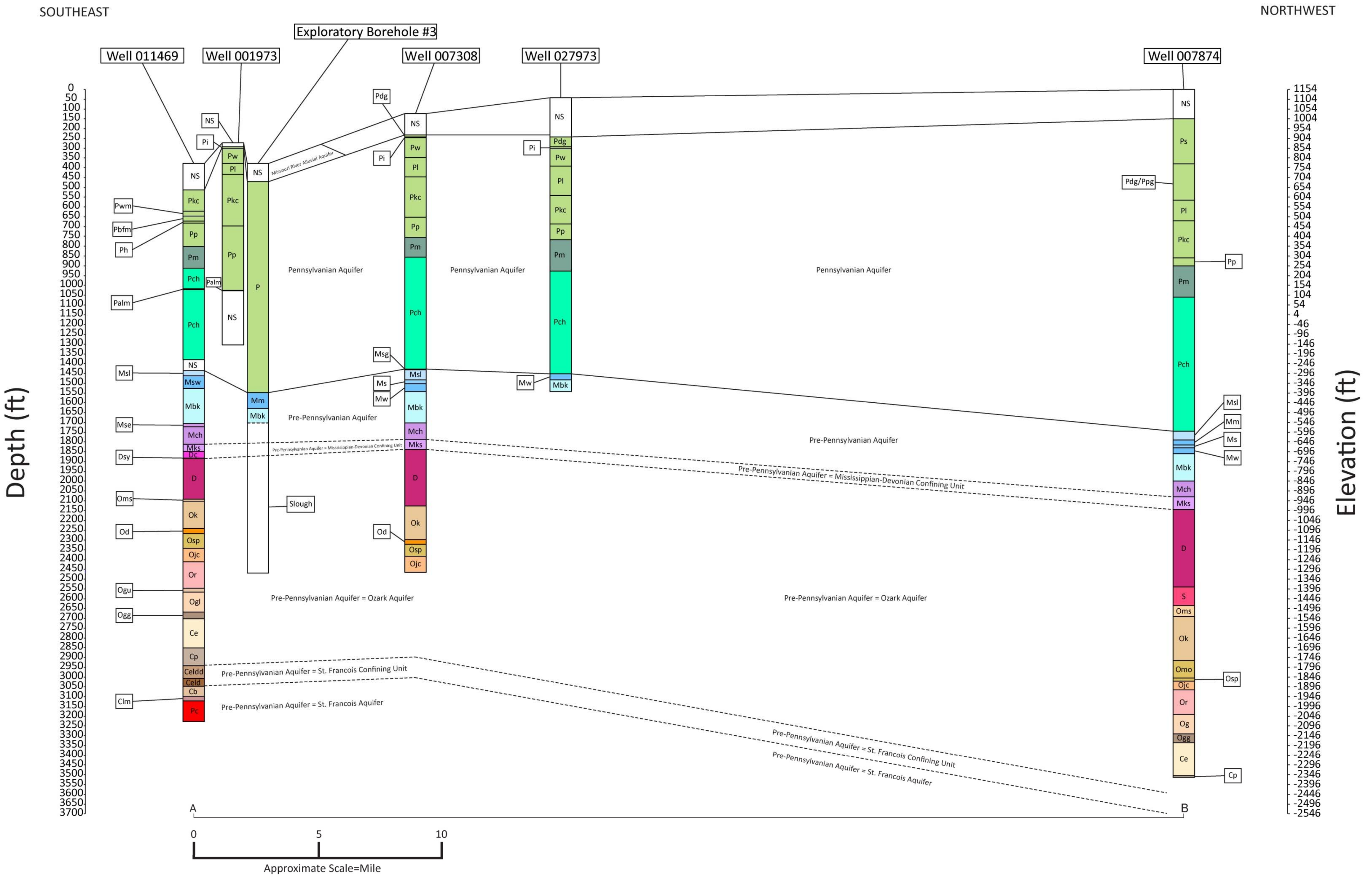


Figure 3.16. Regional geology and hydrology cross section of the Iatan Generation Station area. Stratigraphic symbology is defined in Table 3.6.

TABLE 3.6. FORMATION LIST FOR REGIONAL SECTION IN THE VICINITY OF THE IATAN GENERATING STATION.

Formation	Symbol
No samples	NS
Pennsylvanian System	P
Shawnee Group	Ps
Douglas Group	Pd
Pedee Group	Pp
Iatan Formation	Pi
Weston Formation	Pw
Lansing Group	Plg
Kansas City Group	Pkc
Winterset Limestone Member	Pwm
Bethany Falls Limestone Member	Pbfm
Hertha Formation	Ph
Cherokee Group	Pch
Ardmore Limestone Member	Palm
Meramecian Series	Mm
Ste. Genevieve Limestone	Msg
St. Louis Limestone	Msl
Salem Formation	Ms
Warsaw Formation	Mw
Keokuk-Burlington Limestone	Mbk
Chouteau Group	Mch
Kinderhook Shale	Mks
Devonian System	D
Chattanooga Shale	Dc
Sylamore Sandstone	Dsy
Silurian System	S
Maquoketa Shale	Oms
Kimmswick Limestone	Ok
Decorah Group	Od
Mohawkian Series	Omo
St. Peter Sandstone	Osp
Jefferson City Dolomite	Ojc
Roubidoux Formation	Or
Gasconade Dolomite	Og
Upper Gasconade Dolomite	Ogu
Lower Gasconade Dolomite	Ogl
Gunter Sandstone Member	Ogg
Eminence Dolomite	Ce
Potosi Dolomite	Cp
Derby-Doerun Dolomite	Celdd
Davis Formation	Celd
Bonneterre Formation	Cb
Lamotte Sandstone	Clm
Precambrian Basement	Pc

IV. SIOUX POWER PLANT SITE

A. Introduction

This section describes in detail the bedrock and hydrologic units encountered while drilling borehole #4 at the Sioux Power Plant (SPP) Site. The borehole was drilled over the course of several months, with drilling commenced on October3, 2012 and completed on January 28, 2013. The objective of the project was to analyze the characteristics of the St. Francois Aquifer and the overlying confining units in order to determine the potential for carbon dioxide sequestration in and around SPP.

B. Site Location

SPP is located approximately 0.54 miles north of the intersection of New Halls Ferry Road and Douglas Road (Figure 3.17). The site is located in Florissant, St. Louis County, Missouri in T 47 N, R 6 E. The borehole is located at 38° 52' 09.35" north latitude, 90° 20'15.83"west longitude. Figure 3.18 is an aerial photo of the site and the location of Exploratory Borehole #4.

C. Geologic Setting

SPP is located in the Dissected Till Plains physiographic province. This province consists of loess and glacial tills deposited on Pennsylvanian-age sedimentary rocks. Elevation at the top of the surface casing for this borehole was 450.61 feet above mean sea level.

The surficial materials at the site consist mainly of Missouri River alluvium deposits of silty clays, sands and gravels. Geological maps indicate that the uppermost bedrock is the Mississippian-age Meramecian Series. This series consists of three formations, the Warsaw, Salem, and St. Louis. These formations are mainly composed of limestone except for the Warsaw; of which the uppermost part is shale.

D. Geologic Structure

At SPP the regional dip of the top of the Derby–Doerun is approximately 80 feet per mile to the south (Crews & Bone, 2010). The site is located between two structural features (Harrison, 1995). The axis of the Waterloo–Dupo anticline is located at 0.75 of a mile to the northeast of the site. This northwest- southeast trending anticline plunges to the southeast. The axis of the Cheltenham syncline is located 0.5 mile to the southwest of the site and consists of a northwest–southeast trending syncline plunging to the southeast. Since the site is located between these two close structural features, the strata at the site are likely dipping to the southwest.

E. Hydrology

SPP is located at the boundary of the Northeastern Missouri Groundwater Province and the Salem Plateau Groundwater Province (Miller & Vandike, 1997). This report references aquifers and confining units from both provinces. The hydrogeology of the site consists of four regional aquifer systems, two regional confining units and two local confining units within regional aquifers. The upper most aquifer consists of the Mississippi River alluvial aquifer which is in contact with the underlying Post–Maquoketa aquifer. The Post–Maquoketa aquifer is an aquifer system unique to St. Louis County comprised of Mississippian and Devonian carbonates (Miller & Vandike, 1997). The Post–Maquoketa aquifer at the site also is subdivided by the Mississippian–Devonian–Silurian confining unit. Locally the Post– Maquoketa aquifer is separated from the underlying Ozark aquifer by the Maquoketa Shale. The Ozark aquifer is separated from the lowermost regional aquifer, the St. Francois aquifer, by the St. Francois confining unit. Figure 3.20 is a topographic map of the SPP area depicting regional groundwater wells, a cross section line between two of the wells and the location of Exploratory Borehole #4. Figure 3.21 illustrates the regional geology and hydrology from the cross section line shown on Figure 3.20.

1. Mississippi River Alluvial Aquifer

The Mississippi River alluvial aquifer encountered by the borehole is 89 feet thick (Figure 3.19; Table 3.7). This aquifer at the site consists of low permeability light brown to yellowish brown silty clays over moderate to high permeability light gray to gray, fine to coarse grained sand. Sand grains are well rounded to angular calcite and quartz sands. The Mississippi River alluvial aquifer is utilized regionally for irrigation, industrial and drinking water purposes.

2. Post–Maquoketa Aquifer and Mississippian-Devonian-Silurian Confining Unit

This aquifer system at the site consists of 714 feet of Mississippian and Devonian-age carbonates and shale beginning at a depth of 965 feet below ground (Figure 3.19; Table 3.7). The upper permeable units of this aquifer system are separated from the lower permeable units by a regional confining unit, the Mississippian–Devonian–Silurian confining unit.

The upper permeable units are further subdivided by the locally confining Warsaw Formation. The uppermost permeable formations are the St. Louis and Salem Formations. These low to highly permeable units are comprised of light gray to white, microcrystalline to fine grained, limestone and light gray to buff, fine to medium grained limestone with white to black chert. Significant voids were encountered at depths from 114 to 129 feet. Underlying these units is the Warsaw Formation. The Warsaw Formation is comprised of 135 feet of low to moderately permeable intervals of gray to dark gray, medium to coarse grained limestone interbedded with low permeability dark gray, fine grained limey shale.

The lower permeable zone of the upper Post–Maquoketa aquifer is comprised of units between the Warsaw formation and the Mississippian–Devonian–Silurian confining unit. The uppermost unit is the moderately permeable Burlington/Keokuk Limestone. The Burlington/Keokuk Limestone are light gray to buff, fine to medium grained limestone with chert. The chert is white to gray in color and contain crinoid fragments. The Burlington Limestone is underlain by the Fern Glen Formation. The low to moderately permeable Fern Glen Formation is comprised of light to dark gray, fine to medium grained, limestone, interbedded with light to dark gray chert and intervals of dark greenish to dark gray, fine grained, limey shale. Limestones of the Chouteau Group underlie the Fern Glen Formation. The Chouteau Group is comprised of low to moderately permeable gray to dark gray, microcrystalline to fine to medium grain limestone.

The Mississippian–Devonian–Silurian confining unit at the site is comprised of 45 feet of dark gray to gray, fissile, limey shale (Figure 3.19; Table 3.7). This low permeable shale is part of the widespread Chattanooga–New Albany Shale sequence. The specific formation could not be determined or differentiated from visual inspection of cuttings. This unit could be either the Grassy Creek Shale, Saverton Formation, "Kinderhook" shale or a combination thereof.

The lowermost portion of the Post–Maquoketa aquifer has a thickness of 115 feet (Figure 3.19; Table 3.7). This moderately permeable light gray to gray to buff, fine grained, and pitted dolomite is likely the Silurian-age Bowling Green Dolomite.

Locally, the aquifer is not utilized for drinking water purposes. TDS of the aquifer was expected to be low near the surface and to increase in concentration upwards to 3,000 mg/L at depth (Crews, *et al*, 2010).

3. Maquoketa Shale

The 160 foot thick Ordovician-age Maquoketa Shale is found beginning at a depth of 805 feet and forms the primary confining unit above the Ozark aquifer (Figure 3.19; Table 3.4). This shale is a low permeability dark gray to olive gray, fissile shale.

4. Ozark Aquifer

The Ozark aquifer encountered by the borehole has a thickness of 1,810 feet and begins at a depth of 965 feet (Figure 3.19; Table 3.7). The aquifer is comprised primarily of Ordovician and Cambrian-age formations. The Kimmswick Limestone is the uppermost unit included in the Ozark aquifer. The Kimmswick Limestone is tan to dark gray, fine to medium to coarse grained and has moderate permeability. The low to moderately permeable Ordovician-age Decorah Group is immediately below the Kimmswick Limestone. The Decorah Group is comprised of gray to dark gray, fine grained dolomite. Underlying the Decorah Group is the Ordovician-age Plattin Group. The low to moderately permeable Plattin Group is light gray, fine grained limestone with gray chert interbedded along with minor amounts of blue green shale. The thin low permeability shale layers within the Plattin Group may act as local confining units within the aquifer. The low to moderately permeable Ordovician-age Joachim Dolomite is immediately below the Plattin Group. The Joachim Dolomite is a gray to brown, fine grained limestone interbedded with dark gray, fine grained dolomite. Underlying the Joachim Dolomite is the Ordovician-age St. Peter Sandstone. The moderate to highly permeable St. Peter Sandstone consists of white to gray, well sorted, friable, rounded and fine grained, quartz sandstone. The low to moderately permeable Ordovician-age Cotter Dolomite is immediately below the St. Peter Sandstone. The Cotter Dolomite consists of light gray, fine to coarse dolomite with blue green shale and slight amounts of oolitic chert. The dolomite is interbedded with thin friable fine grained, rounded quartz sandstone.

Underlying the Cotter Dolomite is the Ordovician-age Jefferson City Dolomite. The low to moderately permeable Jefferson City Dolomite is a buff to dark gray, fine to medium grained dolomite with blue green shale and slight amounts of oolitic chert. The dolomite is interbedded with thin friable fine grained, rounded quartz sandstone. The highly permeable Ordovician-age Roubidoux Formation underlies the Jefferson City Dolomite. The Roubidoux Formation is comprised of a light gray, fine to medium crystalline dolomite, interbedded with friable, rounded to subrounded and fine grained quartz sandstone. Minor amounts of white chert and blue green to gray green shale are present. The Roubidoux Formation is underlain by the moderate to highly permeable Ordovician-age Gasconade Dolomite. The Gasconade Dolomite is a light gray, fine to medium grained dolomite with white chert and minor amounts of blue to green shale. The moderate to highly permeable Cambrian-age Eminence Dolomite is found below the Gasconade Dolomite. The Eminence Dolomite is comprised of light gray, fine to medium grained, vuggy dolomite. Vugs are lined with quartz druse and pyrite cubes. The final unit comprising the Ozark aquifer is the Potosi Dolomite. The highly permeable Potosi Dolomite is comprised of gray, fine to medium grained, vuggy dolomite. Individual beds are bioturbated and laminated. Vugs are lined with quartz druse and pyrite crystals.

Locally, the Ozark aquifer is not used as a source of drinking water. Water quality was expected to be non-potable with TDS values over 8,000 mg/L (Crews, *et al*, 2010c). Near to the site, petroleum is produced from the Kimmswick Limestone and the St. Peter Sandstone is used for underground storage of natural gas.

5. St. Francois Confining Unit

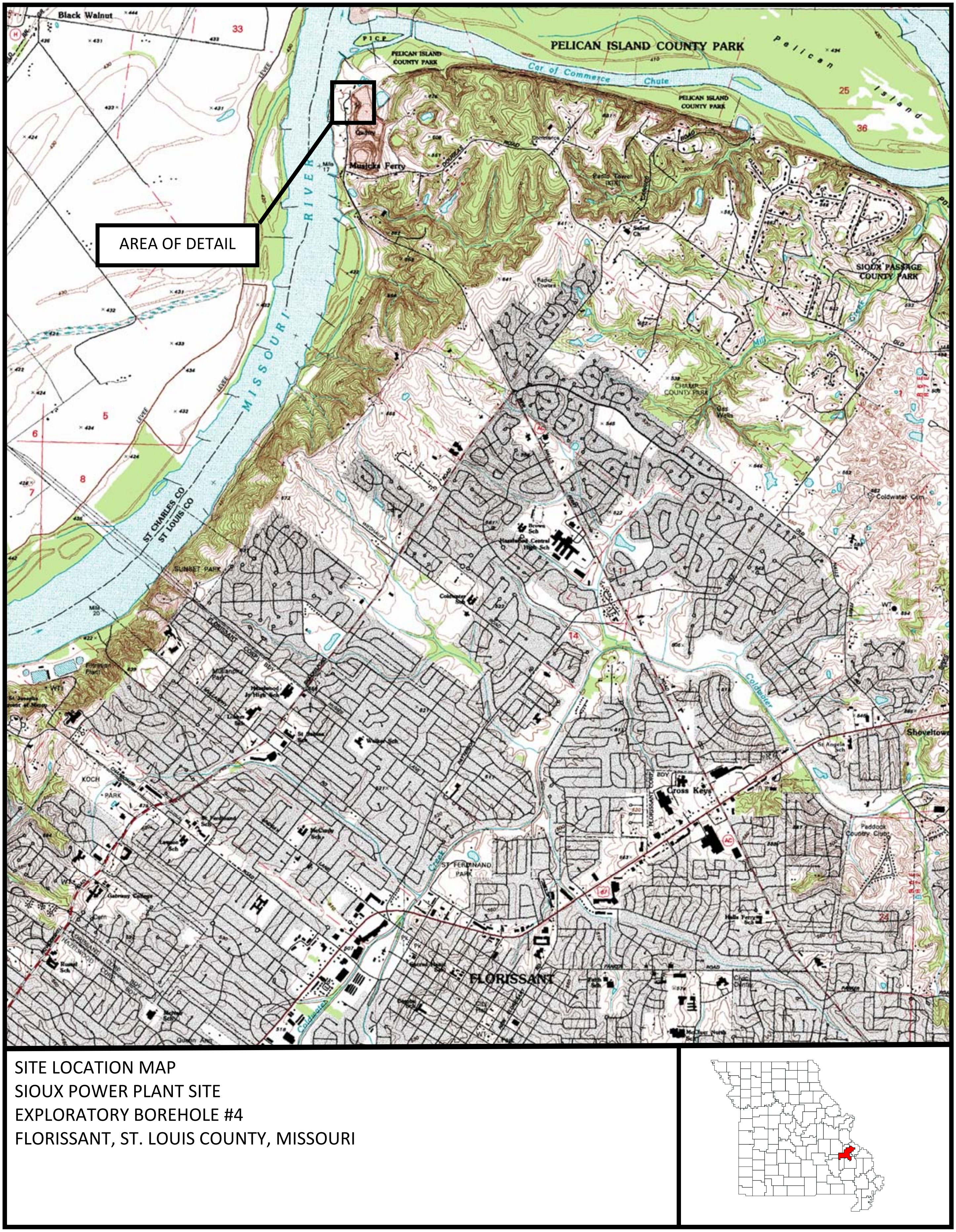
The St. Francois Confining Unit encountered in the borehole has a thickness of 286 feet beginning at a depth of 2,775 feet (Figure 3.19; Table 3.7). This confining unit is comprised of the Cambrian-age Elvins Group. The upper formation of the Elvins Group is the Derby-Doerun Dolomite. The Derby-Doerun Dolomite is comprised of moderate to low permeability light gray to light brown, fine to medium grained, thin to massive bedded dolomite with interbeds of tan and light brown fine grained dolomite. The lower formation of the Elvins Group is the Davis Formation. The low to moderately permeable Davis Formation is comprised of highly variable, glauconitic, very fine grained sandstone, siltstone, and carbonate shale. Interbedded carbonate facies range from packstone to mudstone. Interbedded within the entire sequence are debris flow beds represented by edgewise flat pebble conglomerates.

6. St. Francois Aquifer

The St. Francois aquifer encountered by the borehole has a thickness of 563 feet beginning at a depth of 2,932 feet (Figure 3.19; Table 3.7). The lowermost formation was only partially penetrated by the borehole and the actual aquifer thickness was not determined. The aquifer is comprised of Cambrian- age formations. While these units are typically considered to be a single hydrologic unit in the Salem Plateau Groundwater Province and the Northeastern Missouri Groundwater Province, visual observations of these units indicate that the upper permeable formations are separated from lower permeable formations by aquitards

The uppermost formation of the St. Francois aquifer is the Bonneterre Formation. The Bonneterre Formation varies from low to highly permeable and is controlled by interbedded gray to dark gray, fine to medium grained, oolitic limestone, dolomite with variable glauconite, gray mottled dolomite with grainstones, laminated shale dolomite, laminated limestone, and dark shale. Lower permeability zones within the Bonneterre would be expected to act as localized confining units within the aquifer. Beneath the Bonneterre Formation the Eau Claire Formation is present. This low to moderately permeable unit consists of pink to brown to gray, fine to coarse grained, interbedded siliciclastic and carbonate beds containing dolomite, sandy dolomite, silt, shale and sandstone. Beds are glauconitic and oolitic. The moderately permeable Lamotte Sandstone is over 144 feet thick and is the primary water producing interval of the St. Francois aquifer. The Lamotte Sandstone is composed of white to tan, medium to coarse grained, weakly friable to friable, sub rounded to rounded quartz sandstone. The sandstone contains both fining upwards and coarsening upwards sequences. The lower sand body consists of arkosic sand containing quartz pebbles and cross bedding.

Water samples collected and analyzed by Missouri S&T from the St. Francois aquifer yielded TDS values ranging from 46,272 mg/kg to 46,293 mg/kg, which is approximately 48,000 mg/L. A water sample collected by GSP staff yielded a TDS value of 43,800 mg/L.



SITE LOCATION MAP
SIOUX POWER PLANT SITE
EXPLORATORY BOREHOLE #4
FLORISSANT, ST. LOUIS COUNTY, MISSOURI

Figure 3.17. Topographic map showing the location of the Sioux Power Plant Site which contains Exploratory Borehole #4.

SITE AND BORING LOCATION MAP
SIOUX POWER PLANT SITE
EXPLORATORY BOREHOLE #4
FLORISSANT, ST. LOUIS COUNTY, MISSOURI

● Exploratory Borehole #4

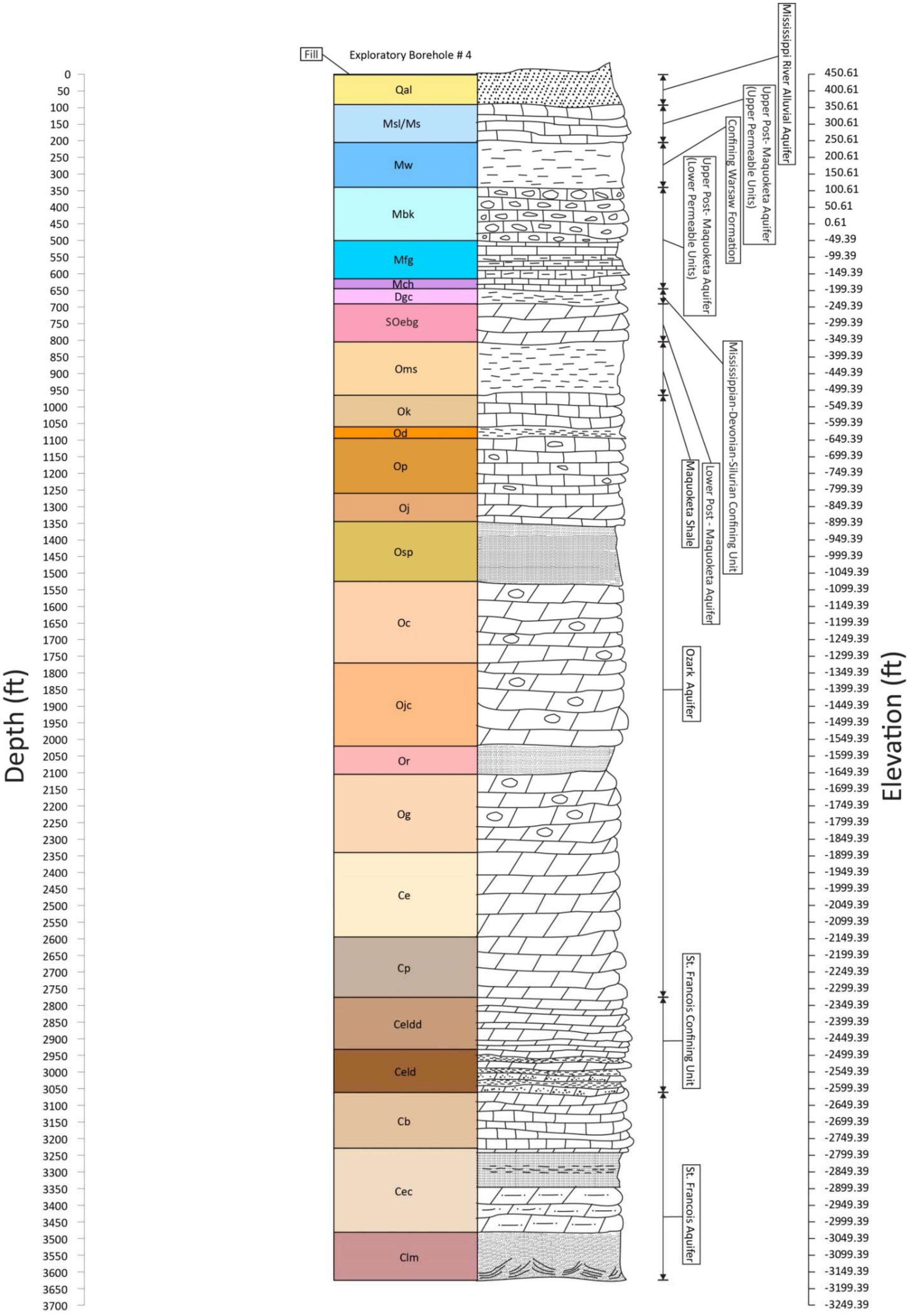


FIGURE 3.19. EXPLORATORY BOREHOLE #4 STRATIGRAPHIC COLUMN. STRATIGRAPHIC SYMBOLOGY DEFINED IN TABLE 3.7.

TABLE 3.7. TOPS OF FORMATION AND HYDROLOGIC UNITS IN EXPLORATORY BOREHOLE #4.

Formation	Symbol	Formation Top	Depth (Feet)	Elevation (Feet)	Hydrologic Unit
Fill Material	Fill	0’	0-2	450.61 to 448.61	
Alluvium Material	Qal	2’	2-91	448.61 to 359.61	Mississippi River Aquifer
St. Louis Formation/Salem Formation	Msl/Ms	91’	91-205	359.61 to 245.61	Upper Post-Maquoketa Aquifer (Upper Permeable Units)
Warsaw Formation	Mw	205’	205-340	245.61 to 110.61	Confining Warsaw Formation
Burlington/Keokuk Formation	Mbk	340’	340-500	110.61 to -49.39	Upper Post-Maquoketa Aquifer (Lower Permeable Units)
Fern Glen Formation	Mfg	500’	500-615	-49.39 to -164.39	
Chouteau Group	Mch	615’	615-645	-164.39 to -194.39	
Grassy Creek Shale	Dgc	645’	645-690	-194.39 to -239.39	Mississippian-Devonian-Silurian Confining Unit
Bowling Green Dolomite	Sbg	690’	690-805	-239.39 to -354.39	Lower Post-Maquoketa Aquifer
Maquoketa Formation	Oms	805’	805-965	-354.39 to -514.39	Maquoketa Shale
Kimmswick Limestone	Ok	965’	965-1060	-514.39 to -609.39	Ozark Aquifer
Decorah Group	Od	1060’	1060-1095	-609.39 to -644.39	
Plattin Group	Op	1095’	1095-1260	-644.39 to -809.39	
Joachim Dolomite	Oj	1260’	1260-1345	-809.39 to -894.39	
St. Peter Sandstone	Osp	1345’	1345-1525	-894.39 to -1074.39	
Cotter Dolomite	Oc	1525’	1525-1770	-1074.39 to -1319.39	
Jefferson City Dolomite	Ojc	1770’	1770-2020	-1319.39 to -1569.39	
Roubidoux Formation	Or	2020’	2020-2105	-1569.39 to -1654.39	
Gasconade Dolomite	Og	2105’	2105-2340	-1654.39 to -1889.39	
Eminence Dolomite	Ce	2340’	2340-2595	-1889.39 to -2144.39	
Potosi Dolomite	Cp	2595’	2595-2775.4	-2144.39 to -2324.79	
Derby-Doerun Dolomite	Celdd	2775.4’	2775.4-2932.2	-2324.79 to -2481.59	St. Francois Confining Unit
Davis Formation	Celd	2932.2’	2932.2-3061.6	-2481.59 to -2610.99	
Bonneterre Formation	Cb	3061.6’	3061.6-3229	-2610.99 to -2778.39	St. Francois Aquifer
Eau Claire Formation	Cec	3229’	3229-3480.9	-2778.39 to -3030.29	
Lamotte Sandstone	Clm	3480.9’	3480.9-3625	-3030.29 to -3174.39	

REGIONAL WELL MAP
SIOUX POWER PLANT SITE
EXPLORATORY BOREHOLE #4
FLORISSANT, ST. LOUIS COUNTY, MISSOURI

FIGURE 3.20. MAP OF REGIONAL WELLS AND CROSS SECTION LINE OF AREA AROUND THE SIOUX POWER PLANT SITE.

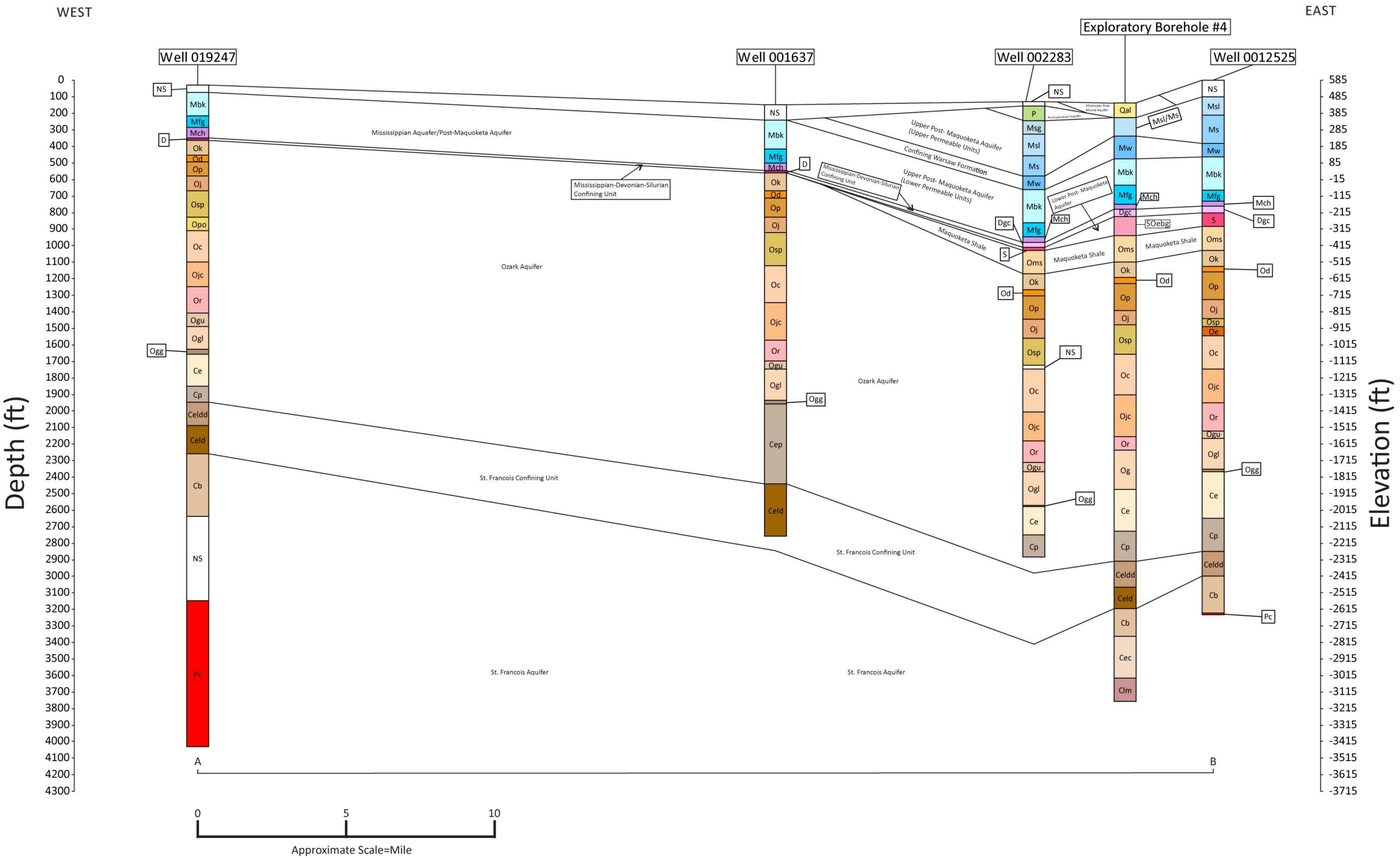


FIGURE 3.21. REGIONAL GEOLOGY AND HYDROLOGY CROSS SECTION OF THE SIOUX POWER PLANT SITE AREA. STRATIGRAPHIC SYMBOLOGY DEFINED IN TABLE 3.8.

TABLE 3.8. FORMATION LIST FOR REGIONAL SECTION IN THE VICINITY OF THE SIOUX POWER PLANT SITE.

Formations	Symbol
No samples	NS
Fill	Fill
Quaternary alluvium	Qal
Pennsylvanian Subsystem	P
Ste. Genevieve Limestone	Msg
St. Louis Limestone and Salem Formation	Msl/Ms
St. Louis Limestone	Msl
Salem Formation	Ms
Warsaw Formation	Mw
Keokuk-Burlington Limestone	Mbk
Fern Glen Formation	Mfg
Chouteau Group	Mch
Devonian System	D
Grassy Creek Shale	Dgc
Silurian System	S
Bowling Green Formation	Sbg
Maquoketa Shale	Oms
Kimmswick Limestone	Ok
Decorah Group	Od
Plattin Group	Op
Joachim Dolomite	Oj
St. Peter Sandstone	Osp
Powell Dolomite	Opo
Everton Formation	Oe
Cotter Dolomite	Oc
Jefferson City Dolomite	Ojc
Roubidoux Formation	Or
Gasconade Dolomite	Og
Upper Gasconade Dolomite	Ogu
Lower Gasconade Dolomite	Ogl
Gunter Sandstone Member	Ogg
Eminence and Potosi Formations	Cep
Eminence Dolomite	Ce
Potosi Dolomite	Cp
Derby-Doerun Dolomite	Celdd
Davis Formation	Celd
Bonneterre Formation	Cb
Eau Claire Formation	Cec
Lamotte Sandstone	Clm
Precambrian Basement	Pc

V. REFERENCES

Bodenhamer, S. (2012). Personal communication.

Crews, J., & Bone, F. (2010). *Structur Contour Map of the Derby-Doerun Dolomite.* Rolla: Missouri Department of Natural Resources, Division of Geology and Land Survey; unplublished.

Crews, J., Mesko, T., & Kaden, S. (2009a). *Total Dissolved Solids Concentrations of Groundwater from the Pennsylvanian Cherokee Group in Missouri.* Rolla: Missouri Department of Natural Resources, Division of Geology and Land Survey, OFM-09-567-GS.

Crews, J., Mesko, T., & Kaden, S. (2009b). *Total Dissolved Solids Concentrations of Groundwater from the Pennsylvanian Marmaton and Pleasanton Groups in Missouri.* Rolla: Missouri Department of Natural Resources, Division of Geology and Land Survey; OFM-09-568-GS.

Crews, J., Mesko, T., & Kaden, S. (2009c). *Total Dissolved Solids Concentrations of Groundwater from the Pennsylvanian Kansas City, Lansing, Douglas, Shawnee, and Wabaunsee Groups in Missouri.*

Rolla: Missouri Department of Natural Resources, Division of Geology and Land Survey; OFM-09- 569-GS.

Crews, J., Mesko, T., & Kaden, S. (2010a). *Total Dissolved Solids Concentrations of Groundwater from the Mississippian Subsystem in Missouri.* Rolla: Missouri Department of Natural Resources, Division of Geology and Land Survey; OFM-10-570-GS.

Crews, J., Mesko, T., & Kaden, S. (2010b). *Total Dissolved Solids Concentrations of Groundwater from the St. Francois Aquifer (Campbrian System) in Missouri.* Rolla: Missouri Department of Natural Resources, Division of Geolgoy and Land Survey; OFM-10-605-GS.

Crews, J., Mesko, T., & Kaden, S. (2010c). *Total Dissolved Solids Concentrations from the Ozark Aquifer (Cambrian-Ordovician Systems) in Missouri.* Rolla: Missouri Department of Natural Resources, Division of Geology and Land Survey; OFM-10-571-GS.

Harrison, R. (1995). *Geologic Map of the Eolia 7.5-Minute Quadrangle, Lincoln and Pike Counties, Missouri.* Denver: United States Geological Survey.

McCracken, M. (1971). *Structural Features of Missouri.* Rolla: Missouri Geological Survey & Water Resources; RI-49.

Miller, D. E., & Vandike, J. E. (1997). *Groundwater Resources of Missouri.* Rolla: Missouri Department of Natural Resources; WR-46.

Robertson, C. (1990). *Geologic Map of the Brookline Quad.* Unpublished Geologic Map; Missouri Department of Natural Resources, Division of Geology and Land Survey; SP9003.

Thompson, T. L. (1986). *Paleozoic Succession in Missouri Part 4 Mississippian System.* Rolla: Missouri Department of Natural Resources, Division of Geology and Land Survey; RI-70.

Thomson, K. C. (1978). *Geologic Map of Greene County.* Missouri Department of Natural Resources, Division of Geology and Land Survey; SP7801.

Thomson, K. C. (1997). Field Trip through the Karst Area of Southern Greene and Northern Christian Counties, Missouri, Emphasizing the Relationships between Surface Features and Springs. *The Engineering Geology and Hydrogeology of Karst Terranes*, 479-506.

VI. LIST OF ACRONYMS AND ABBREVIATIONS

Missouri Geological Survey	**MGS**
Iatan Generating Station	**IGS**
John Twitty Environmental Center	**JTEC**
Missouri Geological Survey Program	**GSP**
Missouri University of Science &Technology	**Missouri S&T**
Missouri State University	**MSU**
Shallow Carbon Sequestration Demonstration Project	**SCSDP**
Thomas Hill Energy Center	**THEC**
Total Dissolved Solids	**TDS**

VII. APPENDICES

APPENDIX 3.A - DESCRIPTIVE STRATIGRAPHIC LOG OF EXPLORATORY BOREHOLE #1 AT JOHN TWITTY ENERGY CENTER, GREENE COUNTY, MISSOURI

STRATIGRAPHIC DESCRIPTION

Surficial Material (0 - 22 feet depth): There were 22 feet of cherty residuum derived from the weathering of Mississippian age Burlington Limestone.

Burlington Limestone (22 - ~150 feet depth): This unit contains white to light gray, medium-to coarsely crystalline, medium to coarsely crinoidal, medium to thick bedded, cherty limestone. Secondary minerals present include pyrite, glauconite and hematite. Significant voids and solution enlarge joints, some containing residual clays, were encountered. These voids complicated drilling operations and resulted in significant loss of returns of cuttings. As such, the Burlington Limestone's contact with underlying strata was inferred from logs of other wells near to Exploratory Well #1.

Elsey – Reed Springs Formation (~150 - 225 feet depth): Primarily white to gray chert nodules with gray to dark gray fine grained limestone were found. Secondary minerals present include pyrite, glauconite and sphalerite. Due to the limitations of analyzing cuttings, distinguishing between the Elsey Formation and Reed Springs Formation was not possible. Local mapping of surface exposures suggest that only the Elsey Formation is present at the site. However, the gray color and fine grained nature of the cuttings suggest the Reed Springs facies was encountered.

Pierson Limestone (225-247 feet depth): This unit contains light gray to brown fine grained limestone with white chert nodules containing crinoid fossils. The secondary mineral pyrite was present and possibly chalcopyrite.

Northview Formation (247-266 feet depth): Primarily gray silty shale with light gray fine grained limestone was found with possibly a slight amount of chert.

Compton Limestone (266-274 feet depth): This unit contains light gray to gray fine grained limestone and possibly a slight amount of chert. The secondary mineral pyrite was present.

Bachelor Formation (274-275 feet depth): Calcite cemented, fine grained, and well rounded, quartz sandstone was found.

Cotter Dolomite (275-416 feet depth): This unit contains light gray to light brown, coarse to finely crystalline dolomite, chert free and cherty dolomite, interbedded with thin sandstones. In particular the relatively thick **"Swan Creek" sandstone** is present between 309 to 320 feet below ground surface. Secondary minerals present include pyrite, and glauconite.

Jefferson City Dolomite (416-605 feet depth): This unit contains typically light brown to gray, fine to medium crystalline chert free and cherty dolomite interbedded with thin sandstones. Cherts are commonly oolitic, banded or mottled. Secondary minerals present include pyrite, and glauconite.

Roubidoux Formation (605-790 feet depth): This unit contains light gray to gray medium crystalline dolomite, interbedded with carbonate and silica cemented sandstones and cherts. Cherts are commonly oolitic or banded. Secondary minerals present include pyrite, glauconite, and galena. Significant voids were encountered within the Roubidoux Formation functioning as a prolific aquifer.

Gasconade Dolomite (790-1,165 feet depth): This unit contains light gray to dark gray fine to medium crystalline vuggy dolomite and cherty dolomites. Cherts are commonly oolitic, banded, or opaque. At the base of the Gasconade Dolomite, the **Gunter Sandstone Member** is present between 1,120 and 1,165 feet below ground surface. The Gunter Sandstone is primarily a clean quartz arenite with thin interbeds of friable dolomite. Secondary minerals present include pyrite, and glauconite. Significant voids were encountered within the Gasconade Dolomite.

Eminence Dolomite (1,165-1,500 feet depth): This unit contains light gray to dark gray fine to medium crystalline vuggy dolomite and cherty dolomites. Cherts are commonly oolitic, banded, or opaque. Secondary minerals present include pyrite, calcite and glauconite. Significant voids were encountered within the Eminence Dolomite.

Potosi Dolomite (1,500-1,507.5 feet depth): This unit contains gray fine to coarse crystalline vuggy dolomite and with dolomite and druse quartz lined vugs.

Elvins Group (1,507.5-1,701.9 feet depth): The Elvins Group is comprised of dolomites and limestones transitioning from a shallow marine silty limestone facies at the base to a deep water shaly carbonate up to a shallow marine facies. The deep water facies consists of laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules. Interbedded within the entire sequence are debris flow beds represented by edgewise flat pebble conglomerates, carbonate sands and mud derived from locally mobilized limestone nodules, distal carbonates sands and local carbonate mud. The uppermost bed is a fining upwards sequence of pebble to flat pebble conglomerate to cross-bedded carbonate sand. The shallower facies are dolomitized and the deeper shaly facies is not.

Bonneterre Formation (1,701.9-1,780.3 feet depth): This unit contains gray to greenish gray fine crystalline brecciated dolomite. Gray mottled dolomite interbedded with grainstones and shaly dolomite also was found, as well as, laminated limestone and limestone mud. Secondary minerals present include marcasite, pyrite, and glauconite

Lamotte Sandstone (1,780.3-2,147 feet depth): The Lamotte Sandstone is comprised of two separated sand bodies separated by burrowed shale and siltstone facies and a deeper water glauconitic sand and carbonate facies. The upper sand body consists of medium to coarse grained marine sand containing numerous brachiopod shells and other shell fragments interbedded with thin marine shale.

The lower sand body consists of a marine facies similar to the upper sand body, and transactions to a lower fluvial facies consisting of medium to coarse grained arkosic sands containing quartz and feldspar pebbles. The fluvial facies also contains a zone with hematite cements.

Precambrian Basement (2,147-2,186.6 feet depth): This unit contains quartz, plagioclase, orthoclase, muscovite, and biotite pegmatite, with greater than 10 cm feldspar crystals veined with quartz. The formation is heavily fractured; fractures dipping approximately 30 degrees with striations on fractures. Ductile deformation is likely in some zones. Extensive weathering exists along fractures with micas and possible epidote altered to chlorite.

APPENDIX 3.B EXPLORATORY BOREHOLE #1 WELL LOG

Missouri Department of Natural Resources
Divison of Geology and Land Survey
Geological Survey Program

Page 1 **of** 58
Project: Shallow Carbon Sequestration Demonstration Project
Site: John Twitty Energy Center
Hole Exploratory Borehole #1

Driller's Information

Drilling Company: Lanye Christensen
Driller: Rusty Bowles
Equipment Description: Atlas Copco

Contractor's Information

Primary Contractor:
P C Represetative:
Sub-Contractor:
S C Representative:

Site Location Information

County: Greene County
Quadrangle:
Land Grant:
Section:
Additional description:

Well longitude: 93° 22' 48.5" W
Well latitude: 37° 09' 09.7" N
Logged by: Jeffery Crews
Alias well ID:
Date drilled: Started 5/2010 **; Ended** 11/2010
Additional location description:

Elevation	Depth
1236.32'	
1231.32	5'
1226.32	10'
1221.32	15'
1216.32	20'
1211.32	25'
1206.32	30'

Formation	Member	Lithologic Description	Samples Interval	Comments
		0-2 : Approximately 2 feet of Limestone Gravel and Geotextile that made up the drill pad above undisturbed soil.		
		2-5: Cherty gravel and red clay residuum		
		5-10: Cherty gravel and red clay residuum		
		10-13: Cherty gravel and red clay residuum		
		13-16: Chert cobbles		
		16-22: Cherty gravel and red clay residuum • At 19' limestone boulder		
		22-25: **Burlington Formation** 90% brown coarse crystalline crinoidal limestone, 10% red clay		
		25-28: Void		
		25-30: 90% brown coarse crystalline crinoidal limestone, 10% red clay		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: John Twitty Energy Center
Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				30-35: 98% white coarse crystalline crinoidal limestone, 2% red clay, glauconitic pellets		
1201.32	35'			35-40: 98% white coarse crystalline crinoidal limestone, 2% red clay		
1196.32	40'			40-45: 94% white to light gray, coarse crystalline, crinoidal limestone, 5% white chert, 1% red clay, glauconitic pellets		
1191.32	45'			45-49: Void		
				49-50: 88% white to light gray, coarse crystalline, crinoidal limestone, 10% white chert, 2% red clay		
1186.32	50'			50-55: 85% white to light gray, coarse crystalline, crinoidal limestone, 15% white chert, pyrite		
1181.32	55'			55-58: Red clay		
				58-59: 55% white to light gray, coarse crystalline, crinoidal limestone, 30% white to brown crinoidal chert, 10% red clay, 5% light brown siltstone, hematite		
				59-60: 90% white to light gray, coarse crystalline, crinoidal limestone, 10% red clay, hematite		
1176.32	60'			60-65: 83% white to light gray, coarse crystalline, crinoidal limestone, 10% white chert, 7% red clay		
1171.32	65'			65-70 77% white to light gray, coarse crystalline, crinoidal limestone, 20% white crinoidal chert, 3% red clay		
1166.32	70'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				70-75: 78% white to light gray, coarse crystalline, crinoidal limestone, 20% white chert, 2% red clay, hematite		
1161.32	75'			75-80: 45% white to light gray, coarse crystalline, crinoidal limestone, 30% red clay, 25% white chert, hematite		
1156.32	80'			80-85: 80% white to light gray, coarse crystalline, crinoidal limestone, 10% white chert, 10% red clay		
1151.32	85'			85-90: 40% white to light gray, coarse crystalline, crinoidal limestone, 30% white to light gray chert, 30% red clay		
1146.32	90'			90-95: 85% white to light gray, coarse crystalline, crinoidal limestone, 10% white chert, 5% red clay		
1141.32	95'			95-100: 88% white to light gray, coarse crystalline, crinoidal limestone, 10% white chert, 2% red clay		
1136.32	100'			100-105: 80% white to light gray, coarse crystalline, crinoidal limestone, 10% white chert, 10% red clay, brachiopod fragment		
1131.32	105'			105-110: 70% white, coarse crystalline, crinoidal limestone, 20% white to dark gray chert, 10% dark gray shaly limestone		
1126.32	110'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: John Twitty Energy Center
Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				110-115: 67% white, coarse crystalline, crinoidal limestone, 20% white chert with calcite filled fractures, 10% dark gray shaly limestone, 3% red clay, pyrite ● 111-113: Void		
1121.32	115'			115-120: 70% white to gray, coarse crystalline, crinoidal limestone, 20% white crinoidal chert, 5% dark gray shaly limestone, 5% red clay, pyrite		
1116.32	120'			120-125: 68% white to dark gray, coarse crystalline, crinoidal limestone, 30% white crinoidal chert, 2% red clay		
1111.32	125'			125-130: 79% white to dark gray, coarse crystalline, crinoidal limestone, 20% white chert, 1% red clay ● 125-129: No Return		
1106.32	130'			130-135: No Return		
1101.32	135'			135-140: No Return		
1096.32	140'			140-145: No Return		
1091.32	145'			145-150: No Return		
1086.32	150'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				150-155: No Returns		
1081.32	155'			155-160: No Returns		
1076.32	160'			160-163: No Returns		
				163-165: **Elsey – Reed Springs Formation** 79% white chert, 20% white to dark gray, fine grained limestone, 1% red clay, glauconite		
1071.32	165'			165-170: 80% white chert, 19% dark gray, fine grained limestone, 1% red clay		
1066.32	170'			170-175: 89% white chert, 10% dark gray, fine grained limestone, 1% red clay		
1061.32	175'			175-180: 89% white to light gray chert, 10% dark gray, fine grained limestone, 1% red clay, pyrite		
1056.32	180'			180-185: 69% white to light gray chert, 30% light to dark gray, fine grained limestone, 1% red clay		
1051.32	185'			185-190: 69% white to light gray chert with sponge spicules, 30% light gray, fine grained limestone, 1% red clay, pyrite, conodont?		
1046.32	190'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				190-195: No Returns		
1041.32	195'			195-200: 64% white to light gray chert, 35% light to dark gray, fine grained limestone, 1% red clay, pyrite		
1036.32	200'			200-205: 80% white to light gray chert, 20% light gray, fine grained limestone, sphalerite		
1031.32	205'			205-210: 69% white chert, 30% light gray to gray, fine grained limestone, 1% red clay		
1026.32	210'			210-215: 74% white chert, 25% light gray, fine grained limestone, 1% red clay		
1021.32	215'			215-220: 78% white chert, 20% light gray, fine grained limestone, 2% red clay, pyrite		
1016.32	220'			220-225:		
1011.32	225'			225-230: **Pierson Limestone** 70% light gray to dark gray, fine grained limestone, 30% white chert		
1006.32	230'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project

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Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				230-235: 70% light gray to light brown, fine grained limestone, 30% white chert, pyrite		
1001.32	235’			235-236: 70% light gray to light brown, fine grained limestone, 30% white chert, pyrite		
				236-240: 85% light gray, fine grained limestone, 15% white chert, crinoid		
996.32	240’			240-245: 80% light gray, fine grained limestone, 20% white crinoidal chert with calcite filled fractures, chalcopyrite?		
991.32	245’			245-247: 80% light gray, fine grained limestone, 20% white crinoidal chert with calcite filled fractures, chalcopyrite?		
				247-250: **Northview Formation** 60% light gray, fine grained limestone, 20% gray shaly carbonate, 20% white crinoidal chert		
986.32	250’			250-255: 50% light gray, fine grained limestone, 40% gray silty shale, 10% white chert		
981.32	255’			255-260: 60% gray silty shale, 30% light gray, fine grained limestone, 10% white chert, sponge spicules?		
976.32	260’			260-265: 70% gray silty shale, 20% light gray fine grained limestone, 10% chert, glauconite		
971.32	265’			265-266: 70% gray silty shale, 20% light gray fine grained limestone, 10% chert		
				266-270: **Compton Limestone** 70% light to dark gray fine grained limestone, 30% gray silty shale, 10% white chert, sponge spicules?		
966.32	270’					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				270-274: 90% light to dark gray fine grained limestone, 10% white chert, pyrite		
				274-275: **Bachelor Formation** Calcite cemented, fine grained, well rounded, quartz sandstone, conodont		
961.32	275'			275-280: **Cotter Dolomite** 55% light to dark gray fine grained limestone, 20% light gray to tan fine grained dolomite, 20% white chert, 5% well rounded fine to coarse quartz sand, pyrite		
956.32	280'			280-285: 48% light to dark gray fine grained limestone, 40% light gray to tan fine grained dolomite, 10% white chert, 2% well rounded fine to coarse quartz sand, pyrite		
951.32	285'			285-287: 80% light gray to tan fine to medium crystalline dolomite, 10% light to dark gray fine grained limestone, 10% white oolitic chert, pyrite		
				287-290: 95% light gray to tan fine crystalline dolomite, 5% white chert		
946.32	290'			290-295: 95% light gray to tan fine crystalline dolomite, 5% white chert, pyrite, glauconite		
941.32	295'			295-300: 95% light gray to light tan fine crystalline dolomite, 5% white chert, pyrite		
936.32	300'			300-305: 90% Light tan to light brown fine to coarse crystalline dolomite, 5% dolomite cemented, subrounded fine grained quartz, sandstone, 5% white chert, druse quartz, pyrite		
931.32	305'			305-309: 95% light brown coarse crystalline dolomite, 5% white chert		
				309-310: **"Swan Creek" Sandstone** 90% carbonate and pyrite cemented, rounded fine grained quartz, sandstone, 10% light brown coarse crystalline dolomite		
926.32	310'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				310-315: 90% carbonate and pyrite cemented, rounded fine grained quartz, sandstone, 10% light brown coarse crystalline dolomite		
921.32	315'			315-320: 60% carbonate and pyrite cemented, rounded fine grained quartz, sandstone, 40% light brown coarse crystalline dolomite, pyrite		
916.32	320'			320-324: **Cotter Dolomite** 95% light gray fine crystalline dolomite, 5% carbonate and pyrite cemented, rounded fine grained quartz, sandstone, pyrite		
				324-325: 100% light tan medium crystalline dolomite		
911.32	325'			325-327: 90% light tan medium crystalline dolomite, 10% carbonate and pyrite cemented, rounded fine grained quartz, sandstone, pyrite		
				327-330: 90% light gray, fine crystalline dolomite, 10% carbonate and pyrite cemented, rounded fine grained quartz, sandstone, pyrite		
906.32	330'			330-335: 90% light gray to gray, coarse crystalline dolomite, 10% carbonate, quartz, and pyrite cemented, well rounded fine grained quartz, sandstone, pyrite veins, stylolite		
901.32	335'			335-340: 89% light tan to gray, fine to coarse crystalline dolomite, 5% white chert, 5% carbonate, quartz, and pyrite cemented, well rounded fine grained quartz, sandstone, pyrite, stylolite, 1% black shaly siltstone		
896.32	340'			340-343: 98% light gray to light brown, fine to coarse crystalline dolomite, 2% carbonate, quartz, and pyrite cemented, well rounded fine grained quartz, sandstone		
				343-345: 99% light green, fine crystalline shaly dolomite, 1% glauconitic shale		
891.32	345'			345-347: 100% light tan fine crystalline dolomite		
				347-350: 90% light gray coarse crystalline dolomite 10% white chert		
886.32	350'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				350-355: 86% light brown to gray, fine to coarse crystalline dolomite, 10% white chert, 4% carbonate cemented, well rounded fine grained quartz, sandstone		
881.32	355'			355-360: 94% gray, fine to coarse crystalline dolomite, 2% white chert, 4% carbonate, quartz, and pyrite cemented, well rounded fine grained quartz, sandstone, pyrite		
876.32	360'			360-363: 94% light gray, fine crystalline dolomite, 6% carbonate, quartz, and pyrite cemented, well rounded fine grained quartz, sandstone		
				363-365: 100% light brown, medium to coarse crystalline dolomite		
871.32	365'			365-370: 96% light tan to gray, fine to coarse crystalline dolomite, 2% white chert,2% carbonate, quartz, and pyrite cemented, well rounded fine grained quartz, sandstone, pyrite		
866.32	370'			370-375: 89% light tan to gray, fine to coarse crystalline dolomite, 10% white chert, 1% carbonate, quartz, and pyrite cemented, well rounded fine grained quartz, sandstone, pyrite		
861.32	375'			375-380: 98% light tan to light gray, fine to medium crystalline dolomite, 1% white chert, 1% carbonate, quartz, and pyrite cemented, well rounded fine grained quartz, sandstone, pyrite		
856.32	380'			380-383: 100% light gray, fine crystalline dolomite		
				383-385: 90% brown fine to medium crystalline dolomite, 10% white chert, pyrite		
851.32	385'			385-387: 90% brown fine to medium crystalline dolomite, 10% white chert, pyrite		
				387-390: 90% light gray, fine crystalline dolomite, 10% white chert, pyrite veins, stylolite		
846.32	390'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				390-395: 97% light gray, fine crystalline dolomite, 2% white chert, 1% carbonate cemented, well rounded medium grained quartz, sandstone, pyrite		
841.32	395'			395-396: 100% light gray, fine crystalline dolomite ● 396: Carbonate, pyrite cemented, well rounded fine grained quartz, sandstone		
				396-400: 100% light gray, fine crystalline dolomite, calcite, pyrite		
836.32	400'			400-405: 100% light to medium gray, fine crystalline dolomite, pyrite		
831.32	405'			405-408: 100% light to medium gray, fine crystalline dolomite, pyrite ● 408: Dark gray shaly fine grained dolomite		
				408-410: 100% light to medium gray, fine crystalline dolomite, pyrite		
826.32	410'			410-415: 100% light to medium gray, fine crystalline dolomite, pyrite		
821.32	415'			415-416: 100% light to medium gray, fine crystalline dolomite, pyrite		
				416-419: **Jefferson City Dolomite** Light brown oolitic chert ● 419: 100% Glauconitic shaly dolomite, pyrite		
				419-420: 100% light to medium gray, fine crystalline dolomite		
816.32	420'			420-425: 98% light to medium gray, fine crystalline dolomite, 2% white oolitic chert, pyrite		
811.32	425'			425-429: 98% light gray, fine crystalline dolomite, 1% glauconitic shaly dolomite, pyrite ● 429: Translucent light brown to grey lightly banded chert		
				429-430: 100% light gray, fine crystalline dolomite, pyrite		
806.32	430'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				430-434: 100% light gray, fine crystalline dolomite, pyrite		
801.32	435’			434-435: 60% light gray to brown, medium crystalline dolomite, 40% white to gray banded chert, pyrite		
				435-440: 60% light gray to reddish brown medium crystalline dolomite, 20% white to light gray banded opaque to translucent chert, 20% white to light brown oolitic chert, pyrite		
796.32	440’			440-445: 50% light gray to reddish brown medium crystalline dolomite, 20% white to light gray banded opaque to translucent chert, 20% white to light brown oolitic chert, 10% glauconitic shaly dolomite, pyrite, calcite		
791.32	445’			445-448: 50% light gray to reddish brown medium crystalline dolomite, 20% white to light gray banded opaque to translucent chert, 20% white to light brown oolitic chert, 10% glauconitic shaly dolomite, pyrite		
				448-450: 100% light gray, fine crystalline dolomite		
786.32	450’			450-455: 90% light gray to light brown fine to medium crystalline dolomite, 5% white oolitic chert, 5% glauconitic shaly dolomite, pyrite		
781.32	455’			455-460: 90% light gray to light brown fine to medium crystalline dolomite 10% white oolitic chert, pyrite, calcite		
776.32	460’			460-465: 90% brown to gray medium crystalline dolomite, 10% gray to white chert		
771.32	465’			465-469: 80% brown to red medium crystalline dolomite, 20% gray to white chert		
766.32	470’			469-470: 100% light gray, fine crystalline dolomite		

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				470-474: 80% brown to red medium crystalline dolomite, 20% gray to white chert		
				474-475: 100% light gray, fine crystalline dolomite		
761.32	475'			475-478: 100% light gray, fine crystalline dolomite		
				478-479: 60% Carbonate, cemented, well rounded fine grained quartz, sandstone, 40% white to light brown oolitic chert		
				479-480: 100% light gray, fine crystalline dolomite		
756.32	480'			480-485: 100% gray, fine crystalline dolomite		
751.32	485'			485-488: 100% gray to greenish, fine crystalline dolomite		
				488-490: 80% light gray, fine crystalline dolomite, 20% carbonate, cemented, well rounded fine grained quartz, sandstone		
746.32	490'			490-492: 100% light gray to brown, fine to medium crystalline dolomite Light tan to brown dolomite		
				492-494: 80% reddish brown, medium crystalline dolomite, 20% white chert ● 494: 100% gray to greenish, fine crystalline dolomite		
				494-495: 70% light gray to reddish brown, fine to medium crystalline dolomite, 20% white to light gray banded opaque to translucent chert, 10% carbonate, cemented, well rounded fine grained quartz, sandstone		
741.32	495'			495-500: 70% light gray to reddish brown, fine to medium crystalline dolomite, 20% white to light gray banded opaque to translucent chert, 10% carbonate, cemented, well rounded fine grained quartz, sandstone		
736.32	500'			500-505: 83% light gray to light brown, fine to medium crystalline dolomite, 15% white to light gray banded opaque to translucent chert, 2% carbonate, cemented, well rounded fine grained quartz, sandstone		
731.32	505'			505-510: 90% light gray to gray, fine crystalline dolomite, 10% white to light gray banded opaque chert, pyrite		
726.32	510'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				510-515: 98% light gray to gray, fine crystalline dolomite, 2% white to light gray banded opaque chert, pyrite		
721.32	515'			515-518: 98% light gray to gray, fine crystalline dolomite, 2% white to light gray banded opaque chert, pyrite ● 518: Light brown medium crystalline dolomite, calcite and druse quartz		
				518-520: 98% light gray to gray, fine crystalline dolomite, 2% white to light gray banded opaque chert, pyrite		
716.32	520'			520-525: 79% light gray to light brown, fine to medium crystalline dolomite, 20% white to light gray banded opaque chert, 1% green shaly dolomite, pyrite		
711.32	525'			525-530: 79% gray to light reddish brown, medium crystalline dolomite, 10% white to oolitic chert, 1% green shaly dolomite, pyrite		
706.32	530'			530-535: 80% gray to light red, medium crystalline dolomite, 20% white oolitic chert, pyrite		
701.32	535'			535-540: 80% brown to light red, medium crystalline dolomite, 20% white opaque chert, pyrite		
696.32	540'			540-545: 80% gray to light red, medium crystalline dolomite, 20% white opaque chert, druse quartz, pyrite, sphalerite		
691.32	545'			545-550: 85% light gray to light brown, medium crystalline dolomite, 15% white to gray opaque chert, pyrite		
686.32	550'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				550-555: 98% light gray to light brown, fine to medium crystalline dolomite, 2% white opaque chert		
681.32	555'			555-560: 85% light gray to light brown, fine to medium crystalline dolomite, 15% white opaque chert, pyrite		
676.32	560'			560-565: 80% light tan, fine crystalline dolomite, 20% white opaque chert, pyrite		
671.32	565'			565-570: 85% light gray to light brown, fine to medium crystalline dolomite, 10% white opaque chert, 5% green shaly dolomite		
666.32	570'			570-575: 99% gray, medium crystalline dolomite, 1% white opaque chert, calcite		
661.32	575'			575-580: 89% gray medium crystalline dolomite, 10% white opaque and translucent chert, 1% green shaly dolomite, druse quartz, calcite, pyrite		
656.32	580'			580-585: 100% light gray to gray, fine to medium crystalline dolomite		
651.32	585'			585-589: 99% gray, medium to coarse crystalline dolomite, 1% white opaque chert		
				589-590: 86% gray to light red medium crystalline dolomite, 10% white opaque chert, 4% glauconitic dolomite, druse quartz, pyrite		
646.32	590'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				590-594: 71% gray to light red medium crystalline dolomite, 20% white opaque chert with some ooids, 8% glauconitic dolomite, 1% carbonate, cemented, well rounded fine grained quartz, sandstone, pyrite		
				594-595: 100% gray medium crystalline dolomite		
641.32	595'			595-599 72% gray to light red medium crystalline dolomite, 20% white opaque chert with some ooids, 8% glauconitic dolomite, pyrite • 599: 100% carbonate cemented, well rounded fine grained quartz, sandstone		
				599-600: 80% gray medium crystalline dolomite, 20% white opaque chert		
636.32	600'			600-605 90% gray to dark gray medium crystalline dolomite, 10% white opaque chert, pyrite		
631.32	605'			605-610: **Roubidoux Formation** 60% gray medium crystalline dolomite, 30% white opaque chert, 10% carbonate cemented, well rounded fine grained quartz, sandstone, pyrite		
626.32	610'			610-615: 88% gray medium crystalline dolomite, 10% white opaque chert, 2% carbonate cemented, well rounded fine grained quartz, sandstone		
621.32	615'			615-616: 88% gray medium crystalline dolomite, 10% white opaque chert, 2% carbona • 616: 100% carbonate cemented, well rounded medium grained quartz, sandstone		
				616-620: 65% light red to gray medium crystalline dolomite, 30% white opaque chert, 15% carbonate cemented, well rounded medium grained quartz, sandstone		
616.32	620'			620-621: Void		
				621-625: 80% light red to gray medium crystalline dolomite, 20% white to gray opaque chert, pyrite, calcite		
611.32	625'			625-627: 80% gray medium crystalline dolomite, 20% druse quartz chert, galena, pyrite		
				627-628: 100% gray medium crystalline dolomite		
				628-629: 45% light gray fine crystalline dolomite, 35% tan oolitic translucent chert, 15% carbonate cemented, well rounded medium grained quartz, sandstone, 5% druse quartz chert, galena, pyrite		
606.32	630'			629-630: 75% gray medium crystalline dolomite, 25% tan oolitic translucent chert		

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				630-635: 55% tan oolitic translucent chert, 30% gray medium crystalline dolomite, 15% carbonate cemented, well rounded medium grained quartz, sandstone, pyrite		
601.32	635'			635-636: Void		
				636-640: 68% gray medium crystalline dolomite, 30% tan oolitic translucent, to white opaque chert, 2% carbonate cemented, well rounded medium grained quartz, sandstone		
596.32	640'			640-643: 100% gray medium crystalline dolomite		
				643-645: 60% gray fine to medium crystalline dolomite, 30% tan oolitic translucent, to white opaque chert, 10% carbonate cemented, well rounded medium grained quartz, sandstone, pyrite		
591.32	645'			645-647: 70% gray medium crystalline dolomite, 30% banded white opaque chert		
				647-648: 100% brown to white oolitic translucent, chert, pyrite		
				648-650: 100% tan fine crystalline dolomite,		
586.32	650'			650-652: 100% light gray to light red medium crystalline dolomite		
				652-654: 78% gray medium crystalline dolomite, 10% carbonate and quartz cemented well rounded medium grained quartz, sandstone, 10% glauconitic dolomite, 2% oolitic translucent, to white opaque chert, pyrite, calcite		
581.32	655'			654-655: 68% gray to light red medium crystalline friable dolomite, 30% gray opaque chert, 2% glauconitic dolomite, pyrite		
				655-660: 68% gray to light red medium crystalline friable dolomite, 30% gray opaque chert, 2% glauconitic dolomite, pyrite		
576.32	660'			660-665 78% gray to light red medium crystalline friable dolomite, 20% gray opaque chert, 2% glauconitic dolomite, pyrite		
571.32	665'			665-666: 60% gray to light red medium crystalline friable dolomite, 20% white opaque chert, 20% glauconitic dolomite, pyrite		
				666-668: 100% light gray to light green fine crystalline, glauconitic, laminated, dolomite		
				668-670: 100% light gray to light brown medium crystalline		
566.32	670'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				670-675: 60% light gray to gray medium crystalline dolomite, 30% white opaque chert, 10% quartz cemented well rounded medium grained quartz, sandstone, pyrite		
561.32	675'			675-680: 100% poorly cemented well rounded medium grained quartz sandstone		
556.32	680'			680-685: 70% friable well rounded medium grained quartz sandstone, 20% light gray to gray medium crystalline friable dolomite, 10% white opaque chert, pyrite		
551.32	685'			685-690: 60% light gray to gray medium crystalline dolomite, 10% quartz cemented well rounded medium grained quartz sandstone, 30% light gray to white opaque oolitic chert, pyrite		
546.32	690'			690-695: 85% light gray to light tan medium to fine crystalline dolomite, 15% white opaque chert, pyrite		
541.32	695'			695-700: 70% light gray to tan medium crystalline dolomite, 30% white opaque chert, calcite		
536.32	700'			700-705: 70% light gray to gray medium crystalline friable dolomite, 30% white opaque chert, pyrite		
531.32	705'			705-710: 85% light gray to gray medium crystalline friable dolomite, 15%white to light gray banded translucent chert, pyrite		
526.32	710'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				710-715: 90% light gray to gray medium crystalline vuggy dolomite, 10% white to light gray banded translucent chert		
521.32	715'			715-720: 60% white opaque chert, 40% light gray to gray medium crystalline vuggy dolomite		
516.32	720'			720-725: 85% light gray to gray medium crystalline dolomite, 10% white opaque chert, pyrite		
511.32	725'			725-730: 75% light gray to gray medium crystalline dolomite, 15% white translucent to opaque chert, 10% silica cemented medium grained well rounded sandstone, pyrite		
506.32	730'			730-735: 60% light tan to gray medium crystalline, vuggy, dolomite, 40% white translucent to gray translucent oolitic chert, gastropod		
501.32	735'			735-740: 90% light gray to gray fine to medium crystalline, dolomite, 10% white opaque chert, pyrite		
496.32	740'			740-745: 90% light gray to gray medium crystalline, dolomite, pyrite		
491.32	745'			745-746: Void		
				746-749: 90% light gray to gray fine to medium crystalline, dolomite, 40% gray translucent to opaque chert, pyrite		
				749-750: 50% silica cemented medium grained well rounded sandstone, 35% light gray to gray medium crystalline dolomite, 15% gray to white translucent to opaque chert, pyrite		
486.32	750'					

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Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				750-755: 55% light gray to gray medium crystalline dolomite, 30% silica cemented medium grained well rounded sandstone, 15% gray to white translucent to opaque chert		
481.32	755'			755-760: 75% light gray to gray medium crystalline dolomite, 15% gray to white translucent to opaque chert, 10% silica cemented medium grained well rounded sandstone, pyrite		
476.32	760'			760-764: 80% light gray to gray medium crystalline dolomite, 20% gray to white translucent to opaque chert, pyrite		
				764-765: Void		
471.32	765'			765-770: 80% light gray to gray medium crystalline dolomite, 10% gray to white translucent to opaque chert, 10% silica cemented medium grained well rounded sandstone , pyrite		
466.32	770'			770-775: 84% light gray to gray medium crystalline dolomite, 15% silica and carbonate cemented medium grained well rounded sandstone, 1% gray to white translucent to opaque chert		
461.32	775'			775-777: 70% light gray to gray medium crystalline dolomite, 20% silica and carbonate cemented medium grained well rounded sandstone, 10% gray to white translucent to opaque chert, pyrite		
				777-778: Void		
				778-78070% light gray to gray medium crystalline dolomite, 20% silica and carbonate cemented medium grained well rounded sandstone, 10% gray to white translucent to opaque chert, pyrite		
456.32	780'			780-785: 68% light gray to gray medium crystalline dolomite, 20% silica cemented medium grained well rounded sandstone, 10% gray to white translucent to opaque chert, 2% glauconitic siltstone		
451.32	785'			785-790: 75% light gray to gray medium crystalline dolomite, 25% gray translucent oolitic chert		
446.32	790'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
441.32	795'			795-800: 78% light gray to gray medium crystalline dolomite, 15% white to gray translucent chert, pyrite		
436.32	800'			800-805: 60% white to gray, opaque to oolitic translucent chert, 40% light gray to gray medium crystalline dolomite with vugs, pyrite		
431.32	805'			805-810: 90% light gray to gray medium crystalline dolomite, 10% white to gray, opaque to oolitic translucent chert		
426.32	810'			810-815: 90% light gray to gray medium crystalline dolomite, 10% white to gray, opaque to oolitic translucent chert, pyrite		
421.32	815'			815-820: 90% light gray to gray medium crystalline dolomite, 10% white opaque chert, pyrite820		
416.32	820'			820-825: 90% light gray to gray medium crystalline dolomite, 10% white to gray, opaque to translucent chert		
411.32	825'			825-830: 95% light gray to gray medium crystalline dolomite, 5% white to gray, opaque to translucent chert		
406.32	830'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				830-835: 99% light gray to light pink medium crystalline dolomite, 1% white opaque chert		
				833-835: 100% carbonate cemented medium grained well rounded sandstone		
401.32	835'			835-836: Void		
				836-840: 90% light gray to gray medium crystalline vuggy dolomite, 10% carbonate cemented medium grained well rounded sandstone, pyrite		
396.32	840'			840-845: 95% light gray to gray medium crystalline dolomite, 5% gray to dark gray, translucent, druse and oolitic chert, pyrite		
391.32	845'			845-850: 50% light gray to gray medium crystalline dolomite, 50% gray to dark gray, translucent, druse chert		
				848-850: 95% light gray to light tan medium crystalline dolomite, 5% light gray to gray, translucent chert		
386.32	850'			850-855: 80% light gray to gray, translucent chert, 20% light gray to light tan gray medium crystalline dolomite, pyrite		
381.32	855'			855-860: 98% light gray medium crystalline dolomite, 2% white to light gray, translucent chert		
376.32	860'			860-864: 90% light gray medium crystalline vuggy dolomite, 10% white to light gray, translucent chert, pyrite		
				864-865: Void		
371.32	865'			865-870: 80% light gray to tan medium crystalline vuggy dolomite, 20% white to gray banded, translucent chert, pyrite		
366.32	870'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				870-875: 60% light gray to gray medium crystalline vuggy dolomite, 40% white opaque chert, pyrite		
361.32	875'			875-880: 70% light gray to gray medium crystalline vuggy dolomite, 30% white opaque and white to gray banded, translucent chert		
356.32	880'			880-885: 70% white opaque and white to gray banded, translucent chert, 20% light gray to gray medium crystalline vuggy dolomite		
351.32	885'			885-886: Void		
				886-890: 78% light gray to gray medium crystalline vuggy dolomite, 20% white opaque and white to gray banded, translucent chert, 2% glauconitic siltstone, calcite		
346.32	890'			890-895: 83% light gray to gray medium crystalline vuggy dolomite, 15% white opaque and white to gray banded, translucent druse chert, 2% glauconitic siltstone, pyrite		
341.32	895'			895-900: 93% light gray to gray medium crystalline vuggy friable dolomite, 5% white to gray banded, translucent chert, 2% carbonate cemented medium grained well rounded sandstone		
336.32	900'			900-904: 80% light gray to gray medium crystalline vuggy friable dolomite, 20% white opaque to gray banded, translucent chert, pyrite		
				904-905: Void		
331.32	905'			905-910: 60% light gray to gray medium crystalline vuggy dolomite, 40% white opaque to gray banded, translucent chert, pyrite		
326.32	910'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				910-911: Void		
				911-914: 70% white opaque to gray banded, translucent druse chert, 30% light gray to gray medium crystalline vuggy dolomite, pyrite		
				914-915: Void		
321.32	915'			915-919: 80% white opaque to gray banded, translucent chert, 20% light gray to gray medium crystalline dolomite		
				919-920: Void		
316.32	920'			920-925: 60% white opaque to gray banded, translucent druse chert, 40% light gray to gray medium crystalline vuggy dolomite, calcite		
311.32	925'			925-930: 80% light gray to gray medium crystalline vuggy dolomite, 20% white opaque to gray banded, translucent chert, pyrite		
306.32	930'			930-935: 89% light gray to gray medium crystalline vuggy dolomite, 10% white opaque to gray banded, translucent chert, 1% glauconitic siltstone, pyrite		
301.32	935'			935-940: 90% light gray to gray medium crystalline vuggy dolomite, 10% white to gray banded, translucent druse chert, pyrite		
296.32	940'			940-945: 95% light gray to gray medium crystalline vuggy dolomite, 5% white to gray banded, opaque chert, pyrite		
291.32	945'			945-950: 60% light gray to gray medium crystalline vuggy dolomite, 40% white to gray banded, opaque chert, pyrite		
286.32	950'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				950-955: 80% light gray to gray medium crystalline vuggy friable dolomite, 20% white to light gray banded, opaque chert, pyrite		
281.32	955'			955-960: 80% light gray to gray medium crystalline vuggy dolomite, 20% white opaque chert, pyrite		
276.32	960'			960-965: 90% light gray to gray medium crystalline vuggy friable dolomite, 10% white, opaque chert, calcite		
271.32	965'			965-970: 90% light brown to gray medium crystalline vuggy friable dolomite, 10% white, opaque chert		
266.32	970'			970-974: 90% light tan to gray medium crystalline vuggy friable dolomite, 15% white, opaque chert		
261.32	975'			974-976:Void		
				976-980: 60% white to light gray banded, opaque chert, 40% light tan to gray medium crystalline vuggy friable dolomite		
256.32	980'			980-982: 80% light gray to gray medium crystalline vuggy friable dolomite, 20% white, opaque chert, pyrite		
				982-983:Void		
				983-985: 80% light gray to gray medium crystalline vuggy friable dolomite, 20% white, opaque chert, pyrite		
251.32	985'			985-990: 95% gray to dark gray medium crystalline vuggy dolomite, 5% white, opaque chert, pyrite		
246.32	990'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				990-995: 78% gray to dark gray medium crystalline vuggy dolomite, 20% white, opaque chert, 2% silica cemented medium grained well rounded sandstone		
241.32	995'			995-1000: 90% gray to dark gray medium crystalline vuggy dolomite, 10% white, opaque chert, pyrite		
236.32	1000'			1000-1005: 90% gray to dark gray medium crystalline vuggy dolomite, 10% white, opaque chert		
231.32	1005'			1005-1010: 90% light gray to gray medium crystalline vuggy dolomite, 10% white to light gray, opaque chert, pyrite		
226.32	1010'			1010-1015: 90% light gray to gray medium crystalline friable vuggy dolomite, 10% white to light gray, opaque to transparent oolitic chert, pyrite		
221.32	1015'			1015-1019: 88% gray medium crystalline vuggy dolomite, 10% white opaque chert, 2% laminated siltstone, pyrite		
				1019-1020: Void		
216.32	1020'			1020-1025: 84% gray medium crystalline vuggy friable dolomite, 5% white opaque chert, 1% laminated glauconitic siltstone, calcite		
211.32	1025'			1025-1030: 60% light gray to dark gray medium crystalline vuggy friable dolomite, 40% white opaque chert		
206.32	1030'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1030-1035: 70% light gray to dark gray medium crystalline vuggy friable dolomite, 30% white opaque chert, pyrite		
201.32	1035'			1035-1040: 90% light gray to gray medium crystalline vuggy dolomite, 10% white opaque chert, pyrite, calcite		
196.32	1040'			1040-1045: 95% light gray to gray medium crystalline vuggy dolomite, 5% white opaque chert, pyrite, calcite		
191.32	1045'			1045-1050: 89% light gray to gray medium crystalline vuggy dolomite, with red dolomite in vugs, 10% white opaque chert, 1% laminated glauconitic siltstone, pyrite, calcite		
186.32	1050'			1050-1055: 100% light gray medium crystalline dolomite		
181.32	1055'			1055-1060: 99% light gray to gray very fine to medium crystalline vuggy dolomite, 1% white opaque chert, pyrite		
176.32	1060'			1060-1065: 99% light gray to gray very fine to medium crystalline vuggy dolomite, 1% white opaque chert		
171.32	1065'			1065-1070: 98% light gray to gray very fine to medium crystalline vuggy dolomite, 1% white opaque chert, 1% dark gray glauconitic siltstone		
166.32	1070'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1070-1075: 96% light gray to gray very fine to medium crystalline vuggy dolomite, 3% dark gray glauconitic siltstone, 1% white opaque chert, pyrite		
161.32	1075'			1075-1080: 89% light gray to gray very fine to medium crystalline vuggy dolomite, 10% white opaque chert, 1% dark gray siltstone, calcite		
156.32	1080'			1080-1085: 85% light gray to gray very fine to medium crystalline vuggy friable dolomite, 15% white opaque chert, calcite		
151.32	1085'			1085-1090: 85% light gray to gray medium crystalline vuggy friable dolomite, 15% white opaque chert, calcite		
146.32	1090'			1090-1095: 80% light gray to gray very fine to medium crystalline vuggy dolomite, 20% white opaque chert, calcite		
141.32	1095'			1095-1100: 60% light gray to gray medium crystalline vuggy friable dolomite, 40% white opaque chert, pyrite		
136.32	1100'			1100-1105: 70% light gray to gray medium crystalline vuggy dolomite, 30% white opaque chert, pyrite		
131.32	1105'			1105-1107: 84% light gray to gray medium crystalline vuggy friable dolomite, 15% white opaque chert, 1% gray siltstone, pyrite		
				1107-1108: Void		
				1108-1110: 84% light gray to gray medium crystalline vuggy friable dolomite, 15% white opaque chert, 1% gray siltstone, pyrite		
126.32	1110'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1110-1115: 55% light gray medium crystalline vuggy friable dolomite, 45% white opaque chert		
121.32	1115'			1115-1120:9 9% light gray medium crystalline vuggy friable dolomite, 1% white opaque chert		
116.32	1120'			1120-1125: **Gunter Sandstone Member** 100% silica and carbonate cemented medium to coarse grained well rounded friable sandstone		
111.32	1125'			1125-1130: 100% silica and carbonate cemented medium to coarse grained well rounded friable sandstone		
106.32	1130'			1130-1135: 100% silica and carbonate cemented medium to coarse grained well rounded friable sandstone		
101.32	1135'			1135-1140: 100% silica and carbonate cemented medium to coarse grained well rounded friable sandstone, pyrite		
96.32	1140'			1140-1145: 100% silica and carbonate cemented fine to medium grained well rounded friable sandstone		
91.32	1145'			1145-1150: 100% silica and carbonate cemented fine to medium grained well rounded friable sandstone		
86.32	1150'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1150-1155: 79% light gray medium crystalline vuggy dolomite, 20% silica and carbonate cemented fine to medium grained well rounded friable sandstone, 1% white opaque chert		
81.32	1155'			1155-1160: 80% silica and carbonate cemented fine to medium grained well rounded friable sandstone, 19% light gray medium crystalline vuggy dolomite, 1% white opaque chert		
76.32	1160'			1160-1165: 84% silica and carbonate cemented fine to medium grained well rounded friable sandstone, 15% light gray medium crystalline vuggy dolomite, 1% white opaque chert		
71.32	1165'			1165-1170: **Eminence Dolomite** 77% light gray fine to medium crystalline vuggy friable dolomite, 20% silica and carbonate cemented, medium grained well rounded friable sandstone, 3% white opaque chert		
66.32	1170'			1170-1174: 99% light gray medium crystalline vuggy dolomite, 1% white opaque chert, calcite, pyrite		
				1173-1174: Void		
				1174-1175: 99% light gray medium crystalline vuggy dolomite, 1% white opaque chert, calcite, pyrite		
61.32	1175'			1175-1180: 99% light gray to gray medium to very coarse crystalline vuggy dolomite, 1% white opaque chert		
56.32	1180'			1180-1183: 96% gray medium crystalline vuggy dolomite, 4% dark green glauconitic siltstone, calcite, pyrite		
				1183-1185: Void		
51.32	1185'			1185-1189: 100% gray fine to medium crystalline vuggy dolomite, calcite, pyrite		
				1189-1190: Void		
46.32	1190'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1190-1195: 97% light gray to gray, fine to medium crystalline vuggy dolomite, 3% white opaque druse chert, calcite, pyrite		
41.32	1195'			1195-1200: 97% gray medium crystalline vuggy dolomite, 2% white opaque chert, 1% dark green glauconitic silty shale, calcite, pyrite		
36.32	1200'			1200-1205: 98% light gray to gray, fine to medium crystalline vuggy dolomite, 2% white opaque chert, calcite, pyrite		
31.32	1205'			1205-1210: 96% light gray to gray medium crystalline vuggy dolomite, 3% white opaque chert, 1% dark green glauconitic siltstone, pyrite		
26.32	1210'			1210-1215: 97% light gray to gray medium crystalline vuggy dolomite, 2% white opaque chert, 1% dark green glauconitic siltstone, calcite, pyrite		
21.32	1215'			1215-1220: 89% light gray to gray medium crystalline vuggy friable dolomite, 10% white opaque chert, 1% dark green glauconitic siltstone, calcite, pyrite		
16.32	1220'			1220-1225: 90% light gray to gray medium crystalline vuggy friable dolomite, 10% white opaque chert, calcite, pyrite		
11.32	1225'			1225-1230: 95% light gray to gray medium crystalline vuggy friable dolomite, 5% white opaque chert, calcite, pyrite		
6.32	1230'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1230-1231: 100% light gray to gray medium crystalline vuggy friable dolomite, calcite		
				1231-1232: Void		
				1232-1235: 100% light gray to gray medium crystalline vuggy friable dolomite, calcite		
1.32	1235'			1235-1240: 98% light gray to gray medium crystalline vuggy friable dolomite, 1% white opaque chert, 1% dark green glauconitic siltstone		
-3.68	1240'			1240-1245: 99% gray medium crystalline vuggy dolomite, 1% dark green glauconitic shale, calcite, pyrite		
-8.68	1245'			1245-1250: 99% gray medium crystalline vuggy dolomite, 1% dark green glauconitic shale, calcite, pyrite		
-13.68	1250'			1250-1255: 98% light gray to gray medium crystalline vuggy dolomite, 1% white opaque chert, 1% dark green glauconitic shale, pyrite		
-18.68	1255'			1255-1259: 99% light gray to gray medium crystalline vuggy dolomite, 1% dark green glauconitic shale, pyrite		
-23.68	1260'			1259-1261: Void		
				1261-1265: 100% light gray to gray medium crystalline vuggy friable dolomite, calcite, pyrite		
-28.68	1265'			1265-1270: 99% light gray to gray medium crystalline vuggy dolomite, 1% dark green glauconitic shale, calcite, pyrite		
-33.68	1270'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1270-1275: 99% light pink and light gray to gray medium crystalline vuggy dolomite, 1% dark green glauconitic shale, calcite, pyrite		
-38.68	1275'			1275-1280: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale, calcite		
-43.68	1280'			1280-1285: 98% light gray to gray medium crystalline vuggy dolomite, 1% white opaque chert, 1% dark green glauconitic shale, calcite, pyrite		
-48.68	1285'			1285-1290: 96% light gray to gray medium crystalline vuggy friable dolomite, 3% white opaque chert, 1% dark green glauconitic shale, calcite, pyrite		
-53.68	1290'			1290-1295: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale, calcite, pyrite		
-58.68	1295'			1295-1300: 100% light gray to gray medium crystalline vuggy friable dolomite, pyrite		
-63.68	1300'			1300-1305: 96% light gray to gray medium crystalline vuggy friable dolomite, 3% white opaque chert, 1% dark green glauconitic shale, calcite		
-68.68	1305'			1305-1310: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale, calcite		
-73.68	1310'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1310-1315: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale, calcite		
-78.68	1315'			1315-1320: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale		
-83.68	1320'			1320-1325: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale		
-88.68	1325'			1325-1330: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale		
-93.68	1330'			1330-1335: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale, pyrite		
-98.68	1335'			1335-1340: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale, calcite		
-103.68	1340'			1340-1345: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale		
-108.68	1345'			1345-1350: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale, pyrite		
-113.68	1350'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1350-1351:Void		
				1351-1355: 100% light pink and light gray to gray medium crystalline vuggy friable dolomite, calcite		
-118.68	1355'			1355-1356: 96% light gray to gray medium crystalline vuggy friable dolomite, 3% white opaque chert, 1% dark green glauconitic shale and siltstone, calcite		
				1356-1357: Void		
				1357-1360: 96% light gray to gray medium crystalline vuggy friable dolomite, 3% white opaque chert, 1% dark green glauconitic shale and siltstone, calcite		
-123.68	1360'			1360-1365: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale		
-128.68	1365'			1365-1370: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale, calcite		
-133.68	1370'			1370-1371: Void		
				1371-1375: 98% light gray to gray medium crystalline vuggy friable dolomite, 1% white opaque chert, 1% dark green glauconitic shale and siltstone, pyrite		
-138.68	1375'			1375-1380: 98% light gray to gray medium crystalline vuggy friable dolomite, 1% white opaque chert, 1% dark green glauconitic shale, pyrite, calcite		
-143.68	1380'			1380-1384: 98% light gray to gray medium crystalline vuggy friable dolomite, 1% white opaque chert, 1% dark green glauconitic shale, pyrite, calcite		
				1384-1385: 100% gray to dark gray medium crystalline vuggy dolomite		
-148.68	1385'			1385-1386: 100% light gray to gray medium crystalline vuggy dolomite, pyrite, calcite		
				1386-1387: Void		
				1387-1389: 100% light gray to gray medium crystalline vuggy dolomite, pyrite, calcite		
				1389-1390: 100% light gray to gray medium crystalline vuggy friable dolomite, pyrite, calcite		
-153.68	1390'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1390-1395: 100% light gray to gray medium crystalline vuggy dolomite, pyrite, calcite		
-158.68	1395'			1395-1396: Void		
				1396-1399: 99% light gray to gray medium crystalline vuggy dolomite, 1% dark green glauconitic shale and siltstone, pyrite, calcite		
				1399-1400: Void		
-163.68	1400'			1400-1405: 100% light gray to gray medium crystalline vuggy dolomite, pyrite, calcite		
-168.68	1405'			1405-1406: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale, pyrite, calcite		
				1406-1407: Void		
				1407-1410: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% dark green glauconitic shale, pyrite, calcite		
-173.68	1410'			1410-1415: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% white opaque chert, pyrite, calcite		
-178.68	1415'			1415-1420: 97% light gray to gray medium crystalline vuggy friable dolomite, 2% white opaque chert, 1% glauconitic siltstone, pyrite, calcite		
-183.68	1420'			1420-1425: 100% light gray to light brown medium crystalline vuggy friable dolomite, pyrite, calcite		
-188.68	1425'			1425-1430: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% white opaque chert, pyrite, calcite		
-193.68	1430'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1430-1435: 100% light gray to gray medium crystalline vuggy friable dolomite, pyrite, calcite		
-198.68	1435'			1435-1440: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% white opaque chert, pyrite, calcite		
-203.68	1440'			1440-1445: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% white opaque chert, pyrite, calcite		
-208.68	1445'			1445-1450: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% white opaque chert, pyrite, calcite		
-213.68	1450'			1450-1455: 99% light gray to gray medium crystalline vuggy friable dolomite, 1% white opaque chert, 1% glauconitic shale, pyrite, calcite End of Cuttings		
-218.68 -223.68	1455' 1460'			1454.3-1455: Light gray medium crystalline vuggy dolomite 1455-1457: Light gray medium crystalline vuggy laminated dolomite, pyrite 1457-1458: Light gray medium crystalline dolomite with dolomite lined vugs 1458-1460: Brecciated light gray medium crystalline dolomite in gray medium crystalline dolomite matrix mottled with glauconitic shale 1460-1462.5: Light gray medium crystalline vuggy dolomite	Run 1	
-228.68	1465'			1460-1462.5 Same As Above 1462.5-1467.1 No recovery due to hole over-reamed with tricone bit.	Run 2	
-233.68	1470'			1467.1-1469.7: Same As Above 1469.7-1470: Gray medium crystalline dolomite with 1 cm diameter dolomite and calcite lined vugs, pyrite	Run 3	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1470-1473: Gray medium crystalline dolomite with 1 cm diameter dolomite and calcite lined vugs, pyrite	Run 3	
-238.68	1475'			1472-1473: Gray medium crystalline dolomite with 1 cm diameter dolomite and calcite lined vugs, pyrite • 1473: Stylolite 1473-1474: Gray fine to medium crystalline dolomite with less than 1 cm diameter dolomite lined vugs	Run 4	1474-1475.9: Gray fine to medium crystalline dolomite with extensive sub vertical fractures 1475.9-1477: Gray fine to medium crystalline dolomite with 1 to 3 cm diameter dolomite and calcite lined vugs, pyrite
-243.68 -248.68	1480' 1485'			1477-1485.4: Gray fine to medium crystalline dolomite with 1 to 3 cm diameter dolomite and calcite lined vugs, pyrite 1485.4-1486.7: Gray fine to medium crystalline dolomite with extensive sub vertical fractures 1486.7-1487: Gray fine to medium crystalline dolomite with less than 1 cm diameter dolomite lined vugs	Run 5	
-253.68 -258.68	1490' 1495'			1487-1487.9: Gray fine to medium crystalline dolomite with less than 1 cm diameter dolomite lined vugs 1487.9-1488: Gray fine to medium crystalline dolomite with extensive dolomite and translucent calcite lined sub vertical fractures and vugs 1488-1492: Gray fine to medium crystalline dolomite with 1 to 2 cm diameter dolomite and calcite lined vugs, and sub vertical fractures 1492-1493: Void 1493-1497: Gray fine to medium crystalline brecciated dolomite with extensive dolomite and translucent calcite lined sub vertical fractures and vugs 1497-1497.5: Gray fine to medium crystalline dolomite with 1 to 2 cm diameter dolomite and calcite lined vugs, and sub vertical fractures	Run 6	
-263.68 -268.68	1500' 1505'			1497.5-1500: Same As Above 1500-1507.5: **Potosi Dolomite** Gray medium to coarse crystalline dolomite with less than 1 to 2 cm diameter dolomite and druse quartz lined vugs, stylolites, possible dolomitized boundstone	Run 7	
-273.68	1510'			1507.5-1510: Gray fine to medium crystalline mottled dolomite with 1 to 2 cm diameter dolomite lined vugs, stylolites, possible dolomitized mudstone	Run 8	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-278.68	1515'			1510-1518.5: Gray fine to medium crystalline mottled dolomite with 1 to 2 cm diameter dolomite lined vugs, stylolites, possible dolomitized mudstone	Run 8	
-283.68 -288.68	1520' 1525'			1517.5-1518.5: Same As Above 1518.5-1528.7: **Elvins Group** Fine crystalline dolomitized cross bedded fining upwards from matrix supported pebble to flat pebble conglomerate, to grain supported coarse grained peloidal carbonate sand, to fine grained carbonate sand with articulated phosphatic brachiopod shells 1 to 3 cm druse quartz lined vugs ● 1528.7 Stylolite	Run 9	
-293.68 -298.68	1530' 1535'			1518.5-1528.7 : Same As Above ● 1528.7: Stylolite 1528.7-1533: Fine crystalline dolomitized fining upwards from clast supported coarse grained peloidal carbonate sand, to fine carbonate mud with less than 1 cm black shale partings, 1 to 3 cm druse quartz and calcite lined vugs at top of sequence 1533-1536.5: Fine crystalline dolomitized laminated carbonate mud with less than 1 cm black shale partings 1536.5-1536.7: Fine crystalline dolomitized carbonate mud matrix supported pebble to flat pebble conglomerate 1537-1537.2: Fine crystalline dolomitized carbonate sand matrix supported pebble to flat pebble conglomerate	Run 10	1537.2-1537.5: Fine crystalline dolomitized fining upwards from grain supported medium grained carbonate sand, to laminated fine carbonate mud
-303.68 -308.68	1540' 1545'			1537.5-1538.1: Same As Above 1538.1-1538.4: Fine crystalline dolomitized mottled carbonate mud 1538.4-1538.6: Fine crystalline dolomitized carbonate mud supported carbonate pebble conglomerate 1538.6-1542.1: Fine crystalline dolomitized fining upwards from grain supported medium grained carbonate sand, to laminated fine carbonate mud 1542.1-1546.9: Fine crystalline dolomitized fining upwards from grain supported medium grained carbonate sand, to lenticular laterally linked carbonated nodules interbedded with fine carbonate mud. 1546.9-1547.3: Fine crystalline dolomitized lenticular laterally linked carbonated nodules interbedded with fine carbonate mud, pyrite, inarticulate phosphatic brachiopod	Run 11	1547.3-1547.5: Fine crystalline dolomitized carbonate sand supported carbonate pebble conglomerate
-313.68	1550'			1547.5-1547.6: Same As Above 1547.6-1549.3: Fine crystalline dolomitized lenticular laterally linked carbonated nodules interbedded with fine carbonate mud. 1549.3-1550: Fine crystalline dolomitized grain supported medium grained carbonate sand, interbedded with thin black shale partings.	Run 12	

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-318.68	1555'			1550-1551: Same As Above 1551-1551.2: Fine crystalline dolomitized lenticular laterally linked carbonated nodules interbedded with fine carbonate black shale. 1551.2-1552: Fine crystalline dolomitized carbonate sand supported carbonate pebble conglomerate with calcite lined vugs 1552-1552.2: Fine crystalline dolomitized laminated fine carbonate mud interbedded with black carbonate shale. 1552.2-1552.3: Fine crystalline dolomitized carbonate mud supported carbonate flat pebble conglomerate	Run 12	1552.3-1554.8: Fine crystalline dolomitized lenticular laterally linked carbonated nodules interbedded with fine carbonate mud 1554.8-1554.9: Fine crystalline dolomitized carbonate sand supported carbonate pebble conglomerate 1554.9-1557.5: Fine crystalline dolomitized lenticular laterally linked carbonated nodules interbedded with fine carbonate mud
-323.68 -328.68	1560' 1565'			1557.5-1561: Fine crystalline dolomitized lenticular laterally linked carbonated nodules interbedded with fine carbonate mud 1561-1561.6: Fine crystalline dolomitized carbonate mud supported carbonate flat pebble conglomerate 1561.6-1561.9: Fine crystalline dolomitized lenticular laterally linked carbonated nodules interbedded with fine carbonate mud 1561.9-1562: Fine crystalline dolomitized carbonate mud supported carbonate flat pebble conglomerate 1562-1562.1: Fine crystalline dolomitized lenticular carbonated nodules interbedded with fine carbonate mud 1562.1-1562.2: Fine crystalline dolomitized carbonate mud supported carbonate flat pebble conglomerate	Run 13	1562.2-1562.6: Fine cry6stalline dolomitized lenticular carbonated nodules interbedded with fine carbonate mud 1562.6-1563.4: Fine crystalline dolomitized carbonate mud supported carbonate flat pebble conglomerate 1563.4-1567.5: Fine crystalline dolomitized lenticular carbonated nodules interbedded with fine carbonate mud
-333.68 -338.68	1570' 1575'			1567.5-1567.6: Same As Above 1567.6-1568.8: Fine crystalline dolomitized fining upwards from sand supported carbonate pebble conglomerate to carbonate sand 1568.8-1573.3: Fine crystalline dolomitized lenticular carbonated nodules interbedded with fine carbonate mud, pyrite 1573.3-1573.4: Fine crystalline dolomitized carbonate mud supported carbonate flat pebble conglomerate 1573.4-1573.5: Fine crystalline dolomitized laminated fine carbonate mud 1573.5-1573.6: Fine crystalline dolomitized carbonate sand supported carbonate pebble conglomerate	Run 14	1573.6-1575.8: Fine crystalline dolomitized lenticular carbonated nodules interbedded with fine carbonate mud 1575.8-1576.4: Fine crystalline dolomitized clast supported carbonate pebble conglomerate with carbonate mud and carbonate sand matrix 1576.4-1577.5: Fine crystalline dolomitized lenticular carbonated nodules interbedded with fine carbonate mud
-343.68 -348.68	1580' 1585'			1577.5-1578.3: Same As Above 1578.3-1578.4: Fine crystalline dolomitized carbonate sand supported carbonate pebble conglomerate 1578.4-1578.7: Fine crystalline dolomitized lenticular carbonated nodules interbedded with fine carbonate mud 1578.7-1579.8: Fine crystalline dolomitized fining upwards from clast supported edgewise flat pebble conglomerate with carbonate mud matrix to carbonate sand 1579.8-1580.7: Fine crystalline dolomitized lenticular carbonated nodules interbedded with fine carbonate mud and shaly carbonate	Run 15	1580.7-1581.2: Fine crystalline dolomitized fining upwards from clast supported flat pebble conglomerate with carbonate sand matrix to carbonate sand supported flat pebble conglomerate 1581.2-1585: Fine crystalline dolomitized lenticular carbonated nodules interbedded with fine carbonate mud and shaly carbonate 1585-1585.2: Fine crystalline dolomitized carbonate mud supported carbonate pebble conglomerate 1585.2-1577: Fine crystalline dolomitized lenticular carbonated nodules interbedded with fine carbonate mud and shaly carbonate
-353.68	1590'			1587-1588.9: Same As Above 1588.9-1589.3: Fine crystalline dolomitized mottled carbonate sand 1589.3-1590: Fine crystalline dolomitized laminated carbonate mud and shaly carbonate interbedded with lenticular carbonated nodules	Run 16	

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-358.68	1595'			1590-1590.6: Same As Above 1590.6-1590.7: Fine crystalline dolomitized carbonate sand supported carbonate pebble conglomerate, pyrite 1590.7-1595.3: Fine crystalline dolomitized laminated carbonate mud and shaly carbonate interbedded with lenticular carbonated nodules 1595.3-1595.7: Fine crystalline dolomitized carbonate sand supported carbonate pebble conglomerate 1595.7-1596.1 Fine crystalline dolomitized laminated carbonate mud and shaly carbonate interbedded with lenticular carbonated nodules	Run 16	1596.1-1596.6 Fine crystalline dolomitized fining upwards from clast supported edgewise flat pebble conglomerate with carbonate mud matrix to carbonate sand 1596.6-1597.5 Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules
-363.68 -368.68	1600' 1605'			1597.5-1598.3: Same As Above 1598.3-1598.7: Limestone sand supported limestone pebble conglomerate 1598.7-1602.4: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules, pyrite 1602.4-1602.7: Limestone sand supported limestone pebble conglomerate 1602.7-1605.2: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1605.2-1606.2: Lenticular limestone nodules interbedded with limestone mud with stylolites 1606.2-1606.5: Limestone mud supported edgewise flat pebble limestone conglomerate	Run 17	1606.5-1607.5 Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules
-373.68 -378.68	1610' 1615'			1607.5-1608.4: Same As Above 1608.4-1609.4: Fining upwards from clast supported flat pebble limestone conglomerate with limestone mud and sand matrix to limestone sand mottled with limestone mud to massive limestone mottled with limestone mud with stylolite and calcite filled vertical fracture 1609.4-1613.5: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1613.5-1613.8: Clast supported edgewise flat pebble limestone conglomerate with limestone mud matrix 1613.8-1616: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules	Run 18	1616-1617.3: Fining upwards from clast supported flat pebble limestone conglomerate with limestone mud and sand matrix to limestone sand mottled with limestone mud to massive limestone mottled with limestone mud, stylolites 1617.3-1617.5: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules
-383.68 -388.68	1620' 1625'			1617.5-1620: Same As Above 1620-1620.2: Mottled limestone sand, stylolites 1620.2-1620.4: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1620.4-1622: Fining upwards from clast supported flat pebble limestone conglomerate with limestone mud and sand matrix to limestone sand mottled with limestone mud to massive limestone mottled with limestone mud 1622-1622.2: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1622.2-1622.4: Clast supported flat pebble limestone conglomerate with limestone mud matrix	Run 19	1622.4-1622.6: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1622.6-1623.5: Fining upwards from clast supported flat pebble limestone conglomerate with limestone mud and sand matrix to limestone sand mottled with limestone mud 1623.5-1627.1: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1627.1-1627.5: Limestone sand mottled with limestone mud
-393.68	1630'			1627.5-1627.7: Limestone sand mottled with limestone mud 1627.7-1630: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules	Run 20	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-398.68	1635'			1630-1635.5: Same As Above 1635.5-1636.4: Limestone sand and mud supported flat pebble limestone conglomerate 1636.4-1637.5: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules	Run 20	
-403.68 -408.68	1640' 1645'			1637.5-1638.2: Same As Above 1638.2-1639.6: Fining upwards from clast supported flat pebble limestone conglomerate with limestone mud and sand matrix to limestone sand mottled with limestone mud to massive limestone mottled with limestone mud, stylolites 1639.6-1639.8: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1639.8-1639.9: Clast supported flat pebble limestone conglomerate with limestone mud matrix 1639.9-1642: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules, stylolite	Run 21	1642-1642.8: Clast supported pebble to cobble limestone conglomerate with limestone mud matrix. One substantial clast appears to be rafted on rounded to subrounded clasts. 1642.8-1647.5: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules
-413.68 -418.68	1650' 1655'			1647.5-1654.5: Same As Above 1654.5-1654.9: Clast supported flat pebble limestone conglomerate with limestone mud and limestones sand matrix 1654.9-1657: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1657-1657.5: Clast supported flat pebble limestone conglomerate with limestone mud and limestones sand matrix	Run 22	
-423.68 -428.68	1660' 1665'			1657.5-1658.1: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1658.1-1658.6: Clast supported flat pebble limestone conglomerate with limestone mud and limestones sand matrix 1658.6-1658.9: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1658.9-1659.2: Clast supported flat pebble limestone conglomerate with limestone mud and limestones sand matrix 1659.2-1659.5: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1659.5-1659.8: Limestone sand and mud supported flat pebble limestone conglomerate 1659.8-1660.1: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1660.1-1660.4: Limestone mud supported flat pebble limestone conglomerate 1660.4-1660.6: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules	Run 23	1660.6-1660.7: Clast supported flat pebble limestone conglomerate with limestone mud and limestones sand matrix 1660.7-1659.9: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1659.9-1663.6: Clast supported flat pebble limestone conglomerate with limestone mud and limestones sand matrix 1663.6-1664.6: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1664.6-1665: Clast supported edgewise flat pebble limestone conglomerate with limestone mud and limestones sand matrix 1665-1666.9: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1666.9-1667.2: Clast supported flat pebble limestone conglomerate with limestone mud and limestones sand matrix 1667.2-1667.5: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules
-433.68	1670'			1667.5-1667.8: Same As Above 1667.8-1668: Clast supported flat pebble limestone conglomerate with limestone mud and limestones sand matrix 1668-1668.4: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1668.4-1668.5: Limestone mud supported flat pebble limestone conglomerate	Run 24	1668.5-1668.6: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1668.6-1670: Fining upwards from clast supported edgewise flat pebble limestone conglomerate with limestone mud and sand matrix to limestone sand mottled with limestone mud to massive limestone mottled with limestone mud

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: John Twitty Energy Center
Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-438.68	1675'			1670-1670.2: Laminated limestone mud 1670.2-1670.3: Clast supported flat pebble limestone conglomerate with limestone mud matrix 1670.3-1670.8: Laminated limestone mud and shaly limestone interbedded with lenticular limestone nodules 1670.8-1675: Clast supported flat pebble limestone conglomerate with limestone mud and limestones sand matrix 1675-1675.6: Laminated limestone mud and shaly limestone	Run 24	1675.6-1677.3: Clast supported flat pebble limestone conglomerate with limestone mud and limestones sand matrix 1677.3-1677.5: Laminated limestone mud and shaly limestone
-443.68 -448.68	1680' 1685'			1677.5-1678.6: Same As Above 1678.6-1678.7: Limestones sand 1678.6-1680.1: Laminated limestone mud and shaly limestone 1680.1-1680.3: Clast supported flat pebble limestone conglomerate with limestone mud and limestones sand matrix 1680.1-1683.7: Laminated limestone mud and shaly limestone 1683.7-1683.9: Clast supported edgewise flat pebble limestone conglomerate with limestone mud and sand matrix, calcite 1683.9-1684: Laminated limestone mud and shaly limestone	Run 25	1684-1684.5: Clast supported flat pebble limestone conglomerate with limestone mud and sand matrix 1684.5-1684.8: Laminated limestone mud and shaly limestone 1684.8-1685.1: Clast supported edgewise flat pebble limestone conglomerate with limestone mud and sand matrix 1685.1 1685.8: Laminated limestone mud and shaly limestone 1685.8-1686.4: Clast supported edgewise flat pebble limestone conglomerate with limestone mud and sand matrix 1686.4-1687.5: Laminated limestone mud and shaly limestone
-453.68 -458.68	1690' 1695'			1687.5-1688: Same As Above 1688-1688.1: Clast supported flat pebble limestone conglomerate with limestone mud and sand matrix 1688.1-1689.9: Laminated limestone mud and shaly limestone 1689.9-1690: Clast supported flat pebble limestone conglomerate with limestone mud and sand matrix 1690-1697.5: Laminated limestone silty mud and shaly limestone	Run 26	
-463.68 -468.68	1700' 1705'			1697.5-1701.9: Same As Above 1701.9-1702.6: **Bonneterre Formation** Gray fine crystalline brecciated dolomite with dolomite filled fractures, stylolite 1702.6-1704.9: Gray fine to medium crystalline brecciated dolomite with dolomite lined sub vertical fractures grading down to mottled dolomite sand and pebble conglomerate, stylolites 1704.9-1708.6: Gray fine crystalline brecciated dolomite with dolomite filled fractures and dolomite lined vugs, stylolites	Run 27	
-473.68	1710'			1708.6-1710: Gray mottled dolomite with interbedded grainstones containing glauconitic pellets and shaly dolomite	Run 28	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-478.68	1715'			1710-1717.5: Same As Above	Run 29	
-483.68 -488.68	1720' 1725'			1717.5-1727.6: Same As Above End of First core	Run 30	
-493.68 -498.68 -503.68 -508.68 -513.68	1730' 1735' 1740' 1745' 1750'					

Notes/Comments:

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Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-438.68	1675'					
-443.68	1680'					
-448.68	1685'					
-453.68	1690'					
-458.68	1695'					
-463.68	1700'			Start of Second Core		
-468.68	1705'			1705.0-1707.5: Gray fine crystalline brecciated dolomite with dolomite filled fractures and dolomite lined vugs, stylolites	Run 1	
				1707.5-1708.6: Same As Above 1708.6-1710: Gray mottled dolomite with interbedded grainstones containing glauconitic pellets and shaly dolomite, grading to limestone with depth, marcasite	Run 2	
-473.68	1710'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1710-1717.5: Same As Above	Run 3	
-478.68	1715'					
				1717.5-1727.5: Same As Above	Run 4	
-483.68	1720'					
-488.68	1725'					
				1727.5-1737.5: Same As Above	Run 5	
-493.68	1730'					
-498.68	1735'					
				1737.5-1747.5: Same As Above	Run 6	
-503.68	1740'					
-508.68	1745'					
				1747.5-1750: Same As Above	Run 7	
-513.68	1750'					

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Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-518.68	1755'			1750-1757.5: Same As Above	Run 7	
-523.68 -528.68	1760' 1765'			1757.5-1765: Same As Above 1765-1767.3: Laminated limestone mud and shaly limestone 1767.3-1767.5: Greenish gray mottled with interbedded grainstones containing glauconitic pellets and shaly dolomite, marcasite, pyrite, brachiopods	Run 8	
-533.68 -538.68	1770' 1775'			1767.5-1773: Greenish gray mottled with interbedded grainstones containing glauconitic pellets and shaly dolomite, marcasite, pyrite, brachiopods 1773-1777.5: Fine crystalline dolomitized carbonate sandstone with glauconitic pellets and thin shale partings, pyrite	Run 9	
-543.68 -548.68	1780' 1785'			1777.5-1780.3: Fine crystalline dolomitized carbonate sandstone with glauconitic pellets and thin shale partings, pyrite 1780.3-1787.5: **Lamotte Sandstone** Medium to coarse grained well rounded quartz sandstone with dolomite cement. **End of second core**	Run 10	
-553.68	1790'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: John Twitty Energy Center
Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-518.68	1755'					
-523.68	1760'					
-528.68	1765'					
-533.68	1770'					
-538.68	1775'					
				Start of third core		
-543.68	1780'			1780-1781.5: Fine crystalline dolomitized carbonate sandstone with glauconitic pellets and thin shale partings, pyrite 1781.5-1787.7: **Lamotte Sandstone** Medium to coarse grained well rounded cross bedded quartz sandstone with glauconite pellets, dolomite and quartz cement, pyrite 1787.7-1788: Medium to coarse grained well rounded quartz sandstone with glauconite pellets and soft sediment deformation 1788-1788.3: Medium to coarse grained well rounded quartz sandstone with glauconite pellets, thin shale partings and quartz cement, pyrite	Run 1	
-548.68	1785'					
				1788.3-1790: Same As Above	Run 2	
-553.68	1790'					

Notes/Comments:

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Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-558.68	1795'			1790-1797.5: Medium to coarse grained well rounded quartz sandstone with glauconite pellets, thin shale partings and quartz cement, pyrite	<u>Run 2</u>	
-563.68 -568.68	1800' 1805'			1797.5-1797.8: Same As Above 1797.8-1798: Greenish gray shale 1798-1802: Well cemented cross-bedded medium grained well rounded quartz sandstone with thin shale partings 1802-1803: Well cemented medium grained well rounded quartz sandstone mottled with thin shale partings and carbonate 1803-1806.8: Well cemented cross-bedded medium grained well rounded quartz sandstone interbedded with thin shale partings and carbonate, pyrite	<u>Run 3</u>	
-573.68 -578.68	1810' 1815'			1806.8-1807.1: Same As Above 1807.1-1808.1: Carbonate mottled with thin shale partings 1808.1-1816.8: Moderately cemented to friable medium grained well rounded quartz sandstone with sparse thin shale and glauconitic pellets	<u>Run 4</u>	
-583.68 -588.68	1820' 1825'			1816.8-1826.1: Same As Above	<u>Run 5</u>	
-593.68	1830'			1826.1-1827.8: Same As Above 1827.8-1828.8: Carbonate 1828.8-1830: Medium to coarse grained well rounded quartz sandstone with sparse thin shale and glauconitic pellets	<u>Run 6</u>	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-598.68	1835'			1830-1834.9: Medium to coarse grained well rounded quartz sandstone with sparse thin shale and glauconitic pellets 1834.9-1835.8: Well cemented medium to coarse grained well rounded quartz sandstone with glauconitic pellets interbedded with thin shale 1835.8-1836.1: Well cemented medium to fine grained well rounded quartz sandstone with glauconitic pellets interbedded with thin shale, brachiopods	Run 6	
-603.68 -608.68	1840' 1845'			1836.1-1846.1: Same As Above	Run 7	
-613.68 -618.68	1850' 1855'			1846.1-1856.1: Same As Above	Run 8	
-623.68 -628.68	1860' 1865'			1856.1-1866: Same As Above	Run 9	
-633.68	1870'			1866.1-1870: Well cemented occasionally burrowed siltstone interbedded with vertically burrowed shale and sandstones with glauconitic pellets, brachiopods	Run 10	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: John Twitty Energy Center
Hole Exploratory Borehole #1

Formation	Member	Lithologic Description	Samples Interval	Comments
		1870-1888.6: Well cemented occasionally burrowed siltstone interbedded with vertically burrowed shale and sandstones with glauconitic pellets, brachiopods	Run 10	
		1876-1886.2: Same As Above	Run 11	
		1886.2-1888.6: Same As Above 1888.6-1891.8: Interbedded glauconitic silts and sands 1891.8-1892.3: Oxidized red clay with sand 1892.3-1896: Interbedded glauconitic silts and sands 1896-1896.2: Interbedded and mottled dolomite with burrows and glauconitic pellets	Run 12	
		1896.2-1906.2: Same As Above	Run 13	
		1906.2-1910: Same As Above	Run 14	

Elevation	Depth
-638.68	1875'
-643.68	1880'
-648.68	1885'
-653.68	1890'
-658.68	1895'
-663.68	1900'
-668.68	1905'
-673.68	1910'

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1900-1916.2: Interbedded and mottled dolomite with burrows and glauconitic pellets	Run 14	
				1916.2-1926.8: Same As Above	Run 15	
				1926.8-1936.8: Same As Above	Run 16	
				1936.8-1946.8: Same As Above	Run 17	
				1946.8-1950: Same As Above	Run 18	

Elevation	Depth
-678.68	1915'
-683.68	1920'
-688.68	1925'
-693.68	1930'
-698.68	1935'
-703.68	1940'
-708.68	1945'
-713.68	1950'

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-718.68	1955'			1850-1955.6: Same As Above 1955.6-1956.8: Well cemented medium to coarse grained arkosic sandstone with glauconitic pellets, brachiopods	Run 18	
-723.68	1960'			1956.8-1960.5: Same As Above 1960.5-1961.8: Well cemented medium grained well rounded quartz sandstone with glauconitic pellets interbedded with thin shale, brachiopods	Run 19	
-728.68	1965'			1961.8-1964: Same As Above 1964-1965.1: Well cemented medium grained well rounded quartz sandstone with shell fragments	Run 20	
-733.68	1970'			1965.1-1966: Same As Above 1966-1966.5: Well cemented medium grained quartz sandstone with shell fragments interbedded with thin shale 1966.5-1968.5: Well cemented medium grained quartz sandstone with brachiopod shell fragments 1968.5-1972.4: Well cemented medium grained quartz sandstone with shell fragments interbedded with thin shale	Run 21	
				1972.4-1973.8: Same As Above	Run 22	
-738.68 -743.68	1975' 1980'			1973.8-1976.1: Same As Above 1976-1977: Well cemented medium grained quartz sandstone with brachiopod shell fragments 1977-1978: Well cemented medium grained quartz sandstone with shell fragments interbedded with thin shale 1978-1979: Well cemented medium grained quartz sandstone	Run 23	1979-1980.1: Well cemented medium grained quartz sandstone with shell fragments interbedded with burrowed shale and siltstones
-748.68	1985'			1980.1-1987.5 Well cemented medium grained quartz sandstone with shell fragments interbedded with burrowed shale and siltstones 1987.5-1987.6 Well cemented medium grained cross-bedded quartz sandstone with glauconitic pellets	Run 24	
-753.68	1990'			1987.6-1990: Same As Above	Run 25	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: John Twitty Energy Center
Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-758.68	1995'			1990-1997.6: Well cemented medium grained cross-bedded quartz sandstone with glauconitic pellets	Run 25	
-763.68 -768.68	2000' 2005'			1997.6-1997.8 Same As Above 1997.8-2007.6: Well cemented cross-bedded arkosic sandstone fining upwards from coarse grained somewhat sorted sandstone with feldspathic pebbles to medium grained well sorted arkosic sandstone to fine quartz sand with few thin shale interbedded	Run 26	
-773.68	2010'			2007.6-2012.1: Same As Above	Run 27	
-778.68 -783.68	2015' 2020'			2012.1-2022.6: Same As Above	Run 28	
-788.68 -793.68	2025' 2030'			2022.6-2030: Same As Above	Run 29	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				2030-2032.6: Same As Above	Run 29	
-798.68 -803.68	2035' 2040'			2032.6-2042.6: Same As Above	Run 30	
-808.68 -813.68	2045' 2050'			2042.6-2050.7: Same As Above	Run 31	
-818.68 -823.68	2055' 2060'			2050.7-2060.8: Same As Above	Run 32	
-828.68	2065'			2060.8-2065: Same As Above 2065-2069.6: Well cemented cross-bedded coarse grained somewhat sorted arkosic sandstone with feldspathic and quartz pebbles and quartz and hematite cements with few thin shale interbedded	Run 33	
-833.68	2070'			2069.6-2070: Same As Above	Run 34	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-838.68	2075'			2070-2078.1: Same As Above	Run 33	
-843.68 -848.68	2080' 2085'			2078.1-2087.6: Same As Above	Run 34	
-853.68 -858.68	2090' 2095'			2087.6-2097.6: Same As Above	Run 35	
-863.68 -868.68	2100' 2105'			2087.6-2100: Same As Above 2100-2107.6: Well cemented cross-bedded arkosic sandstone fining upwards from coarse grained somewhat sorted sandstone with feldspathic pebbles to medium grained well sorted arkosic sandstone to fine quartz sand with few thin shale interbedded	Run 36	
-873.68	2110'			2107.6-2110: Same As Above	Run 37	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-878.68	2115'			2100-2117.6: Well cemented cross-bedded arkosic sandstone fining upwards from coarse grained somewhat sorted sandstone with feldspathic pebbles to medium grained well sorted arkosic sandstone to fine quartz sand with few thin shale interbedded	Run 37	
-883.68 -888.68	2120' 2125'			2117.6-2127.6: Same As Above	Run 38	
-893.68 -898.68	2130' 2135'			2127.6-2134.4: Same As Above 2134.4-2137.6: Well cemented cross-bedded coarse grained somewhat sorted arkosic sandstone with feldspathic and quartz pebbles and quartz and hematite cements with few thin shale interbedded	Run 39	
-903.68 -908.68	2140' 2145'			2137.6-2146.9: Same As Above 2146.9-2147: Weathered quartz and feldspar breccia	Run 40	
-913.68	2150'			2147-2186.6: **Precambrian Basement** Quartz, plagioclase, orthoclase, muscovite, and biotite pegmatite, with greater than 10 cm feldspar crystals veined with quartz. Rock is heavily fractured, fractures dipping approximately 30 degrees with striations on fractures. Ductile deformation is likely in some zones. Extensive weathering along fractures with micas and possible epidote altered to chlorite.	Run 41	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: John Twitty Energy Center
Hole Exploratory Borehole #1

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-918.68	2155'			2150-2156.7: Same As Above	Run 42	
-923.68 -928.68	2160' 2165'			2156.7-2165.7: Same As Above	Run 43	
-933.68	2170'			2165.7-2172.9: Same As Above	Run 44	
-938.68	2175'			2172.9-2177.6: Same As Above	Run 45	
-943.68	2180'			2177.6-2180.6: Same As Above	Run 46	
-948.68	2185'			2180.6-2186.6: Same As Above	Run 47	
-953.68	2190'			Bottom of EXP#1		

Notes/Comments:

APPENDIX 3.C - DESCRIPTIVE STRATIGRAPHIC LOG OF EXPLORATORY BOREHOLE #2 AT THE THOMAS HILL ENERGY CENTER, RANDOLPH COUNTY, MISSOURI

STRATIGRAPHIC DESCRIPTION

Fill Material (0-2 feet depth): Approximately two feet of limestone gravel.

Loess (2-35 feet depth): This unit contains yellowish brown, silty clay to sandy silty clay.

Glacial Till (35-73 feet depth): This unit contains gray, brown, yellowish silty clays, sandy clays with granite, calcite, chert, quartz, sands, pebbles and gravels, and coal. Secondary mineral present includes pyrite.

Pennsylvania (73-118 feet depth): This unit contains dark brown, gray to dark gray, silty to sandy silty clays, calcite, quartz and chert coarse sands with coal fragments and traces of crinoid fragments. Secondary mineral present includes pyrite.

Warsaw Formation (118-179 feet depth): This unit contains light gray to buff, fine to medium to coarsely grained, limestone to cherty limestone with traces of crinoids, gastropods and brachiopod fragments. Secondary minerals consisted of glauconite and pyrite.

Burlington/Keokuk Formation (179-274 feet depth): This unit contains light gray, medium to coarse grained, limestone to cherty limestone, white to gray cherts to with crinoid fragments. Secondary minerals present include glauconite.

Chouteau Group: Sedalia Formation (274-334 feet depth): This unit contains alternating beds of light gray to buff, medium to coarse grained limestone to buff, fine grained, sandy texture pitted dolomite, slight amount of chert.

Chouteau Group (334-464 feet depth): This unit contains olive gray to light gray, fine grained, sandy textured dolomite to dolomitic limestone. Also found were light gray to olive gray, fine grained, limestone to sandy textured limestone, white, milky white, bluish gray, to gray cherts. Traces of brachiopods and fossil fragments were found, as well as, slight chert to cherty. Secondary mineral present includes pyrite.

Kinderhook Shale (464-479 feet depth): This unit contains light gray, olive gray, to dark gray shale.

Cedar Valley Limestone: Callaway Facies (479-519 feet depth): This unit contains light gray, gray to buff, fine grained, limestone to microcrystalline, conchoidal fracturing limestone, as well as a coral fragment. Secondary minerals present include glauconite.

Cedar Valley Limestone: Mineola Facies (519– 659 feet depth): This unit contains primarily light gray, to gray, fine grained to microcrystalline, limestone, glauconitic limestone, platy limestone, sandy textured limestone with bluish green limey shale. Traces of brachiopods and Mollusca fragments were found. Secondary minerals present are glauconite and pyrite.

Cedar Valley Limestone: Hoing Sandstone Member (659-674 feet depth): This unit contains calcite cemented, fine grained, and well-rounded quartz sandstone.

St. Peter Sandstone (674-1,117 feet depth): This unit contains white, well-sorted, friable, fine grained, rounded frosted quartz sand. Secondary mineral present is pyrite. From 1,022-1,117 feet is the Kress member which is a light gray, fine grained, dolomite with bluish green to dark gray shale and slight amounts of fine grained, friable, frosted quartz sand, gray to white cherts. Secondary mineral present is pyrite.

Cotter Dolomite (1,117-1,217 feet depth): This unit contains light gray, fine, medium to coarse, dolomite, with bluish green to dark gray shale, slight amounts of fine grained, gray to white oolitic chert to gray to white chert. Secondary mineral present is pyrite.

Jefferson City Dolomite (1,217-1,347 feet depth): This unit contains light gray, fine, medium to coarse, dolomite, with bluish green to dark gray shale, slight amounts of fine grained, gray to white oolitic chert to gray to white chert. Secondary mineral present is pyrite.

Rubidoux Formation (1,347-1,487 feet depth): This unit contains light gray, medium grained, dolomite to cherty dolomite, as well as, white cherts. Slight amount of cemented sandstone also were found. Secondary minerals present are pyrite and glauconite.

Gasconade Dolomite (1,487-1,577 feet depth): This unit contains light gray to dark gray, fine to medium grained, dolomite, as well as, white platy cherts. Secondary minerals present are pyrite and glauconite. From 1557-1577 feet is the **Gunter Sandstone member** which is a tan to buff, fine grained, rounded calcite cemented quartz sandstone with tan to buff, medium grained, dolomite.

Eminence Dolomite (1,577-1,717 feet depth): This unit contains light gray to brownish gray to dark gray, fine to medium grained, dolomite, rounded, quartz sand, as well as, slight amounts of white chert and bluish green shale.

Potosi Dolomite (1,717-1,797 feet depth): This unit contains light gray, fine grained, dolomite, as well as, small amounts of white chert and bluish green to dark gray shale. Secondary minerals present are pyrite.

Derby-Doerun Dolomite (1,797-1,942 feet depth): This unit contains light gray, brownish gray to dark gray, fine to medium grained, dolomite. The **Lower Derby-Doerun Dolomite** is from 1,827-1,942 feet which is a light gray, medium grained dolomite to peppered glauconitic dolomite.

Davis Formation (1,942-2,087 feet depth): This unit contains intertwined (Transitional zone) variably glauconitic, very fine-grained sandstone, siltstone, and carbonate shale: interbedded carbonate facies ranging from packstone to mudstone. Interbedded within the entire sequence are debris flow beds represented by edgewise flat pebble conglomerates.

Bonneterre Formation (2,087-2,333.6 feet depth): This unit contains gray to dark gray, fine to medium grained, oolitic limestone to dolomite, and variably glauconitic. Gray mottled dolomite with grainstones and laminated shaly dolomite were also found. The layer also contains laminated limestones and dolomites with dark shales.

Lamotte Sandstone (2,333.6-2,539.8 feet depth): The Lamotte Sandstone is comprised of two distinct sand bodies that gradually grade upwards from an alluvium fan facies into a fluvial plain or marine sequence. The upper sand body (2,333.6 - 2,452 feet depth) consist predominately of white to tan to light-brown, very fine to coarse grained, rounded to subrounded, weakly friable to friable, quartz sand with minor amounts of shale and clay partings at the top.

The basal sand body (2,452 – 2,539.8 feet depth) consists predominately of varied brown to tan to red, fine to coarse grained, rounded to angular, weakly friable to friable, arkosic sand containing intervals of quartz and feldspar pebbles. Cross bedding is mostly observed in the basal portion of the formation. Granitic rock fragments also are observed in the basal Lamotte.

Precambrian Basement (2,539.8-2,577 feet depth): This unit contains mottled red to salmon pink to bluish gray, quartz (clear to light gray in color), plagioclase, orthoclase, biotite, and phaneritic weathered granite. Heavily fractured, fractures range from 29 to 65 degrees.

APPENDIX 3.D EXPLORATORY BOREHOLE #2 WELL LOG

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Divison of Geology and Land Survey
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Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Driller's Information

Drilling Company: Lanye Christensen
Driller: Rusty Bowles
Equipment Description: Atlas Copco

Contractor's Information

Primary Contractor:
P C Represetative:
Sub-Contractor:
S C Representative:

Site Location Information

County: Randolph County
Quadrangle:
Land Grant:
Section:
Additional description:

Well longitude: 92° 37' 32.5" W
Well latitude: 39° 32' 57.9" N
Logged by: John Pate
Alias well ID:
Date drilled: Started 2/20/12 **; Ended** 6/23/12

Additional location description:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
790.41'				0-2 : Fill: Approximately 2ft of limestone gravel		No Sample
				2-5: **Loess** Yellowish Brown Silty Clay		
785.41'	5'			5-10: Yellowish Brown Silty Clay		No Sample
780.41'	10'			10-15: Yellowish Brown Silty Clay	S-1	
775.41'	15'			15-20: Yellowish Brown Silty Clay	S-2	
770.41'	20'			20-25: Yellowish Brown Sandy Silty Clay	S-3	
765.41'	25'			25-30: Yellowish Brown Sandy Silty Clay	S-4	
760.41'	30'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				30-35: Yellowish Brown Sandy Silty Clay with some very angular to angular chert and quartz sand pebbles and gravels.	S-5	
755.41’	35’			35-38: **Glacier Till.** Brown to light gray Sandy silty Clay with angular to surrounded granite, chert, quartz sand pebbles and gravels.	S-6	
750.41’	40’			38-43: Brown Sandy Silty Clay with angular to surrounded granite, chert, quartz sand pebbles and gravels.	S-7	
745.41’	45’			43-48: Brown to light gray Silty Clay with angular to rounded granite, chert, quartz sand pebbles and gravels.	S-8	
740.41’	50’			48-53: Gray Silty Clay with angular to rounded granite, chert, quartz sand pebbles.	S-9	
735.41’	55’			53-58: Glacier Till. Gray Silty Clay with angular to rounded granite, chert, quartz sand pebbles.	S-10	
730.41’	60’			58-63: Glacier Till. Gray Silty Clay with angular to rounded granite, chert, quartz sand pebbles.		No Sample
725.41’	65’			63-68: Glacier Till. Yellowish Brown to Gray Silty Clay Quartz and chert coarse sands	S-11	
720.41’	70’			68-73: Glacier Till. Brown Sandy Silty Clay Quartz and chert coarse sands	S-12	

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
					S-12	
715.41’	75’			73-78: **Pennsylvania System** Dark Brown Sandy Silty Clay Quartz and chert coarse sands	S-13	
710.41’	80’			78-83: Brown Silty Clay Coal fragments mixed with calcite, quartz and chert coarse sands	S-14	
705.41’	85’			83-88: Gray Silty Clay Coal fragments mixed with calcite, quartz and chert coarse sands	S-15	
700.41’	90’			88-93: Gray Silty Clay Coal fragments mixed with calcite, quartz and chert coarse sands • Crinoid fragment	S-16	
695.41’	95’			93-98: Dark Gray Silty Clay Coal fragments mixed with calcite, quartz and chert coarse sands	S-17	
690.41’	100’			98-103: Gray Silty Clay Coal fragments mixed with calcite, quartz and chert coarse sands • Shell fragment	S-18	
685.41’	105’			98-103: Gray Silty Clay Coal fragments mixed with calcite, quartz and chert coarse sands • Brachiopod fossil • Pyrite crystal	S-19	
680.41’	110’			98-103: Yellowish Brown Silty Clay Coal fragments mixed with calcite, quartz and chert coarse sands	S-20	

Notes/Comments:

Missouri Department of Natural Resources
Divison of Geology and Land Survey
Geological Survey Program

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
					S-20	
675.41’	115’			113-118: Yellowish Brown Silty Clay Coal fragments mixed with calcite, quartz and chert coarse sands • Crinoid fragments • Pyrite crystals	S-21	
670.41’	120’			118-123: **Warsaw Formation** Light gray to gray fine to medium grained weathered limestone • Crinoid fragments • Pyrite crystals	S-22	
665.41’	125’			123-128: Light gray to gray fine to medium grained weathered limestone, limey clay • Crinoid fragments • Pyrite crystals	S-23	
660.41’	130’			128-133: 98% gray fine to medium grained limestone, 2% greenish gray fine grained limestone. • Crinoid fragments • Pyrite crystals	S-24	
655.41’	135’			133-138: 100% gray fine to medium grained limestone • Crinoid fragments • Pyrite crystals	S-25	
650.41’	140’			138-143: 64% Buff, fine grained limestone, 1% limestone is peppered with pyrite crystals, 35% white chert • Crinoid fragments, brachiopod fragments • Pyrite crystal	S-26	
645.41’	145’			143-148 Warsaw Formation 89% Buff, fine to medium grained limestone, 1% limestone is peppered with pyrite crystal, 10% gray to white chert	S-27	
640.41’	150’			148-153 Warsaw Formation 95% Buff, fine to medium grained limestone, 5% gray to white chert • Crinoid fragments	S-28	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
					S-28	
635.41’	155’			153-158: 95% light gray to buff, fine to medium grained limestone slightly peppered with glauconite, 5% gray to white chert	S-29	
630.41’	160’			158-164: 99% light gray to buff, fine to medium grained limestone , 1% gray to white chert	S-30	
625.41’	165’			158-164: 99% light gray to buff, fine to medium grained limestone , 1% gray to white chert	S-31	
620.41’	170’			158-164: 99% light gray to buff, fine to medium grained limestone , 1% gray to white chert	S-32	
615.41’	175’			169-174: 97% light gray, medium grained limestone slightly peppered with glauconite, 3% gray to white chert • Brachiopod and crinoid fragments • Pyrite	S-33	
610.41’	180’			174-179: 75% light gray, medium grained limestone, 25% gray to white chert • Gastropod and crinoid fragments in some of the chert • Glauconite	S-34	
605.41’	185’			179-184: **Burlington-Keokuk Formation** 50% light gray, medium grained limestone, 50% gray chert • Crinoid and brachiopod fragments	S-35	
600.41’	190’			189-194: 50% light gray, medium to coarse grained limestone, 50% white chert • Fossil fragments in some of the chert	S-36	

Notes/Comments:

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Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
					S-36	
595.41’	195’			194-199: 80% light gray, medium to coarse grained limestone, 20% white chert • Fossil fragments in some of the chert	S-37	
590.41’	200’			199-204: 100% light gray, medium to coarse grained limestone	S-38	
585.41’	205’			204-209: 97% light gray, medium to coarse grained limestone, 3% white chert	S-39	
580.41’	210’			209-214: 95% light gray, medium to coarse grained limestone, 5% white chert • Crinoid fragments in some of the chert	S-40	
575.41’	215’			214-219: 95% light gray, medium to coarse grained limestone, 5% white chert • Fossil fragments in some of the chert	S-41	
570.41’	220’			219-224: 100% light gray, medium to coarse grained limestone	S-42	
565.41’	225’			224-229: 97% light gray, medium to coarse grained limestone, 3% white chert	S-43	
560.41’	230’			229-234: 97% light gray, medium to coarse grained limestone, 3% white chert	S-44	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
					S-44	
555.41’	235’			234-239 50% light gray, medium to coarse grained limestone, 50% white chert	S-45	
550.41’	240’			239-244 100% light gray, medium to coarse grained limestone ● Glauconite	S-46	
545.41’	245’			244-249 99% light gray, medium to coarse grained limestone, 1% white chert	S-47	
540.41’	250’			249-254 100% light gray, medium to coarse grained limestone	S-48	
535.41’	255’			254-259 100% light gray, medium to coarse grained limestone ● Glauconite	S-49	
530.41’	260’			259-264 99% light gray, medium to coarse grained limestone, 1% white chert	S-50	
525.41’	265’			264-269 40% light gray, medium to coarse grained limestone, 60% white chert to fossiliferious white chert	S-51	
520.41’	270’			269-274 97% light gray, medium to coarse grained limestone, 3% white chert	S-52	

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project

Site: Thomas Hill Energy Center

Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
					S-52	
515.41’	275’			274-279: **Chouteau Group: Sedalia Formation** 95% Buff, fine grained, sandy texture dolomite to pitted dolomite, 5% white chert	S-53	Alternating beds from dolomite to limestone
510.41’	280’			279-284 99% Buff, fine grained, sandy texture dolomite to pitted dolomite, 1% white chert	S-54	
505.41’	285’			284-289 97% Buff, fine grained, sandy texture dolomite to pitted dolomite, 3% white chert	S-55	
500.41’	290’			289-294 100% Light gray to buff, medium to coarse grained limestone	S-56	
495.41’	295’			294-299 75% Light gray, fine grained dolomite to pitted dolomite, 22% Light gray, medium to coarse grained limestone, 3% white chert	S-57	
490.41’	300’			299-304 95% Buff, fine grained, sandy texture dolomite to pitted dolomite, 5% white chert to pitted chert	S-58	
485.41’	305’			304-309 95% Buff, medium to coarse grained limestone, 3% buff, fine grained, sandy texture dolomite, 2% white chert.	S-59	
480.41’	310’			309-314 60% Buff, fine grained, sandy texture dolomite to pitted dolomite, 40% white chert to fossiliferious chert	S-60	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
					S-60	Alternating beds from dolomite to limestone
475.41’	315’			314-319 98% Light gray, medium to coarse grained limestone, 1% light gray, fine grained, sandy texture dolomite, 1% white chert	S-61	
470.41’	320’			319-324 100% light gray, fine to coarse grained limestone • Crinoid fragments	S-62	
465.41’	325’			324-329 72% Light gray to buff, medium to coarse grained limestone, 25% light gray to buff, fine grained, sandy texture dolomite, 3% white chert • Crinoid fragments	S-63	
460.41’	330’			329-334 50% light gray to buff, medium to coarse grained limestone, 30% light gray to buff, fine grained, sandy texture dolomite, 20% gray, fine grained dolomite	S-64	
455.41’	335’			334-339 **Chouteau?** 100% Olive gray, fine grained, sandy textured dolomite	S-65	
450.41’	340’			339-344 99% Olive gray, fine grained, sandy textured dolomite, 1% milky calcite crystals	S-66	
445.41’	345’			344-349 100% Olive gray, fine grained, sandy textured dolomite	S-67	
440.41’	350’			349-354 100% light gray, fine grained, sandy textured dolomitic limestone	S-68	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
					S-68	
435.41'	355'			354-359: 50% olive gray, fine grained, sandy textured dolomitic limestone, 50% light gray chert	S-69	
430.41'	360'			359-364 : 95% light gray, fine grained, sandy textured limestone, 5% light gray chert	S-70	
425.41'	365'			364-369: 100% light gray, fine grained, sandy textured limestone	S-71	
420.41'	370'			369-374: 90% light gray, fine grained limestone, 10% light gray chert	S-72	
415.41'	375'			374-379: 100% light gray, fine (sandy texture) to medium grained, limestone	S-73	
410.41'	380'			379-384: 100% olive gray to light gray, fine grained, limestone • Brachiopod fragments	S-74	
405.41'	385'			384-389: 99% olive gray, fine grained, sandy texture limestone, 1% light gray chert • Brachiopod fragments	S-75	
400.41'	390'			389-394: 100% olive gray to light gray, fine grained, limestone	S-76	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
395.41’	395’			394-399: 99% olive gray to light gray, fine grained, limestone, 1% pyrite crystals	S-77	
390.41’	400’			399-404: 84% olive gray to light gray, fine grained, limestone, 15% light gray to bluish gray chert, 1% pyrite crystals	S-78	
385.41’	405’			404-409: 100% light gray, fine grained, sandy textured limestone	S-79	
380.41’	410’			409-414: 90% light gray, fine grained, limestone, 10% light gray, microcrystalline limestone	S-80	
375.41’	415’			414-419: 97% light gray, fine grained, sandy textured limestone, 3% light gray, microcrystalline limestone	S-81	
370.41’	420’			419-424: 100% light gray, fine grained, limestone	S-82	
365.41’	425’			424-429: 100% olive gray to gray, fine grained, limestone	S-83	
360.41’	430’			429-434: 99% olive gray to gray, fine grained limestone, 1% white to milky chert	S-84	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
355.41’	435’			434-439: 100% olive gray to light gray, fine grained, limestone • Fossil fragments	S-85	
350.41’	440’			439-444: 100% olive gray to light gray, fine grained, limestone	S-86	
345.41’	445’			444-449: 100% olive gray to light gray, fine grained, limestone • Fossil fragments	S-87	
340.41’	450’			449-454: 100% gray to light gray, fine grained, limestone • Fossil fragments	S-88	
335.41’	455’			454-459: 100% light gray, fine grained, limestone	S-89	
330.41’	460’			459-464: 100% light gray, fine grained, limestone	S-90	
325.41’	465’			464-469: **Kinderhook Shale** 100% light gray shale	S-91	
320.41’	470’			469-474 : 100% olive gray to light gray shale	S-92	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
315.41’	475’			474-479: 100% dark gray to olive gray shale	S-93	
310.41’	480’			479-484: **Cedar Valley Limestone: Callaway Facies** 100% light gray to buff, fine grained, limestone peppered with iron staining	S-94	
305.41’	485’			484-489: 100% light gray, fine grained, limestone • Coral fragment	S-95	
300.41’	490’			489-494: 100% light gray, fine grained, limestone	S-96	
295.41’	495’			494-499: 100% light gray to gray, fine grained, limestone	S-97	
290.41’	500’			499-504: 100% light gray, fine grained to microcrystalline, concordail fracturing, limestone • Calcite crystal growth on some pieces of limestone	S-98	
285.41’	505’			504-509: 100% light gray, microcrystalline, concordail fracturing, limestone • Calcite crystal growth on some pieces of limestone	S-99	
280.41’	510’			509-514: 100% light gray, microcrystalline, concordail fracturing, limestone • Calcite crystal growth on some pieces of limestone	S-100	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
275.41’	515’			514-519: 97% light gray, microcrystalline, concordail fracturing, limestone, 3% light gray to olive gray, medium crystalline, glauconitic limestone	S-101	
270.41’	520’			519-524: **Cedar Valley Limestone: Mineola Facies** 50% light gray to white, fine grained, sandy textured limestone, 50% light gray to olive gray, medium crystalline, glauconitic limestone	S-102	
265.41’	525’			524-529: 100% light gray to olive gray, medium crystalline, glauconitic limestone	S-103	
260.41’	530’			529-534: 100% light gray, fine grained, sandy textured dolomite	S-104	
255.41’	535’			534-539: 95% light gray, fine grained, sandy textured dolomite, 5% light gray to olive gray, medium crystalline, glauconitic limestone	S-105	
250.41’	540’			539-544: 100% light gray, fine grained, sandy textured dolomite	S-106	
245.41’	545’			544-549: 100% light gray, fine grained, platy limestone	S-107	
240.41’	550’			549-554: 100% light gray, fine grained, platy limestone	S-108	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
235.41’	555’			554-559: 100% gray, fine grained, platy limestone	S-109	
230.41’	560’			559-564: 100% light gray, fine grained to microcrystalline, platy limestone • Iron staining on some pieces of limestone Note 561 to 562: No sample, brown clay seam	S-110	
225.41’	565’			564-569: 100% light gray, fine grained, platy limestone	S-111	
220.41’	570’			569-574 : 100% light gray, fine grained, platy limestone	S-112	
215.41’	575’			574-579: 100% light gray, fine grained, limestone	S-113	
210.41’	580’			579-584: 100% gray to olive gray, fine grained, limestone • Brachiopod fragment	S-114	
205.41’	585’			584-589: 97% dark gray, medium grained, limestone, 3% light gray to buff, microcrystalline, limestone	S-115	
200.41’	590’			589-594: 100% light gray, fine grained to microcrystalline, limestone	S-116	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
195.41’	595’			594-599: 100% light gray, fine grained, limestone	S-117	
190.41’	600’			599-604: 100% light gray, microcrystalline, concordial fracturing, limestone ● Sparsely iron staining and glauconite	S-118	
185.41’	605’			604-609: 100% light gray to gray, fine grained to microcrystalline, limestone ● Sparsely glauconitic	S-119	
180.41’	610’			609-614: 95% light gray , fine to medium grained, limestone, 5% greenish gray, fine to medium grained, glauconitic limestone	S-120	
175.41’	615’			614-619: 97% light gray , fine grained, limestone, 3% greenish gray, fine grained, glauconitic limestone	S-121	
170.41’	620’			619-624: 97% light gray, fine to medium grained, limestone, 3% greenish blue shale	S-122	
165.41’	625’			624-629: 99% light gray, fine to medium grained, limestone, 1% greenish gray, fine to medium grained, glauconitic limestone	S-123	
160.41’	630’			629-634: 100% light gray, fine to medium grained, limestone	S-124	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
155.41’	635’			634-639: 100% light gray, fine to medium grained, limestone	S-125	
150.41’	640’			639-644: 99% light gray, fine to medium grained, limestone, sparsely peppered with iron staining, 1% bluish green shale	S-126	
145.41’	645’			644-649: 95% light gray, fine grained, limestone, 5% bluish green, limey shale	S-127	
140.41’	650’			649-654: 94% light gray, fine grained, limestone, 5 % bluish green, limey shale, 1% pyrite • Brachiopod and fossil fragments	S-128	
135.41’	655’			654-659: 48% dark gray, fine grained, dolomite, 48% light gray, fine grained limestone, 3% bluish green, limey shale, 1% pyrite • Mollusca fragments	S-129	
130.41’	660’			659-664: **Cedar Valley Limestone: Hoing Sandstone Member** 99% white calcareous quartz sandstone sparsely iron staining, 1% bluish green shale Note quartz sand held together with calcite cement	S-130	
125.41’	665’			664-669: 97% light gray, fine grained, limestone, 3% bluish green, limey shale	S-131	
120.41’	670’			669-674: 99% gray to dark gray, fine grained, sandy limestone, 1% bluish green, limey shale Note quartz sand is well rounded	S-132	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
115.41’	675’			674-679: **St. Peter Sandstone** 96% white calcareous quartz sandstone, 2% light gray to dark gray, fine grained, limestone, 2% bluish green shale, 1% pyrite Note quartz sand held together with calcite cement	S-133	
110.41’	680’			679-684: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-134	
105.41’	685’			684-689: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-135	
100.41’	690’			689-694: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-136	
95.41’	695’			694-699: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-137	
90.41’	700			699-704 87% white, well-sorted, friable fine grained, sub-rounded to rounded, quartz sand, 10% bluish green shale to sandy shale, 3% light gray, fine grained, limestone	S-138	
85.41’	705’			704-709 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-139	
80.41’	710’			709-714 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-140	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
75.41’	715’			714-719: 99% white, well-sorted, friable fine grained, rounded frosted quartz sand, 1% pyrite	S-141	
70.41’	720’			719-724: No recovery	S-142	
65.41’	725’			724-729: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-143	
60.41’	730’			729-734: 99% white, well-sorted, friable fine grained, rounded frosted quartz sand, 1% pyrite	S-144	
55.41’	735’			734-739: 99% white, well-sorted, friable fine grained, rounded frosted quartz sand, 1% pyrite	S-145	
50.41’	740’			739-744: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-146	
45.41’	745’			744-749: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-146	
40.41’	750’			749-754: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-147	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
35.41’	755’			754-759: 99% white, well-sorted, friable fine grained, rounded frosted quartz sand,1% pyrite	S-149	
30.41’	760’			759-764: No recovery	S-150	
25.41’	765’			764-769: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-151	
20.41’	770’			769-774: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-152	
15.41’	775’			774-779: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-153	
10.41’	780’			779-784: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-154	
5.41’	785’			784-789: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-155	
0.41’	790’			789-794: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-156	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-4.59’	795’			794-799: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-157	
-9.59’	800’			799-804: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-158	
-14.59’	805’			804-809: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-159	
-19.59’	810’			809-814: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-160	
-24.59’	815’			814-819: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-161	
-29.59’	820’			819-824: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-162	
-34.59’	825’			824-829: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-163	
-39.59’	830’			829-834: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-164	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-44.59’	835’			834-839: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-165	
-49.59’	840’			839-844: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-166	
-54.59’	845’			844-849: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-167	
-59.59’	850’			849-854: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-168	
-64.59’	855’			854-859: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-169	
-69.59’	860’			859-864: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-170	
-74.59’	865’			864-869: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-171	
-79.59’	870’			869-874: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-172	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-84.59’	875’			874-879: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-173	
-89.59’	880’			879-884: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-174	
-94.59’	885’			884-889: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-175	
-99.59’	890’			889-894: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-176	
-104.59’	895’			894-899: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-177	
-109.59’	900’			899-904: 100% tan to buff, well-sorted, friable fine grained, rounded frosted quartz sand	S-178	
-114.59’	905’			904-909: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-179	
-119.59’	910’			909-914: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-180	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-124.59’	915’			914-919: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-181	
-129.59’	920’			919-924: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-182	
-134.59’	925’			924-929: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-183	
-139.59’	930’			929-934: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-184	
-144.59’	935’			934-939: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-185	
-149.59’	940’			939-944: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-186	
-154.59’	945’			944-949: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-187	
-159.59’	950’			949-954: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-188	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-164.59'	955'			954-959: 100% white, well-sorted, friable fine grained, rounded frosted quartz sand	S-189	
-169.59'	960'			959-962: 94% tan or buff, well-sorted, friable fine grained, rounded frosted quartz sand, 5% iron cement holding quartz grains together, 1% chalcopyrite • Iron staining on quartz crystals	S-190	
-174.59'	965'			962-967: 94% tan or buff, well-sorted, friable fine grained, rounded frosted quartz sand, 5% iron cement holding quartz grains together, 1% chalcopyrite • Iron staining on quartz crystals	S-191	
-179.59'	970'			967-972: 94% tan or buff, well-sorted, friable fine grained, rounded frosted quartz sand, 5% iron cement holding quartz grains together, 1% chalcopyrite • Iron staining on quartz crystals	S-192	
-184.59'	975'			972-977: 96% tan or buff, well-sorted, friable fine grained, rounded frosted quartz sand, 3% iron cement holding quartz grains together, 1% chalcopyrite • Iron staining on quartz crystals	S-193	
-189.59'	980'			977-982: 96% tan or buff, well-sorted, friable fine grained, rounded frosted quartz sand, 3% iron cement holding quartz grains together, 1% chalcopyrite • Iron staining on quartz crystals	S-194	
-194.59'	985'			982-987: 97% tan or buff, well-sorted, friable fine grained, rounded frosted quartz sand, 3% iron cement holding quartz grains together • Iron staining on quartz crystals	S-195	
-199.59'	990'			987-992: 96% tan or buff, well-sorted, friable fine grained, rounded frosted quartz sand, 3% cement holding quartz grains together, 1% chalcopyrite • Iron staining on quartz crystals	S-196	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-204.59’	995’			992-997: 96% tan or buff, well-sorted, friable, fine grained, rounded frosted quartz sand, 3% iron cement holding quartz grains together, 1% chalcopyrite • Iron staining on quartz crystals	S-197	
-209.59’	1000’			997-1002: 70% tan to light brown, friable, fine grained, sub rounded to rounded frosted quartz sand, 15% bluish green shale, 15% hematite	S-198	
-214.59’	1005’			1002-1007: 91% tan or buff, well-sorted, friable, fine grained, rounded frosted quartz sand, 3% bluish green shale, 3% iron cement holding quartz grains together, 3% hematite • Iron staining on quartz crystals	S-199	
-219.59’	1010’			1007-1012: 95% tan or buff, well-sorted, friable, fine grained, rounded frosted quartz sand, 3% iron cement holding quartz grains together, 1% bluish green shale, 1% hematite • Iron staining on quartz crystals	S-200	
-224.59’	1015’			1012-1017: 93% tan or buff, well-sorted, friable, fine grained, rounded frosted quartz sand, 5% iron cement holding quartz grains together, 1% bluish green shale, 1% hematite • Iron staining on quartz crystals	S-201	
-229.59’	1020’			1017-1022: 71% white, well-sorted, friable, fine grained, rounded frosted quartz sand, 25% bluish green shale, 3% iron cement holding quartz grains together, 1% hematite • Iron staining on quartz crystals	S-202	
-234.59’	1025’			1022-1027: **Kress Member** 50% light gray, fine grained, dolomite, 49% bluish green shale, 1% white chert	S-203	
-239.59’	1030’			1027-1032: 75% light gray, fine grained, dolomite, 25% bluish green shale	S-204	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-244.59’	1035’			1032-1037: 60% bluish green shale, 39% light gray, fine grained, dolomite, 1% pyrite	S-205	
-249.59’	1040’			1037-1042: 47% light gray, fine grained, dolomite, 46% bluish green shale, 3% white chert, 2% fine grained, rounded, friable, quartz sand, 1% hematite, 1% pyrite	S-206	
-254.59’	1045’			1042-1047: 59% light gray, fine grained, dolomite, 25% white chert, 14% bluish green shale, 1% fine grained, rounded, friable, quartz sand	S-207	
-259.59’	1050’			1047-1052: 93% light gray , fine grained, dolomite, 5% bluish green shale, 1% white chert, 1% pyrite • Iron staining on some pieces of dolomite	S-208	
-264.59’	1055’			1052-1057: 75% bluish green shale, 10% light gray, fine grained, dolomite, 10% white, fine grained, calcite cemented, sandstone, 4% white chert, 1% white, rounded, friable, quartz sand	S-209	
-269.59’	1060’			1057-1062: 80% bluish green shale, 19% light gray to olive gray, fine grained, dolomite, 1% white, fine grained, calcite cemented, sandstone	S-210	
-274.59’	1065’			1062-1067: 80% light gray to olive gray, fine grained, dolomite, 17% bluish green shale, 3% iron cement holding quartz grains together	S-211	
-279.59’	1070’			1067-1072: 80% light gray, fine grained, dolomite, 15% bluish green shale,5% white, rounded, friable, quartz sand	S-212	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-284.59’	1075’			1072-1077: 93% light gray, fine grained, dolomite, 5% bluish green shale, 2% white, rounded, friable, quartz sand	S-213	
-289.59’	1080’			1077-1082: 80% bluish green shale, 19% light gray, fine grained, dolomite, 1% white, rounded, friable, quartz sand	S-214	
-294.59’	1085’			1082-1087: 83% light gray, fine grained, dolomite, 15% bluish green shale, 1% white, rounded, friable, quartz sand, 1% pyrite	S-215	
-299.59’	1090’			1087-1092: 75% light gray, fine grained, dolomite, 24% bluish green shale, 1% white, rounded, friable, quartz sand	S-216	
-304.59’	1095’			1092-1097: 90% light gray, fine grained, shale, 5% bluish green shale to sandy shale, 4% white, rounded, friable, quartz sand, 1% pyrite	S-217	
-309.59’	1100’			1097-1102: 50% bluish green to dark gray shale, 50% light gray, fine grained, dolomite	S-218	
-314.59’	1105’			1102-1107: 75% bluish green to dark gray shale, 14% light gray, fine to medium grained, dolomite, 1% pyrite	S-219	
-319.59’	1110’			1107-1112: 50% bluish green to dark gray shale, 49% light gray, fine grained , dolomite, 1% pyrite	S-220	

Notes/Comments:

Missouri Department of Natural Resources
Divison of Geology and Land Survey
Geological Survey Program

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-324.59’	1115’			1112-1117: 49% bluish green , 49% light gray, fine grained , dolomite, 1% white chert, 1% pyrite	S-221	
-329.59’	1120’			1117-1122: **Cotter Dolomite** 50% bluish green shale, 35%, light gray, fine grained, dolomite, 14 % white to light gray, oolitic chert, 1% pyrite	S-222	
-334.59’	1125’			1122-1127 : 48% bluish green to dark gray shale, 48% light gray, fine grained, dolomite, %3% white to light gray chert,1% pyrite	S-223	
-339.59’	1130’			1127-1137: 60% light gray, fine to medium grained, dolomite, 38% bluish green shale, 1% white chert, 1% pyrite	S-224	
-344.59’	1135’			1132-1137: 60% light gray, fine to medium grained, dolomite, 38% bluish green shale, 1% white chert, 1% pyrite	S-225	
-349.59’	1140’			1137-1142: 60% light gray, medium grained, dolomite, 40% bluish green to dark gray shale	S-226	
-354.59’	1145’			1142-1147: 60% light gray, medium grained, dolomite, 38% bluish green shale, 1% white chert, 1% pyrite	S-227	
-359.59’	1150’			1147-1152: 60% light gray, medium grained, dolomite, 30% bluish green shale, 10% white to gray chert	S-228	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-364.59’	1155’			1152-1157: 50% bluish green shale, 47% light gray, fine to medium grained, dolomite 3% white to gray chert	S-229	
-369.59’	1160’			1157-1162: 49% bluish green shale, 49% light gray, fine grained, dolomite, 1% quartz sand conglomerate, 1% white chert	S-230	
-374.59’	1165’			1162-1167: 52% light gray, fine grained, dolomite, 36% bluish green shale, 1% white chert, 1% pyrite	S-231	
-379.59’	1170’			1167-1172: 47% light gray, fine grained to medium grained, dolomite, 41% bluish green shale, 10% white to gray chert, 1% white, rounded, friable, quartz sand 1% pyrite	S-232	
-384.59’	1175’			1172-1177: 46% light gray, fine grained to medium grained, dolomite, 43% bluish green shale, 10% white to gray chert, 1% pyrite	S-233	
-389.59’	1180’			1177-1182: 94% bluish green shale, 4% light gray, fine grained to medium grained, dolomite, 1% white to gray, oolitic chert, 1% quartz conglomerate	S-234	
-394.59’	1185’			1182-1187: 50% bluish green shale, 39% light gray fine, grained to medium grained dolomite,10% white to gray chert to oolitic chert, 1% pyrite	S-235	
-399.59’	1190’			1187-1192: 53% bluish green shale, 36% light gray fine, grained to medium grained dolomite,10% white to gray chert, 1% pyrite	S-236	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-404.59’	1195’			1192-1197: 53% bluish green shale, 36% light gray fine, grained to medium grained dolomite,10% white to gray chert to oolitic, 1% pyrite	S-237	
-409.59’	1200’			1197-1202: 75% light gray, fine to medium to coarse grained, dolomite, 21% bluish green shale, 3% white to gray, chert to oolitic chert , 1% pyrite	S-238	
-414.59’	1205’			1202-1207: 75% light gray, fine to medium to coarse grained, dolomite, 21% bluish green shale, 3% white to gray, chert to oolitic chert , 1% pyrite	S-239	
-419.59’	1210’			1207-1212: 80% light gray, medium to coarse grained, dolomite, 14% bluish green shale, 5% white to gray, chert to oolitic chert, 1% pyrite	S-240	
-424.59’	1215’			1212-1217: 85% light gray, medium to coarse grained, dolomite, 9% bluish green shale, 5% white to gray, chert to oolitic chert, 1% pyrite	S-241	
-429.59’	1220’			1217-1222: **Jefferson City Dolomite** 50% bluish green shale, 43% light gray to gray, fine to coarse grained, dolomite, 5% white fine grained, sub-rounded to rounded, loose sand grains to cemented together sand, 1% white to gray chert, 1% pyrite	S-242	
-434.59’	1225’			1222-1227 : 90% light gray , coarse grained, dolomite, 5% bluish green, shale, 3% white fine grained, sub-rounded to rounded, loose sand grains to cemented together sand, 1% white to gray chert, 1% pyrite	S-243	
-439.59’	1230’			1227-1232: 90% light gray , coarse grained, dolomite, 5% bluish green, shale, 3% white fine grained, sub-rounded to rounded, loose sand grains to cemented together sand, 1% white to gray chert, 1% pyrite	S-244	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-444.59’	1235’			1232-1237: 83% light gray , coarse grained, dolomite, 10% white to light gray chert, 3% bluish green, shale, 3% white fine grained, sub-rounded to rounded, loose sand , 1% pyrite	S-245	
-449.59’	1240’			1237-1242: 50% light gray to gray, fine to coarse grained, dolomite, 47% bluish green shale, 3% white to light gray chert	S-246	
-454.59’	1245’			1242-1247: 90% light gray, coarse grained, dolomite, 10% bluish green shale	S-247	
-459.59’	1250’			1247-1252: 90% light gray, fine to coarse grained, dolomite, 9% bluish green shale, 1% white to light gray chert	S-248	
-464.59’	1255’			1252-1257: 94% light gray, fine to coarse grained, dolomite, 5% bluish green shale, 1% white to light gray chert	S-249	
-469.59’	1260’			1257-1262: 94% light gray, fine to coarse grained, dolomite, 5% bluish green shale, 1% white to light gray chert	S-250	
-474.59’	1265’			1262-1267: 50% light gray, fine to coarse grained, dolomite, 47% bluish green shale, 3% pyrite	S-251	
-479.59’	1270’			1267—1272: 80% light gray , fine to coarse grained, dolomite, 20% bluish green shale	S-252	

Notes/Comments:

Missouri Department of Natural Resources
Divison of Geology and Land Survey
Geological Survey Program

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-484.59’	1275’			1272-1277: 85% light gray, coarse grained, dolomite, 10% bluish green, shale, 5% white to light gray, chert to oolitic chert	S-253	
-489.59’	1280’			1277-1282: 50% light gray, coarse grained, dolomite, 47% bluish green, shale, 3% white to light gray, chert	S-254	
-494.59’	1285’			1282-1287: 85% light gray, coarse grained, dolomite, 10% bluish green, shale, 5% white to light gray, chert	S-255	
-499.59’	1290’			1287-1292: 90% light gray, coarse grained, dolomite, 9% bluish green, shale, 1% white to light gray, chert	S-256	
-504.59’	1295’			1292-1297: 94% light gray, coarse grained, dolomite, 5% bluish green, shale, 1% white to light gray, chert	S-257	
-509.59’	1300’			1297-1302: 94% light gray, coarse grained, dolomite, 5% bluish green, shale, 1% white to light gray, chert	S-258	
-514.59’	1305’			1302-1307: 93% light gray, fine to coarse grained dolomite, 4% white to light gray chert, 3% bluish green shale	S-259	
-519.59’	1310’			1307-1312: 94% light gray to gray, coarse grained dolomite, 3% white to light gray chert, 3% bluish green shale	S-260	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-524.59'	1315'			1312-1317: 94% light gray to gray, coarse grained dolomite, 3% white to light gray chert, 3% bluish green shale	S-261	
-529.59'	1320'			1317-1322: 92% light gray to gray, coarse grained dolomite, 5% bluish green shale 3% white to light gray chert to oolitic chert,	S-262	
-534.59'	1325'			1322-1327: 96% light gray to gray, coarse grained dolomite, 2% bluish green shale 2% white to light gray chert	S-263	
-539.59'	1330'			1327-1332: 87% light gray to gray, coarse grained dolomite, 10% bluish green shale 3% white to light gray chert	S-264	
-544.59'	1335'			1332-1337: 70% light gray to gray, coarse grained dolomite, 25% white to light gray chert , 5% bluish green shale	S-265	
-549.59'	1340'			1337-1342: 87% light gray to gray, coarse grained dolomite, 10% bluish green shale, 3% white to light gray chert	S-266	
-554.59'	1345'			1342-1347: 96% light gray to gray, coarse grained dolomite, 3% bluish green shale, 1% white to light gray chert	S-267	
-559.59'	1350'			1347-1352 : **Roubidoux Formation** 90% light gray to gray, coarse grained dolomite, 5% bluish green shale, 5% white platy to light gray chert	S-268	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-564.59’	1355’			1352-1357: 92% light gray to gray, coarse grained dolomite, 5% white platy chert to light gray chert , 3% bluish green shale	S-269	
-569.59’	1360’			1357-1362: 87% light gray to gray, coarse grained dolomite, 10% white platy chert to light gray chert , 3% bluish green shale	S-270	
-574.59’	1365’			1362-1367: 60% light gray to gray, coarse grained dolomite, 39% white platy chert to gray chert, 1% bluish green shale	S-271	
-579.59’	1370’			1376-1372: 87% light gray to gray, coarse grained dolomite, 10% white platy chert to gray chert, 3% bluish green shale	S-272	
-584.59’	1375’			1372-1377: 94% light gray to gray, medium grained dolomite, 3% white platy chert to gray chert, 3% bluish green shale	S-273	
-589.59’	1380’			1377-1382: 94% light gray to gray, coarse grained dolomite, 3% white to gray chert, 3% bluish green shale	S-274	
-594.59’	1385’			1382-1387: 96% light gray to gray, coarse grained dolomite, 3% white to gray chert, 1% bluish green shale	S-275	
-599.59’	1390’			1387-1392: 50% light gray to gray, coarse grained dolomite, 49% white chert, 1% bluish green shale	S-276	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-604.59’	1395’			1392-1397: 89% light gray to gray, coarse grained dolomite, 10% white chert, 1% bluish green shale	S-277	
-609.59’	1400’			1397-1402: 94% light gray to gray, coarse grained dolomite, 3% white chert to oolitic chert, 3% bluish green shale	S-278	
-614.59’	1405’			1402-1407: 97% light gray to gray, coarse grained dolomite, 2% white chert, 1% bluish green shale	S-279	
-619.59’	1410’			1407-1412: 98% light gray to gray, coarse grained dolomite, 1% bluish green shale, 1% white chert	S-280	
-624.59’	1415’			1412-1417: 96% light gray to gray, coarse grained dolomite, 3% white chert, 1% bluish green shale	S-281	
-629.59’	1420’			1417-1422: 97% light gray to gray, coarse grained dolomite, 2% white chert, 1% bluish green shale	S-282	
-634.59’	1425’			1422-1427: 97% light gray to gray, coarse grained dolomite, 2% white chert, 1% green shale	S-283	
-639.59’	1430’			1427-1432: 98% light gray to buff, fine to medium grained, platy dolomite, 2% white chert, 2% dark green shale	S-284	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-644.59’	1435’			1432-1437: 50% light gray to buff, fine to medium grained, platy dolomite, 49% white platy chert, 1% green shale	S-285	
-649.59’	1440’			1437-1442: 94% light gray, medium grained, platy dolomite, 5% white chert, 1% green shale	S-286	
-654.59’	1445’			1442-1447: 97% light gray, fine to medium grained, dolomite, 2% white chert, 1% green shale	S-287	
-659.59’	1450’			1447-1452: 98% light gray, fine to medium grained, dolomite, 1% white chert, 1% green shale	S-288	
-664.59’	1455’			1452-1457: 96% light gray to gray, fine to medium grained, dolomite, 3% white to light gray chert, 1% green shale	S-289	
-669.59’	1460’			1457-1462: 59% light gray to gray, fine to medium grained, dolomite, 40% white chert, 1% green shale	S-290	
-674.59’	1465’			1462-1467: 95% light gray, fine grained, dolomite, 5% white chert	S-291	
-679.59’	1470’			1467-1472: 98% light gray to gray, fine to medium grained, dolomite, 1% white chert, 1% green shale	S-292	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project

Site: Thomas Hill Energy Center

Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-684.59’	1475’			1472-1477 : 98% light gray, medium to coarse grained, dolomite to pitied dolomite, 1% white chert, 1% bluish green shale	S-293	
-689.59’	1480’			1477-1482: 94% light gray to gray, fine to medium grained, dolomite, 5% white to tan, fine grained, rounded, quartz sandstone, 1% gray chert	S-294	
-694.59’	1485’			1482-1487: 93% light gray, medium, dolomite to pitied dolomite, 5% white to tan, fine grained, rounded, quartz sandstone, 1% bluish green shale, 1% glauconite	S-295	
-699.59’	1490’			1487-1492: **Gasconade Dolomite** 99% light gray, medium grained, dolomite to pitied dolomite, 1% white chert	S-296	
-704.59’	1495’			1492-1497: 100% light gray to buff, fine grained, dolomite	S-297	
-709.59’	1500’			1497-1502: 100% gray, fine to medium grained, dolomite	S-298	
-714.59’	1505’			1502-1507: 100% gray, fine to medium grained, dolomite	S-299	
-719.59’	1510’			1507-1512: 99% gray to buff, fine to medium grained, dolomite, 1% greenish blue shale	S-300	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-724.59’	1515’			1512-1517: 100% gray, fine to medium grained, dolomite	S-301	
-729.59’	1520’			1517-1522: 100% light gray to gray, fine to medium grained, dolomite	S-302	
-734.59’	1525’			1522-1527: 100% light gray to gray, fine to medium grained, dolomite	S-303	
-739.59’	1530’			1527-1532: 100% light gray, fine to medium grained, dolomite	S-304	
-744.59’	1535’			1532-1537: 99% light gray, fine grained, dolomite to sandy dolomite, 1% bluish green shale	S-305	
-749.59’	1540’			1537-1542: 98% light gray to dark gray, fine grained, dolomite, 1% white to gray, 1% pyrite and calcite	S-306	
-754.59’	1545’			1542-1547: 99% light gray, medium grained, dolomite to sandy dolomite, 1% bluish green shale	S-307	
-759.59’	1550’			1547-1552: 100% light gray, fine to medium grained, dolomite	S-308	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-764.59’	1555’			1552-1557: 99% Dark gray, medium grained, dolomite, 1% bluish green shale	S-309	
-769.59’	1560’			1557-1562: **Gasconade Dolomite: Gunter Sandstone Member** 90% tan to buff, fine grained, rounded, calcite cemented quartz sandstone, 9% tan to buff, medium grained, dolomite , 1% bluish green shale	S-310	
-774.59’	1565’			1562-1567: 90% tan to buff, fine grained, rounded, calcite cemented quartz sand, 9% tan to buff, medium grained, dolomite , 1% bluish green shale	S-311	
-779.59’	1570’			1567-1572: 94% light gray, fine grained, dolomite, 3% tan to buff, fine grained rounded, calcite cemented quartz sand, 3% bluish green shale	S-312	
-784.59’	1575’			1572-1577: 50% tan to buff, fine grained, rounded, calcite cemented quartz sand, 47% tan to buff, medium grained, dolomite , 3% bluish green shale	S-313	
-789.59’	1580’			1577-1582: **Eminence Dolomite** 97% light gray, fine grained, sandy textured dolomite, 3% bluish green shale	S-314	
-794.59’	1585’			1582-1587: 99% light gray to buff, fine grained, sandy textured dolomite, 1% tan to buff, fine grained, rounded, calcite cemented quartz sand, bluish green shale, white chert	S-315	
-799.59’	1590’			1587-1592: 99% light gray, fine grained, dolomite, 1% bluish green shale	S-316	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-804.59’	1595’			1592-1597: 99% brownish gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale	S-317	
-809.59’	1600’			1597-1602: 99% brownish gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale	S-318	
-814.59’	1605’			1602-1607: 99% brownish gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale	S-319	
-819.59’	1610’			1607-1612: 99% light gray, fine to medium grained, dolomite, 1% bluish green shale	S-320	
-824.59’	1615’			1612-1617: 99% brownish gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale	S-321	
-829.59’	1620’			1617-1622: 96% light gray to brownish gray to dark gray, fine to medium grained, dolomite, 3% white, fine grained, well rounded, quartz sand, 1% bluish green shale	S-322	
-834.59’	1625’			1622-1627: 99% light gray to brownish gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale, white chert	S-323	
-839.59’	1630’			1627-1632: 99% light gray to brownish gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale, white chert	S-324	

Notes/Comments:

Elevation	**Depth**	**Formation**	**Member**	**Lithologic Description**	**Samples Interval**	**Comments**
-844.59’	1635’			1632-1637: 99% light gray to brownish gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale	S-325	
-849.59’	1640’			1637-1642: 99% light gray, fine to medium grained, dolomite, 1% bluish green shale, white to light gray chert	S-326	
-854.59’	1645’			1642-1647: 99% light gray to brownish gray, to dark gray, fine to medium grained, dolomite, 1% bluish green shale, white to light gray chert	S-327	
-859.59’	1650’			1647-1652: 99% light gray to brownish gray, to dark gray, fine to medium grained, dolomite, 1% bluish green shale, white to light gray chert	S-328	
-864.59’	1655’			1652-1657: 99% light gray to brownish gray, to dark gray, fine to medium grained, dolomite, 1% bluish green shale, white to light gray chert	S-329	
-869.59’	1660’			1657-1662: 99% light gray to brownish gray, to dark gray, fine to medium grained, dolomite, 1% bluish green shale, white to light gray chert	S-330	
-874.59’	1665’			1662-1667: 99% light gray to brownish gray, to dark gray, fine to medium grained, dolomite, 1% bluish green shale, white to light gray chert	S-331	
-879.59’	1670’			1667-1672: 99% light gray to brownish gray, to dark gray, fine to medium grained, dolomite, 1% bluish green shale, white to light gray chert • Peppered iron staining	S-332	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-884.59’	1675’			1672-1677: 99% light brownish gray, medium grained, dolomite, 1% bluish green shale, white to light gray chert	S-333	
-889.59’	1680’			1677-1682: 99% light gray to brownish gray, to dark gray, fine to medium grained, dolomite, 1% bluish green shale	S-334	
-894.59’	1685’			1682-1687: 99% light gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale	S-335	
-899.59’	1690’			1687-1692: 99% light gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale	S-336	
-904.59’	1695’			1692-1697: 99% light gray to dark gray, medium grained, dolomite, 1% bluish green shale	S-337	
-909.59’	1700’			1697-1702: 99% light gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale	S-338	
-914.59’	1705’			1702-1707: 99% light gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale, white to light gray chert	S-339	
-919.59’	1710’			1707-1712: 97% light gray to dark gray, fine to medium grained, dolomite, 2% bluish green shale, 1% white to light gray chert	S-340	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-924.59’	1715’			1712-1717: 97% light gray to dark gray, fine to medium grained, dolomite, 2% bluish green shale, 1% white to light gray chert, pyrite	S-341	
-829.59’	1720’			1717-1722: **Potosi** 99% light gray to dark gray, fine grained, dolomite, 1% bluish green shale, white to light gray chert	S-342	
-834.59’	1725’			1722-1727: 99% light gray to dark gray, fine grained, dolomite, 1% bluish green shale, white to light gray chert	S-343	
-839.59’	1730’			1727-1732: 99% light gray, fine grained, dolomite, 1% bluish green shale, white to light gray chert,	S-344	
-944.59’	1735’			1732-1737: 99% light gray, fine grained, dolomite, 1% bluish green shale, white to light gray chert	S-345	
-949.59’	1740’			1737-1742: 99% light gray to dark gray, fine grained, dolomite, 1% bluish green shale, white to light gray chert	S-346	
-954.59’	1745’			1742-1747: 99% light gray to gray, fine grained, dolomite, 1% bluish green shale, white to light gray chert	S-347	
-959.59’	1750’			1747-1752: 100% light gray to dark gray, fine grained, dolomite	S-348	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-964.59’	1755’			1752-1757: 100% light gray to gray, fine grained, dolomite	S-349	
-969.59’	1760’			1757-1762: 100% light gray to gray, fine grained, dolomite	S-350	
-974.59’	1765’			1762-1767: 99% light gray, fine grained, dolomite, 1% black shale	S-351	
-979.59’	1770’			1767-1772: 99% light gray, fine grained, dolomite, 1% black shale	S-352	
-984.59’	1775’			1772-1777: 98% light gray, fine grained, dolomite, 2% bluish green to black shale	S-353	
-989.59’	1780’			1777-1782: 97% light gray to gray, fine grained, dolomite, 2% bluish green	S-354	
-994.59’	1785’			1782-1787: 98% light gray to gray, fine grained, dolomite, 1% bluish green, 1% white to gray chert, pyrite ● Peppered with iron staining	S-355	
-999.59’	1790’			1787-1792: 99% light gray to dark gray, fine grained, dolomite, 1% bluish green, white chert	S-356	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1004.59’	1795’			1792-1797: 100% light gray to gray, fine to medium grained, dolomite	S-357	
-1009.59’	1800’			1797-1802: **Derby-Doe Run** 96% light gray to brownish gray to dark gray, fine to medium grained, dolomite, 3% bluish green shale, 1% white chert	S-358	
-1014.59’	1805’			1802-1807: 99% light gray to brownish gray to dark gray, fine to medium grained, dolomite, 1% bluish green shale	S-359	
-1019.59’	1810’			1807-1812: 100% light gray to brownish gray to dark gray, fine to medium grained, dolomite	S-360	
-1024.59’	1815’			1812-1817: 100% light gray to brownish gray to dark gray, fine to medium grained, dolomite	S-36	
-1029.59’	1820’			1817-1822: 100% brownish gray to dark gray, medium to coarse grained, dolomite	S-362	
-1034.59’	1825’			1822-1827: 100% light gray to brownish gray to dark gray, medium to coarse grained, dolomite	S-363	
-1039.59’	1830’			1827-1832: **Lower Derby-Doe Run** 100% light gray, medium grained, dolomite peppered with glauconite	S-364	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1044.59’	1835’			1832-1837: 100% light gray, medium grained, dolomite to peppered glauconitic dolomite	S-365	
-1049.59’	1840’			1837-1842: 100% light gray, medium grained, dolomite to peppered glauconitic dolomite	S-366	
-1054.59’	1845’			1842-1847: 100% light gray, medium grained, dolomite to peppered glauconitic dolomite	S-367	
-1059.59’	1850’			1847-1852: 100% light gray, medium grained, dolomite to peppered glauconitic dolomite	S-368	
-1064.59’	1855’			1852-1857: 100% light gray, medium grained, dolomite to peppered glauconitic dolomite	S-369	
-1069.59’	1860’			1857-1862: 99% light gray to brownish gray, medium grained, dolomite to peppered glauconitic dolomite, 1% pyrite ● Slightly peppered with iron staining	S-370	
-1074.59’	1865’			1862-1867: 100% light gray to brownish gray, medium grained, dolomite to peppered glauconitic dolomite,	S-371	
-1079.59’	1870’			1867-1872: 100% light gray to brownish gray to dark gray, medium to coarse grained, dolomite to peppered glauconitic dolomite	S-372	

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Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1084.59’	1875’			1872-1877: 100% light gray, medium to coarse grained, dolomite to slightly glauconitic dolomite	S-373	
-1089.59’	1880’			1877-1882: 100% light gray to dark gray, fine grained, dolomite to slightly glauconitic dolomite	S-374	
-1094.59’	1885’			1882-1887: 100% light gray to dark gray, fine to medium grained, dolomite to slightly glauconitic dolomite	S-375	
-1099.59’	1890’			1887-1892: 100% light gray to gray, fine to medium grained, dolomite to slightly glauconitic dolomite	S-376	
-1104.59’	1895’			1892-1897: 100% light gray to gray, fine to medium grained, dolomite to slightly glauconitic dolomite	S-377	
-1109.59’	1900’			1897-1902: 100% light gray to gray, fine to medium grained, dolomite to slightly glauconitic dolomite	S-378	
-1114.59’	1905’			1902-1907: 100% light gray to gray, fine to medium grained, dolomite to slightly glauconitic dolomite	S-379	
-1119.59’	1910’			1907-1912: 100% light gray, to brownish gray, fine to medium grained, dolomite	S-380	

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1124.59'	1915'			1912-1917: 100% light gray to brownish gray, fine to medium grained, dolomite	S-381	
-1129.59'	1920'			1917-1922: 98% light gray to brownish gray, fine to medium grained, dolomite, 2% bluish green shale	S-382	
-1134.59'	1925'			1922-1927: 98% light gray to brownish gray, fine to medium grained, dolomite, 2% bluish green shale	S-383	
-1139.59'	1930'			1927-1932: 100% light gray to brownish gray to dark gray, fine to medium grained, dolomite	S-384	
-1144.59'	1935'			1932-1937: 100% light gray to brownish gray, medium grained, dolomite	S-385	
-1149.59'	1940'			1937-1942: 100% light gray to brownish gray, medium grained, dolomite	S-386	
-1154.59'	1945'			1942-1947: **Davis** 100% light gray to brownish gray, fine grained to medium grained, limestone	S-387	
-1159.59'	1950'			1947-1952: 100% light gray to brownish gray, fine grained to medium grained, limestone	S-388	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				End of Cuttings		
-1164.59’	1955’			1952-1957: Light gray, fine to medium grained, limestone, inter-bedded with dark gray calcareous shale	Box 1 Run 1 Run2	
-1169.59’ -1174.59’	1960’ 1965’			1957-1958.15: Light gray, fine to medium grained, limestone, inter-bedded with dark gray calcareous shale 1958.15 to 1961.1: Light gray, medium grained limestone, with irregularly rounded greenish gray, fine grained, limestone intraclast 1961.1-1967: Light gray, medium grained, oolitic limestone, with irregularly rounded greenish gray, fine grained, limestone intraclast	Run 3 Box 1 Box 2	
-1179.59’ -1184.59’	1970’ 1975’			1967-1977: Light gray, medium grained, oolitic limestone, with irregularly rounded greenish gray to olive gray, fine grained, limestone intraclast • 1970.3-1970.3: calcite filled vug • 1973.6-1976.3: 90 degree fracture	Run 4 Box 2 Box 3	
-1189.59’ -1194.59’	1980’ 1985’			1977-1979.6: Light gray, medium grained, oolitic limestone 1979.6-1982.7: Light gray, fine grained, limestone, with greenish gray to olive gray, fine grained, limestone intraclast 1982.7-1983.3: Light gray, fine grained, limestone, interbedded with thin beds (.1 thru.5 cm) dark gray calcareous shale 1983.3-1984.8: Light gray, fine grained, limestone, with greenish gray to olive gray, fine grained, limestone intraclast	Run 5 Box 3 Box 4	1984.8-1985.65: Light gray, fine grained, limestone, interbedded with thin beds (.1 thru.5 cm) dark gray calcareous shale 1985.65-1986.2: Light gray, fine grained, limestone, with greenish gray to olive gray, fine grained, limestone intraclast 1986.2 1987: Olive gray to dark gray, thick bedded calcareous shale • Stylolite's throughout • 1977-1987.45: 90 degree fracture, calcite crystals fill the fracture
-1199.59’	1990’			1987-1988.8: Olive gray to dark gray, thick bedded shale 1988.8-1989: Olive gray to dark gray, thick bedded shale with irregularly rounded to rounded light gray, fine grained, limestone intraclast	Run 6 Box 4 Box 5	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1204.59’	1995’			1989-1994.5 : Olive gray to dark gray, thick bedded calcareous shale 1994.5-1996.1: Light gray, fine to medium grained limestone, intrabedded with thin beds (.1 cm) of olive gray to dark gray shale 1996.1-1997: Olive gray to dark gray, thick bedded calcareous shale		
-1209.59’ -1214.59’	2000’ 2005’			1997-1997.65: Light gray, fine to medium grained, limestone with light gray, fine grained, limestone intraclast (1997.60-1997.65: intraclast with brachiopods) 1997.65-1998.6: Olive gray to dark gray, thick bedded calcareous shale 1998.6-2000.3: Light gray, fine to medium grained, limestone with light gray, fine grained, limestone intraclast, thin beds (.1 cm) olive gray to dark gray calcareous shale 2000.3-2001.6: Olive gray to dark gray, thick bedded calcareous shale, with light gray, fine grained, limestone intraclast	Run 7 Box 5 Box 6	2001.6-2003.1 Light gray, fine to medium grained, limestone with light gray, fine grained, limestone intraclast, thin beds (.1 to 2cm) olive gray to dark gray calcareous shale 2003.1-2005.5 Olive gray to dark gray, thick bedded calcareous shale, with light gray, fine grained, limestone intraclast 2005.5-2007 Light gray, fine to medium grained, limestone with light gray, fine grained, limestone intraclast, thin beds (.1 to 2cm) olive gray to dark gray calcareous shale (2005.75-2005.95: edge wise conglomerate
-1219.59’ -1224.59’	2010’ 2015’			2007-2008.9: Light gray, fine to medium grained, limestone with light gray, fine grained, limestone intraclast, thin beds (.1 to .5 cm) olive gray to dark gray calcareous shale 2008.9-2009.2: Light gray, fine grained to medium grained limestone with greenish gray, fine grained limestone and reddish brown siltstone intraclast. 2009.2-2009.7: Light gray, fine to medium grained, limestone with light gray, fine grained, limestone intraclast, thin beds (.1 to .5 cm) olive gray to dark gray calcareous shale 2009.7-2011.5 : Greenish gray, fine grained, peppered glauconitic sandstone, with light gray fine grained, limestone intraclast	Run 8 Box 6 Box 7	2011.5-2014.4: Greenish gray, fine grained, peppered glauconitic sandstone, with light gray fine grained, limestone intraclast, thin beds (.1 to.2cm) olive gray to dark gray calcareous shale 2014.4-2016.3: Light gray, fine to medium grained, limestone, with greenish gray to tan, fine grained, limestone intraclast incased in reddish brown siltstone. (Edgewise conglomerate) 2016.3-2017: Light gray fine grained, peppered glauconitic sandstone with interbedded with thin layers (.1 to 2 cm) olive gray to dark gray calcareous shale
-1229.59’ -1234.59’	2020’ 2025’			2017-2017.6: Light gray , fine to medium grained, limestone with light gray, fine grained limestone intraclast, interbedded with thin layer of olive gray to dark gray shale 2017.6-2019.8: Olive gray to dark gray, thick bedded shale, interbedded light gray, fine grained, limestone 2019.8-2027: Greenish gray, fine grained, peppered glauconitic sandstone, with light gray fine grained, limestone intraclast, thin beds (.1 to.2cm) olive gray to dark gray calcareous shale	Run 9 Box 7 Box 8	
-1239.59’	2030’			2027-2037: Greenish gray, fine grained, peppered glauconitic sandstone, with light gray fine grained, limestone intraclast (some intraclast incased in reddish brown siltstone), thin beds (.1 to.2cm) olive gray to dark gray calcareous shale	Run 10 Box 8 Box 9	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1244.59’	2035’					
-1249.59’ -1254.59’	2040’ 2045’			1237-1247: Greenish gray, fine grained, peppered glauconitic sandstone, laminated • 2037.8-2038.1: 90 degree fracture • 2040.5– 2040.9 90 degree fracture	Run 11 Box 9 Box 10	
-1259.59’ -1264.59’	2050’ 2055’			2047-2051.2: Brownish gray to tan, fine grained, peppered glauconitic sandstone interbedded dark greenish gray, fine grained, peppered glauconitic sandstone 2051.2-2057: Dark greenish gray, fine grained, peppered glauconitic sandstone • 2053.5-2054.9 90 degree fracture	Run 12 Box 10 Box 11	
-1269.59’ -1274.59’	2060’ 2065’			2057-2065.3: Brownish gray to tan, fine grained, peppered glauconitic sandstone interbedded dark greenish gray, fine grained, peppered glauconitic sandstone 2065.3-2067: Light gray to dark greenish gray fine grained, peppered glauconitic sandstone, with light gray, fine grained, limestone intraclast	Run 13 Box 11 Box 12	
-1279.59’	2070’			2067-2069.5: Light gray to dark greenish gray fine grained, peppered glauconitic sandstone, with light gray, fine grained, limestone intraclast	Run 14 Box 12 Box 13 Box 14	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1284.59’	2075’			2069.5-2071.2: Olive gray to dark gray, calcareous shale, interbedded with light gray fine grained limestone 2071.2-2071.5: Brownish gray to tan, fine grained, peppered glauconitic sandstone 2071.5-2072.5: Olive gray to dark gray, calcareous shale		2072.5-2077: light gray, fine grained glauconitic limestone interbedded with thin beds (.1 cm) of olive gray to dark gray shale
-1289.59’ -1294.59’	2080’ 2085’			2077-2078.2: light gray, fine grained glauconitic limestone interbedded with thin beds (.1 cm) of olive gray to dark gray shale 2078.2-2078.9: light gray, fine grained glauconitic limestone with fine gained limestone intraclast 2078.9-2079.4: light gray, fine grained glauconitic limestone interbedded with thin beds (.1 cm) of olive gray to dark gray shale 2079.4-2079.7: light gray, fine grained glauconitic limestone with fine gained limestone intraclast	Run 15 Box 14 Box 15	2079.7-2080.4: light gray, fine grained glauconitic limestone interbedded with thin beds (.1 cm) of olive gray to dark gray shale 2080.4-2002.5: light gray, fine grained glauconitic limestone with fine gained limestone intraclast with olive gray to dark gray shale 2082.5-2083: light gray, fine grained glauconitic limestone interbedded with thin beds (.1 cm) of olive gray to dark gray shale 2083-2084.1: Light gray, medium grained, oolitic limestone, with stylites 2084.1-2087: Light gray, fine grained, oolitic limestone, with stylites
-1299.59’ -1304.59’	2090’ 2095’			2087-2097: **Bonneterre Formation** Light gray, fine grained, oolitic limestone, with styolites	Run 16 Box 15 Box 16	
-1309.59’ -1314.59’	2100’ 2105’			2097-2107: Light gray, fine grained, peppering with glauconite, oolitic limestone, with styolites ● 2104.7-2105.5: 90 degree fractures with calcite filled vugs	Run 17 Box 16 Box 17	
-1319.59’	2110’			2107-2117: Light gray, fine grained, peppering with glauconite, oolitic limestone, with styolites	Run 18 Box 17 Box 18	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1324.59'	2115'					
				2117-2127: Light gray, fine grained, peppering with glauconite, oolitic limestone, with styolites	Run 19 Box 18 Box 19	
-1329.59'	2120'					
-1334.59'	2125'					
				2127-2128.1: Light gray, fine grained, peppering with glauconite, oolitic limestone, with styolites 2128.1-2128.6: Light gray fine to medium grained, peppered glauconitic limestone 2128.6-2129.3: Light gray, fine to medium grained, limestone 2129.3-2129.4: Light gray fine to medium grained, fossiliferious limestone 2129.4-2137: Light gray, fine grained, peppering with glauconite, oolitic limestone, with styolites	Run 20 Box 19 Box 20	
-1339.59'	2130'					
-1344.59'	2135'					
				2137-2138.7: Light gray, fine grained, peppering with glauconite, oolitic limestone, with stylolites 2138.7-2142.2: Light gray, fine grained to medium grained, peppered glauconitic limestone (fracture planes 45 degrees, fractures filled with calcite crystals, slicken lines) 2142.2-2147: Light gray, fine to medium grained, oolitic limestone with stylolites	Run 21 Box 20 Box 21	
-1349.59'	2140'					
-1354.59'	2145'					
				2147-2150.5: Light gray, fine to medium grained, oolitic limestone with stylolites 2150.5-2153.9: Light gray, fine grained to medium grained, peppered glauconitic limestone with styolites (fracture planes 45 degrees, fractures filled with calcite crystals, slicken lines)	Run 22 Box 21 Box 22	
-1359.59'	2150'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1364.59’	2155’			2153.9-2157: Light gray, fine to medium grained, oolitic limestone to limestone. (fracture planes 45 degrees, fractures filled with calcite crystals, slicken lines)		
-1369.59’ -1374.59’	2160’ 2165’			2157-2157.8: Light gray, fine to medium grained, oolitic limestone to limestone. (fracture planes 45 degrees, fractures filled with calcite crystals, slicken lines) 2157.8-2162.4: Light gray, fine to medium grained, peppered glauconitic limestone 2162.4-2167: Light gray, fine to medium grained limestone • 2157-2167: Stylolites	Run 23 Box 22 Box 23	
-1379.59’ -1384.59’	2170’ 2175’			2167-2173.9: Light gray, fine to medium grained oolitic limestone with stylolites (2171.97-2173.9: vuggy zone) 2173.9-2176.1: Greenish gray, fine grained, peppered glauconitic sandstone 2176.1-2176.7: Light gray, fine to medium grained, peppered glauconitic limestone with stylolites 2176.65-2177: Light gray, fine to medium grained oolitic limestone with stylolites	Run 24 Box 23 Box 24	
-1389.59’ -1394.59’	2180’ 2185’			2177-2187: Alternating beds from light gray, fine to medium grained glauconitic limestone with styolites to a greenish gray, fine grained glauconitic sandstone • Fractures have slickenlines	Run 25 Box 24 Box 25	
-1399.59’	2190’			2187-2188.2: Alternating beds from light gray, fine to medium grained glauconitic limestone with styolites to a greenish gray, fine grained glauconitic sandstone 2188.2-2189.1: Light gray , fine to medium grained limestone with limestone intraclast, periods of glauconitic peppering and oolitic limestone	Run 26 Box 25 Box 26	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1404.59’	2195’			2194.6-2194.8: Light gray, fine grained, limestone to carbonate mud 2194.8-2197: Gray to brown, fine to medium grained, oolitic limestone • 2197-2207: styolites		
-1409.59’ -1414.59’	2200’ 2205’			2197-2198.2: Gray to brown, fine to medium grained, oolitic limy dolomite 2198.2-2201.5: Gray to brownish gray, fine to medium grained oolitic limestone to peppered with glauconitic and thin layers of carbonate mud 2201.5-2207: Dark gray, fine grained, glauconitic dolomite • 2197-2207: styolites	Run 27 Box 26 Box 27	
-1419.59’ -1424.59’	2210’ 2215’			2207-2213: Alternating from light gray to gray, fine to medium grained oolitic limey dolomite to light gray, fine to medium grained glauconitic limey dolomite 2213-2217: Gray to brownish gray, fine to medium grained, oolitic dolomite with pitting • 2207-2217: styolites	Run 28 Box 27 Box 28	
-1429.59’ -1434.59’	2220’ 2225’			2217-2220: Gray, fine grained, dolomite 2220-2227: Light gray, medium grained, peppered glauconitic dolomite to limy dolomite with greenish gray to dark gray shale laminations	Run 29 Box 28 Box 29	
-1439.59’	2230’			2227-2237: Light gray to light brown, fine to medium grained, glauconitic dolomite with greenish gray to dark gray shale laminations	Run 30 Box 29 Box 30	

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Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1444.59’	2235’					
				2237-2247: Light brown to light gray, fine to medium grained, glauconitic dolomite to dolomite with draping greenish gray to dark gray shale laminations	Run 31 Box 30 Box 31	
-1449.59’	2240’					
-1454.59’	2245’					
				2247-2257: Light brown to light gray, fine to medium grained, glauconitic dolomite to dolomite with draping greenish gray to dark gray shale laminations	Run 32 Box 31 Box 32	
-1459.59’	2250’					
-1464.59’	2255’					
				2257-2267: Light brown to light gray, fine to medium grained, glauconitic dolomite to dolomite with draping greenish gray to dark gray shale laminations	Run 33 Box 32 Box 33	
-1469.59’	2260’					
-1474.59’	2265’					
				2267-2277: Light brown to light gray, fine to medium grained, glauconitic dolomite to dolomite with draping greenish gray to dark gray thin beds (.1 to .4 cm) shale to sandy shale, laminations	Run 34 Box 33 Box 34 Box 35	
-1479.59’	2270’					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project

Site: Thomas Hill Energy Center

Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1484.59’	2275’					
				2277-2287: Light brown to reddish brown, fine to medium grained, dolomite to limy dolomite, conglomeratic and vugs in some intervals with thin beds (.1 to .4cm) olive gray to dark gray shale	Run 35 Box 35 Box 36	
-1489.59’	2280’					
-1494.59’	2285’					
				2287-2297: Tan to brownish gray, fine to medium grain, sandy dolomite to dolomite, with thin beds (.1 to .2cm) dark gray shale ● 2290.0-2290.3 red granite clast	Run 36 Box 36 Box 37	
-1499.59’	2290’					
-1504.59’	2295’					
				2297-2299.1: Gray, fine grained, glauconitic dolomite to dolomite with dark gray shale laminations 2299.1-2307 Dark brown to dark gray, silty dolomite to mudstone with dark brown yellow iron oxide streaking and specks ● 2299.1-2297.4 red granite clast	Run 37 Box 37 Box 38	
-1509.59’	2300’					
-1514.59’	2305’					
				2307-2310: Dark brown to dark gray, silty dolomite to mudstone with dark brown yellow iron oxide streaking and specks	Run 38 Box 38 Box 39	
-1519.59’	2310’			2310-2315: Green, fine grained, glauconitic sandstone to siltstone		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1524.59'	2315'			2315-2317: Light gray, fine grained to medium grained, dolomite to sandy dolomite		
-1529.59' -1534.59'	2320' 2325'			2317-2318.5: Conglomerate, clast green, fine grained, glauconitic sandstone to siltstone, matrix light gray, fine grained, dolomite 2318.5-2327: Light gray, fine grained, dolomite with olive gray, draping shale, interlaminated	Run 39 Box 39 Box 40	
-1539.59'	2330'			2327-2333.6: Gray, fine grained, sandy glauconitic dolomite, with olive gray draping shale, interlaminated	Run 40 Box 40 Box 41	
-1544.59'	2335'			2333.6-2337: **Lamotte Sandstone** White, fine to coarse grained, quartz sandstone, interbedded with olive green to dark green shale		
-1549.59' -1554.59'	2340' 2345'			2337-2347: Light brown to tan, fine grained, sub-rounded to sub-angular, friable, quartz sandstone	Run 41 Box 41 Box 42	
-1559.59'	2350'			2347-2357: White to tan, fine grained to coarse grained, rounded to subrounded, friable, quartz sandstone, clay partings	Run 42 Box 42 Box 43	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1564.59’	2355’					
				2357-2367: Light brown to tan, fine grained to coarse grained, rounded to sub-rounded, friable, quartz sandstone, some clay partings	Run 43 Box 43 Box 44	
-1569.59’	2360’					
-1574.59’	2365’					
				2367-2377: Light brown to tan, fine grained to coarse grained, rounded to sub-rounded, friable, quartz sandstone, some clay partings • Shearing and healing	Run 44 Box 44 Box 45	
-1579.59’	2370’					
-1584.59’	2375’					
				2377-2387: Light brown to tan, fine grained to coarse grained, rounded to sub-rounded, friable, quartz sandstone, some clay partings	Run 45 Box 45 Box 46	
-1589.59’	2380’					
-1594.59’	2385’					
				2387-2397: Light brown, fine grained to coarse grained, subangular to subrounded, quartz sandstone	Run 46 Box 46 Box 47	
-1599.59’	2390’					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1604.59’	2395’					
				2397-2407: Light brown to tan, fine grained to coarse grained, subangular to subrounded, quartz sandstone	<u>Run 47</u> Box 48 Box 49	
-1609.59’	2400’					
-1614.59’	2405’					
				2407-2417: White to gray to light brown, fine to coarse grained, angular to subangular, quartz sandstone, non friable to weakly friable • 2412-2417: Abundant fractures	<u>Run 48</u> Box 49 Box 50	
-1619.59’	2410’					
-1624.59’	2415’					
				2417-2427: White to gray to light brown, medium grained, angular to subangular, quartz sandstone, weakly friable, frosted grains • 2417-2427: fractures healed with calcite, some vugs with large quartz crystals • 2422-2427 abundant fracturing	<u>Run 49</u> Box 50 Box 51	
-1629.59’	2420’					
-1634.59’	2425’					
				2427-2437: Light brown to tan, fine grained to coarse grained, subangular to subrounded, quartz sandstone • Mildly arkosic/iron oxide, moderately fractured, fractures healed with calcite and marcasite	<u>Run 50</u> Box 51 Box 52	
-1639.59’	2430’					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Thomas Hill Energy Center
Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1644.59’	2435’					
				2437-2447 : White, fine to coarse grained, angular to subrounded, cross bedding, quartz sandstone weakly friable to friable • Moderately fractured	Run 51 Box 52 Box 53	
-1649.59’	2440’					
-1654.59’	2445’					
				2447-2452: White gray to light brown, fine to coarse grained, angular to subrounded, quartz sandstone, weakly friable • Moderately fractured 2452– 2457: White gray to light brown, fine to coarse grained to pebbles, rounded to well rounded, quartz sandstone to quartz sandstone conglomerate, friable to weakly friable • Highly fractured	Run 52 Box 53 Box 54	
-1659.59’	2450’					
-1664.59’	2455’					
				2457-2459.5: White gray to light brown, fine to coarse grained, angular to subrounded, quartz sandstone, friable to weakly friable 2459.5-2460 : weathered granite boulder, sparkling with galena and mica	Run 53 Box 54	
-1669.59’	2460’			2460-2461.4: Weathered granite boulder 2461.4-2462.6: Green shale mixed with weathered granite and quartz sand 2462.6-2462.6-2464.8: White to gray, fine to coarse grained angular to subrounded, peoples, sandy conglomerate 2464.8-2468: Brown to tan, fine grained, rounded, quartz sandstone, weakly friable, frosted • Fracture healing	Run 54 Box 54 Box 55	
-1674.59’	2465’					
				2468-2478: Brown to tan, fine grained, rounded quartz sandstone, lenses of white to gray, fine grained, rounded, quartz, weakly friable • Pink fracture healing	Run 55 Box 55 Box 56	
-1679.59’	2470’					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1684.59’	2475’					
				2478-2487: Brown to tan, fine grained, rounded quartz sandstone, lenses of white to gray, fine grained, rounded, quartz, weakly friable • Pink fracture healing	Run 56 Box 56 Box 57	
-1689.59’	2480’					
-1694.59’	2485’					
				2487-2497: Brown to tan, fine grained, rounded quartz sandstone, lenses of white to gray, fine grained, rounded, quartz, weakly friable	Run 57 Box 57 Box 58	
-1699.59’	2490’					
-1704.59’	2495’					
				2497-2499.8: Brown to tan, fine grained, rounded to subrounded quartz sandstone, lenses of white to gray, fine grained, rounded, quartz, weakly friable 2499.8-2507: Alternating from dark red, med to coarse grained, rounded to subrounded, ferric sandstone to brownish, fine to coarse grained, rounded to subrounded sandstone, weakly friable • Slight fracturing	Run 58 Box 58 Box 69	
-1709.59’	2500’					
-1714.59’	2505’					
				2507-2517: Alternating from dark red, fine to med to coarse grained, rounded to subrounded, ferric sandstone to brownish, fine to coarse grained, rounded to subrounded sandstone, weakly friable • 2514.2-2114.3 Calcite filled vug	Run 59 Box 60 Box 61	
-1719.59’	2510’					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1724.59’	2515’					
				2517-2527: Alternating from dark red, med to coarse grained, rounded to subrounded, ferric sandstone to brownish, fine to coarse grained, rounded to subrounded sandstone, weakly friable	Run 60 Box 60 Box 61	
-1729.59’	2520’					
-1734.59’	2525’					
				2527-2534: Alternating from dark red, med to coarse grained, rounded to subrounded, ferric sandstone to brownish, fine to coarse grained, rounded to subrounded sandstone, weakly friable • 2527-2534: cross bedding 2534-2537: Light brown to tan, alternating from medium to coarse grained, subrounded, quartz sandstone to medium grained, subrounded quartz sandstone, weakly friable	Run 61 Box 61 Box 62	
-1739.59’	2530’					
-1744.59’	2535’					
				2537-2539.8: Light brown, alternating from medium to coarse grained, subrounded, quartz sandstone to fine grained, subrounded quartz sandstone	Run 62 Box 62 Box 63	
				2539.8-2547: **Pre-Cambrian Granite** Mottled red to salmon pink to bluish gray, quartz is clear to light gray in color, plagioclase, orthoclase, biotite, phaneritic weathered granite. Heavily fractured, fractures range from 29 to 65 degrees		
-1749.59’	2540’					
-1754.59’	2545’					
				2547-2557: Mottled red to salmon pink to bluish gray, quartz is clear to light gray in color, plagioclase, orthoclase, biotite, phaneritic weathered granite. Heavily fractured, fractures range from 29 to 65 degrees	Run 63 Box 63 Box 64 Box 65	
-1759.59’	2550’					

Notes/Comments:

Missouri Department of Natural Resources
Divison of Geology and Land Survey
Geological Survey Program

Page 65 of 65

Project: Shallow Carbon Sequestration Demonstration Project

Site: Thomas Hill Energy Center

Hole Exploratory Borehole #2

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-1764.59’	2555’					
				2557-2567: Mottled red to salmon pink to bluish gray, quartz is clear to light gray in color, plagioclase, orthoclase, biotite, phaneritic weathered granite. Heavily fractured, fractures range from 29 to 65 degrees	Run 64 Box 65 Box 66	
-1769.59’	2560’					
-1774.59’	2565’					
				2577-2587: Mottled red to salmon pink to bluish gray, quartz is clear to light gray in color, plagioclase, orthoclase, biotite, phaneritic weathered granite. Heavily fractured, fractures range from 29 to 65 degrees	Run 65 Box 67	
-1779.59’	2570’					
-1784.59’	2575’					
				Total Depth 2577’		
-1789.59’	2580’					
-1794.59’	2585’					
-1799.59’	2590’					

Notes/Comments:

APPENDIX 3 E DGLS-GSP EXPLORATORY BOREHOLE #2 GEOPHYSICAL LOG

ALT DGLS-GSP

CO AECI
WELL EXP #2
FLD
CTY
STE
FILING No

COMPANY	AECI		
WELL ID	MCSP-EXP #2		
FIELD	Thomas Hill		
COUNTRY		STATE	Missouri

LOCATION
39° 32' 57.9"92° 37' 32.5"

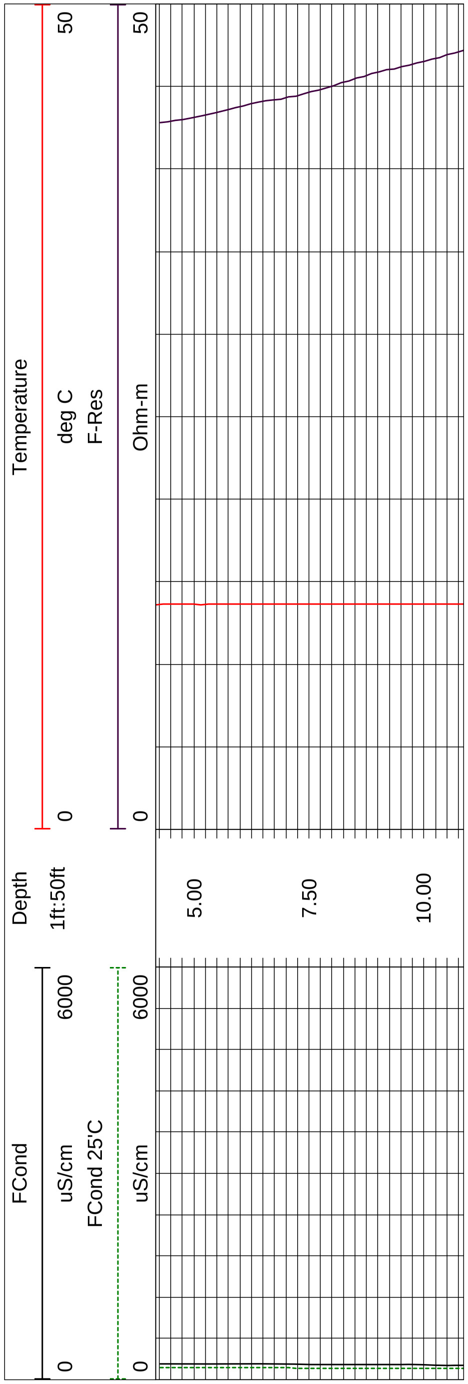
SEC 19 TWP 55N RGE 15W

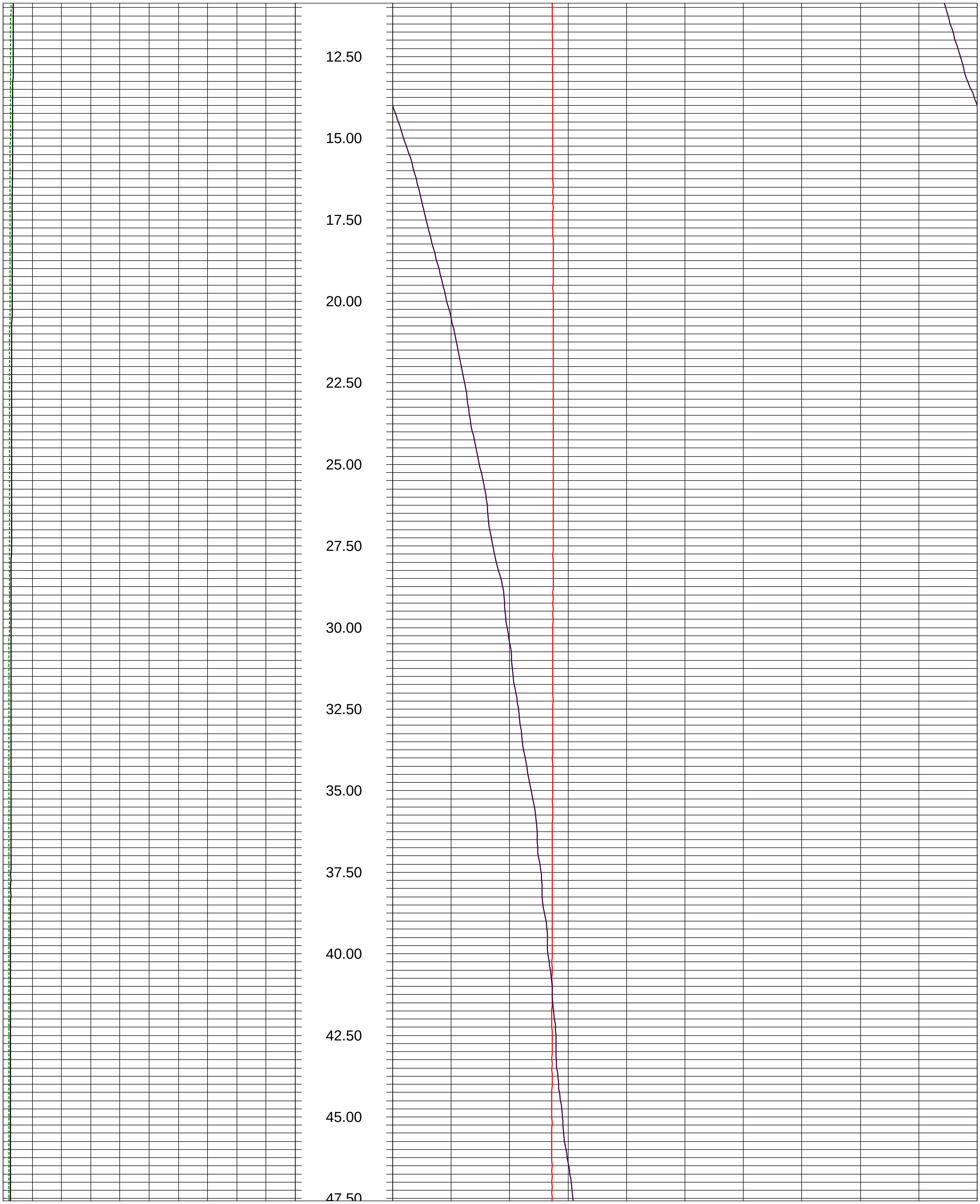
OTHER SERVICES
The tool encountered and did not penetrate drilling mud below a depth of 1138 feet.

PERMANENT DATUM	MSL	ELEVATION	790.1	K.B.
LOG MEAS. FROM	Surface	ABOVE PERM. DATUM		D.F.
DRILLING MEAS. FROM				G.L.

DATE	11-8-2012	TYPE FLUID IN HOLE	water over mud
RUN No		SALINITY	
TYPE LOG	Conductivity/Resistivity Temp	DENSITY	
DEPTH-DRILLER		LEVEL	
DEPTH-LOGGER		MAX. REC. TEMP.	
BTM LOGGED INTERVAL			
TOP LOGGED INTERVAL			
OPERATING RIG TIME			
RECORDED BY	Young		
WITNESSED BY	Price		

RUN	BOREHOLE RECORD			CASING RECORD			
NO.	BIT	FROM	TO	SIZE	WGT.	FROM	TO

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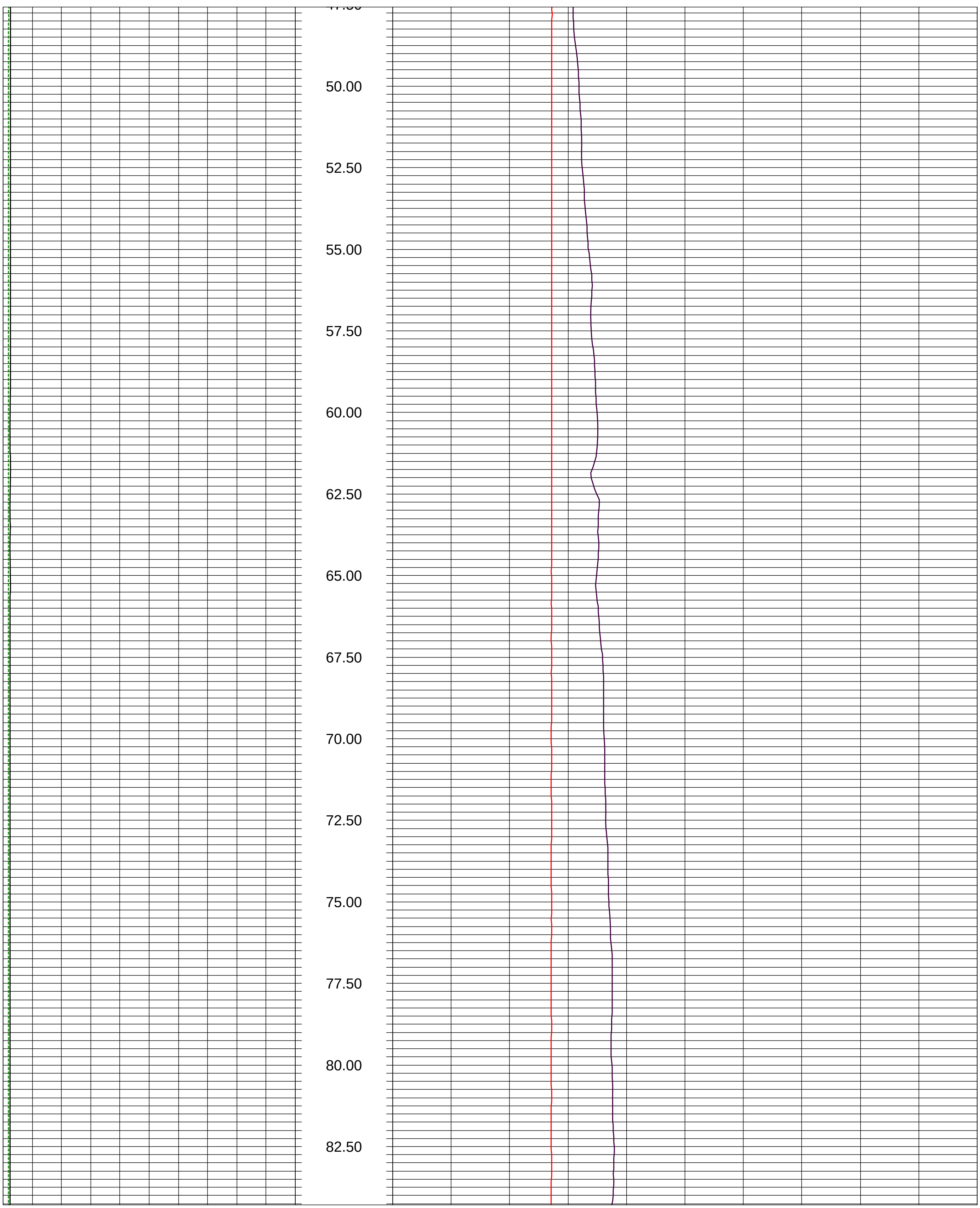
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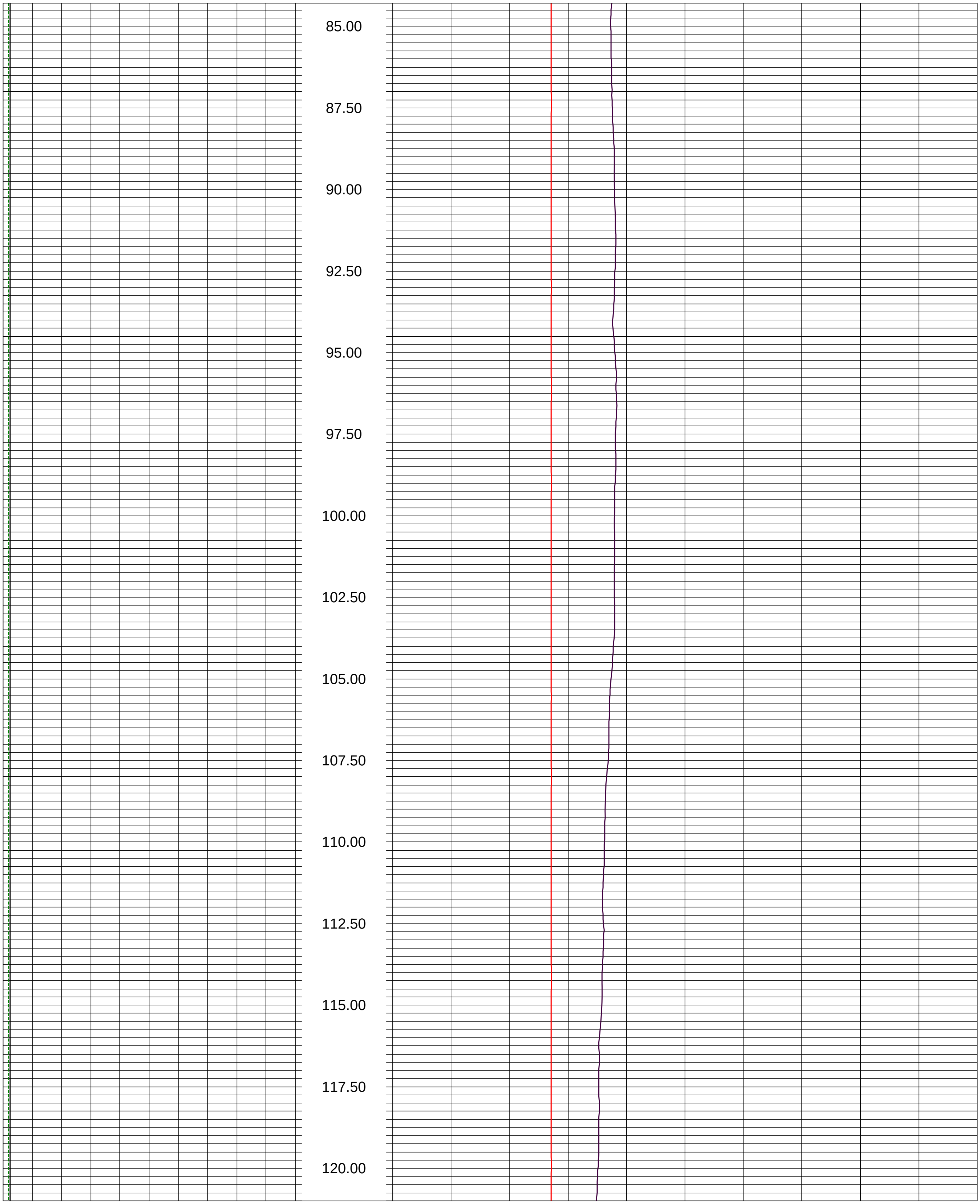
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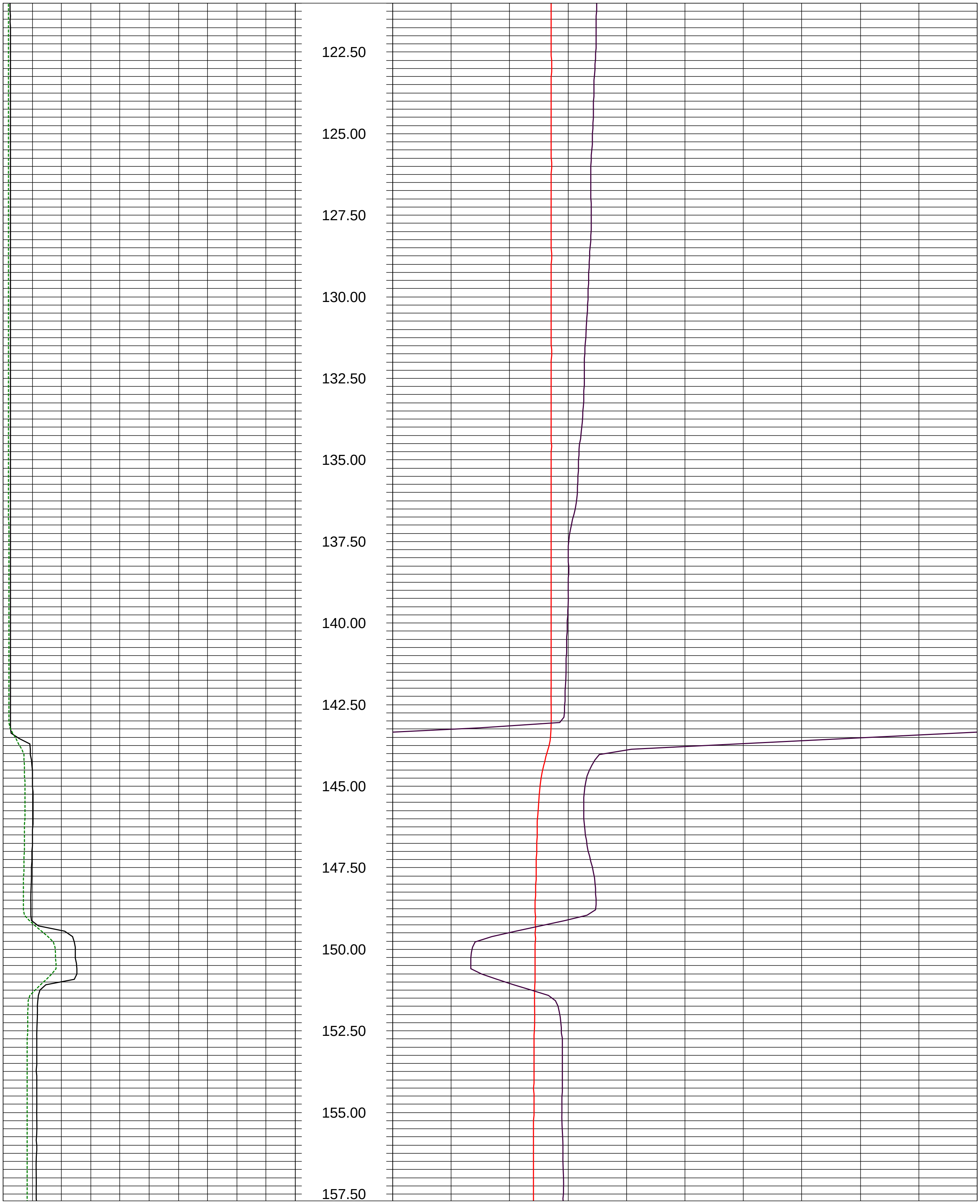
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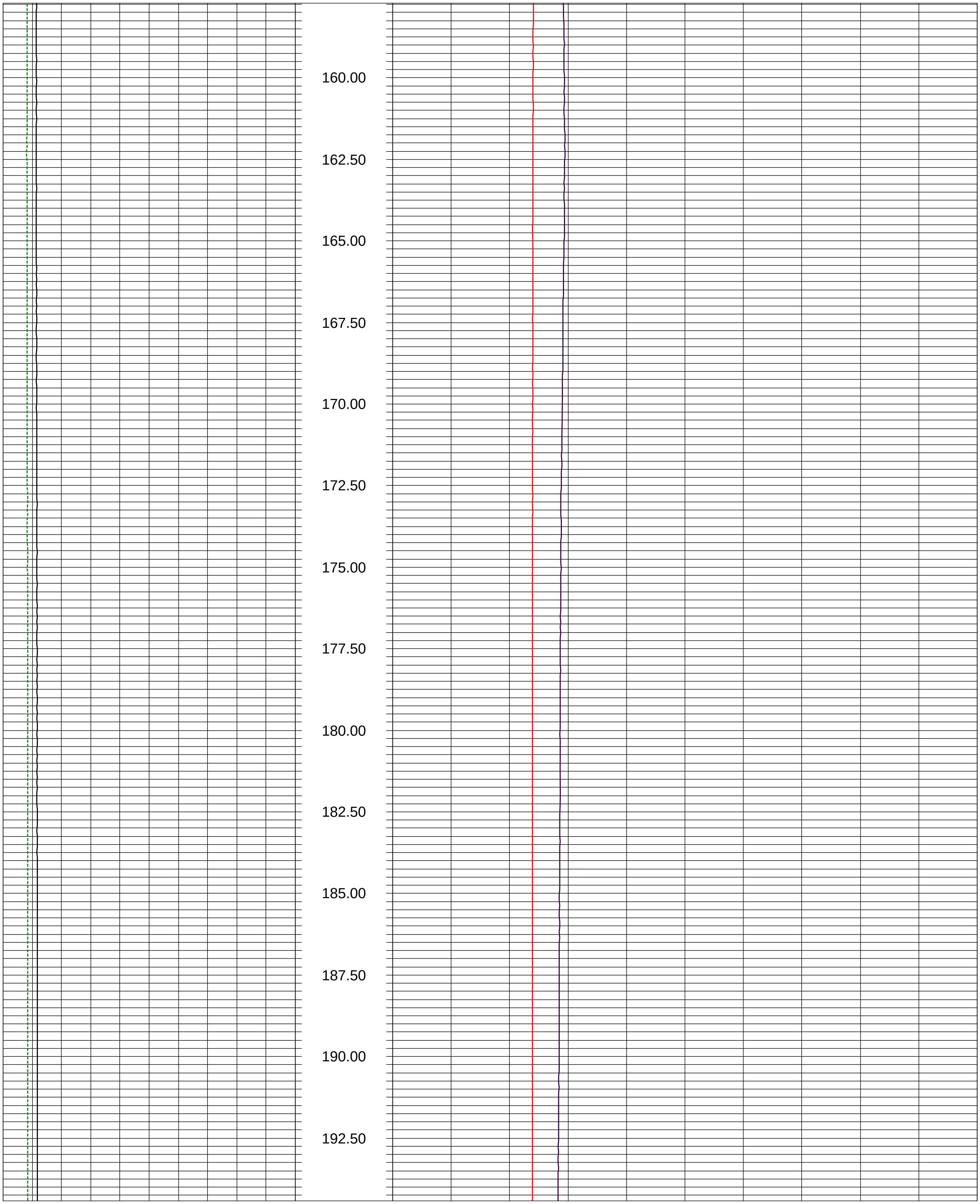
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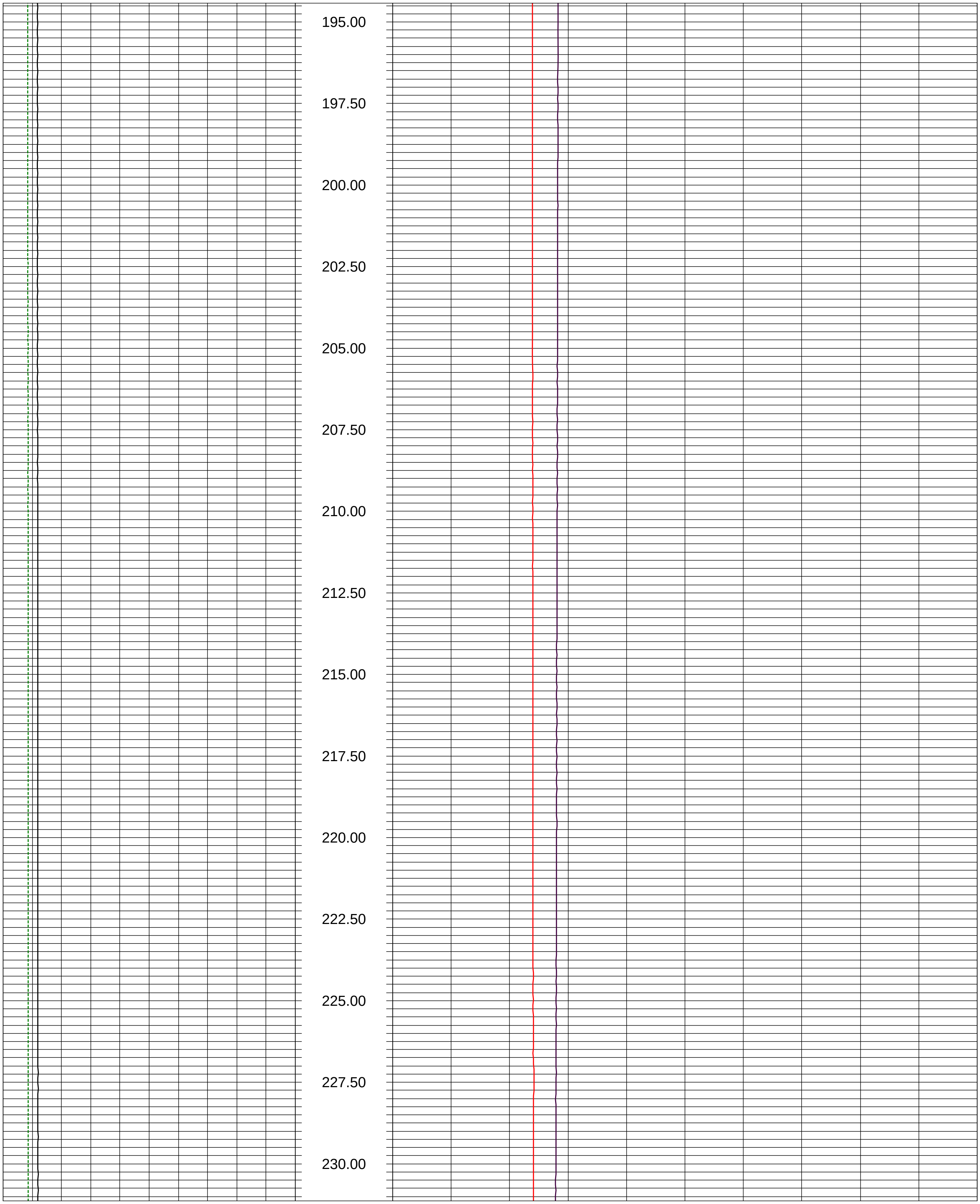
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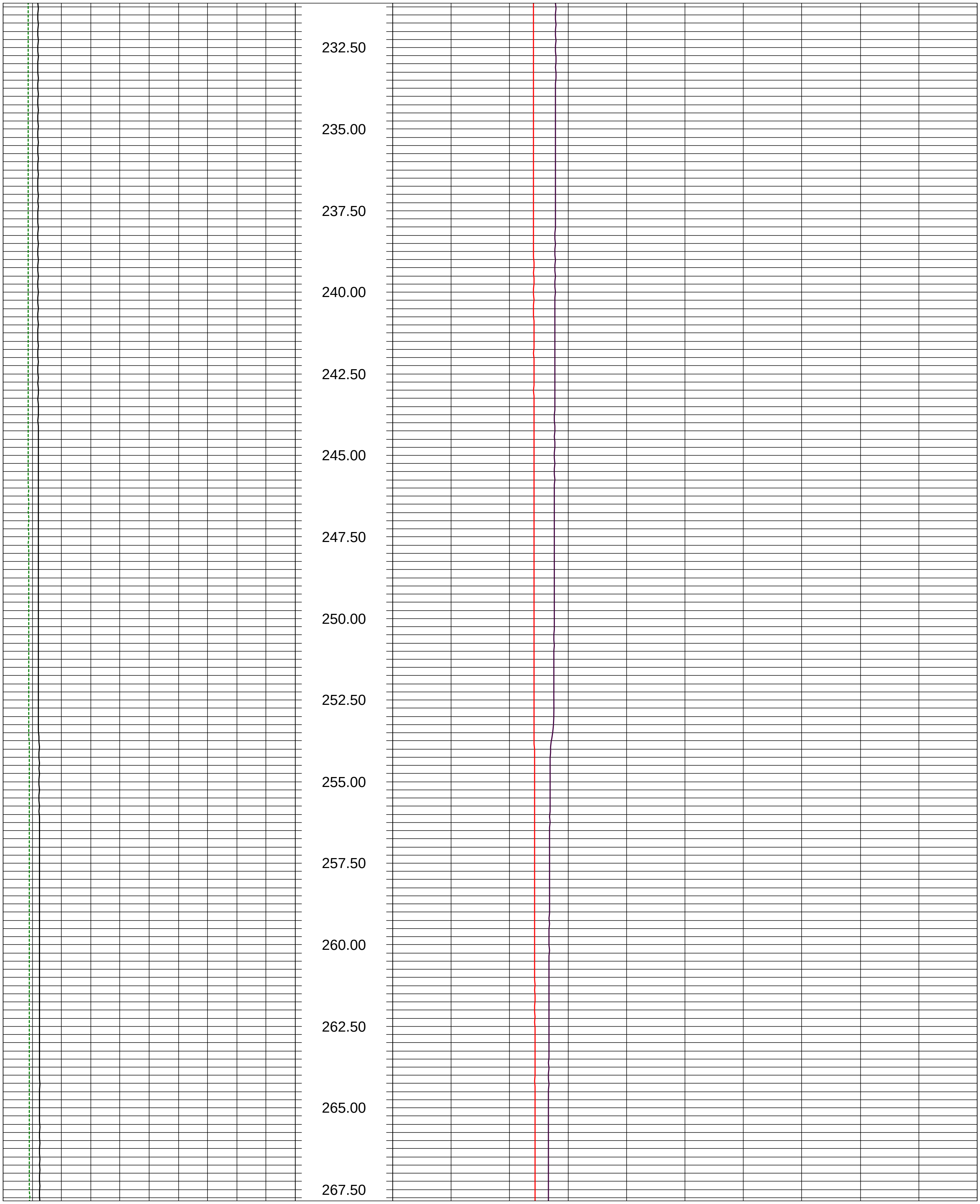
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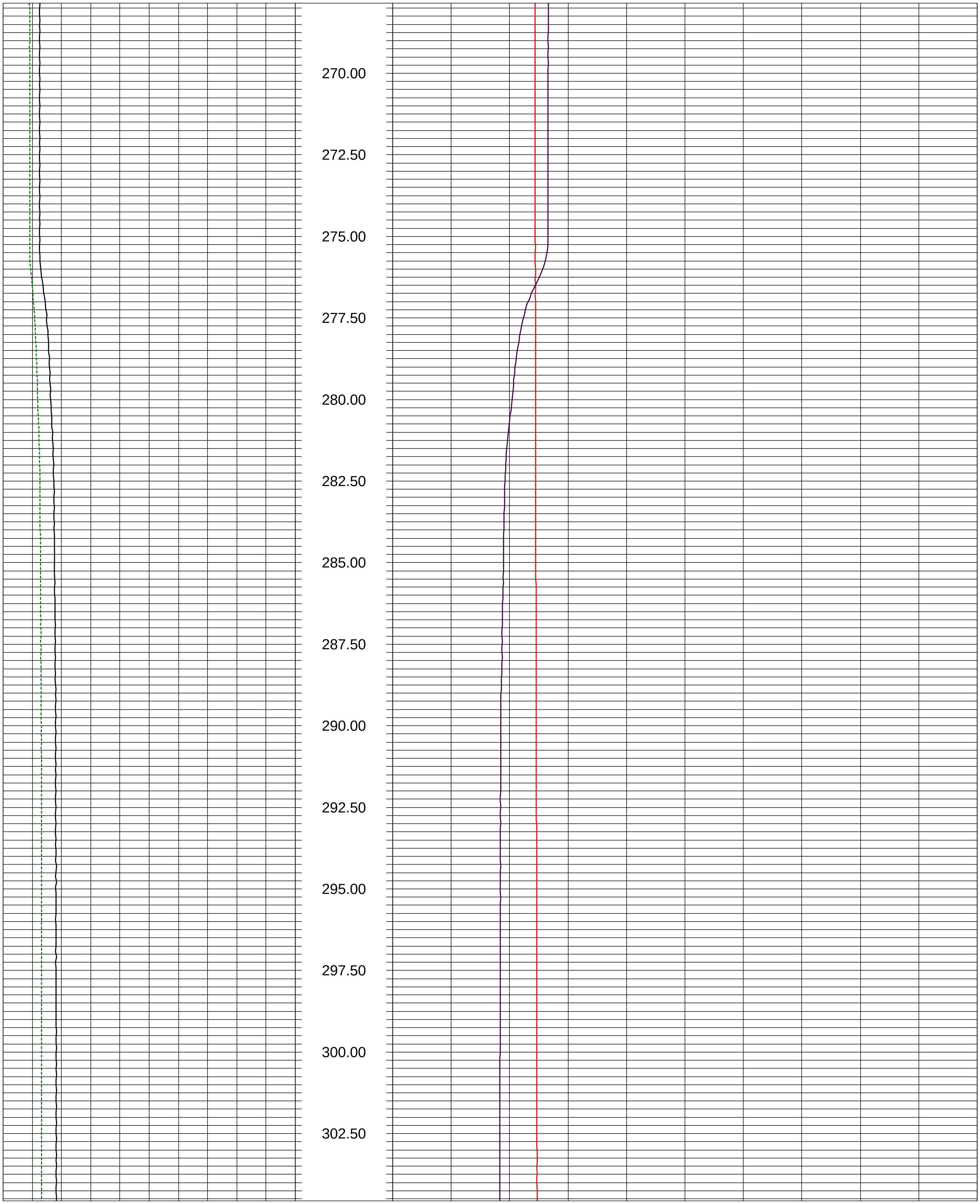
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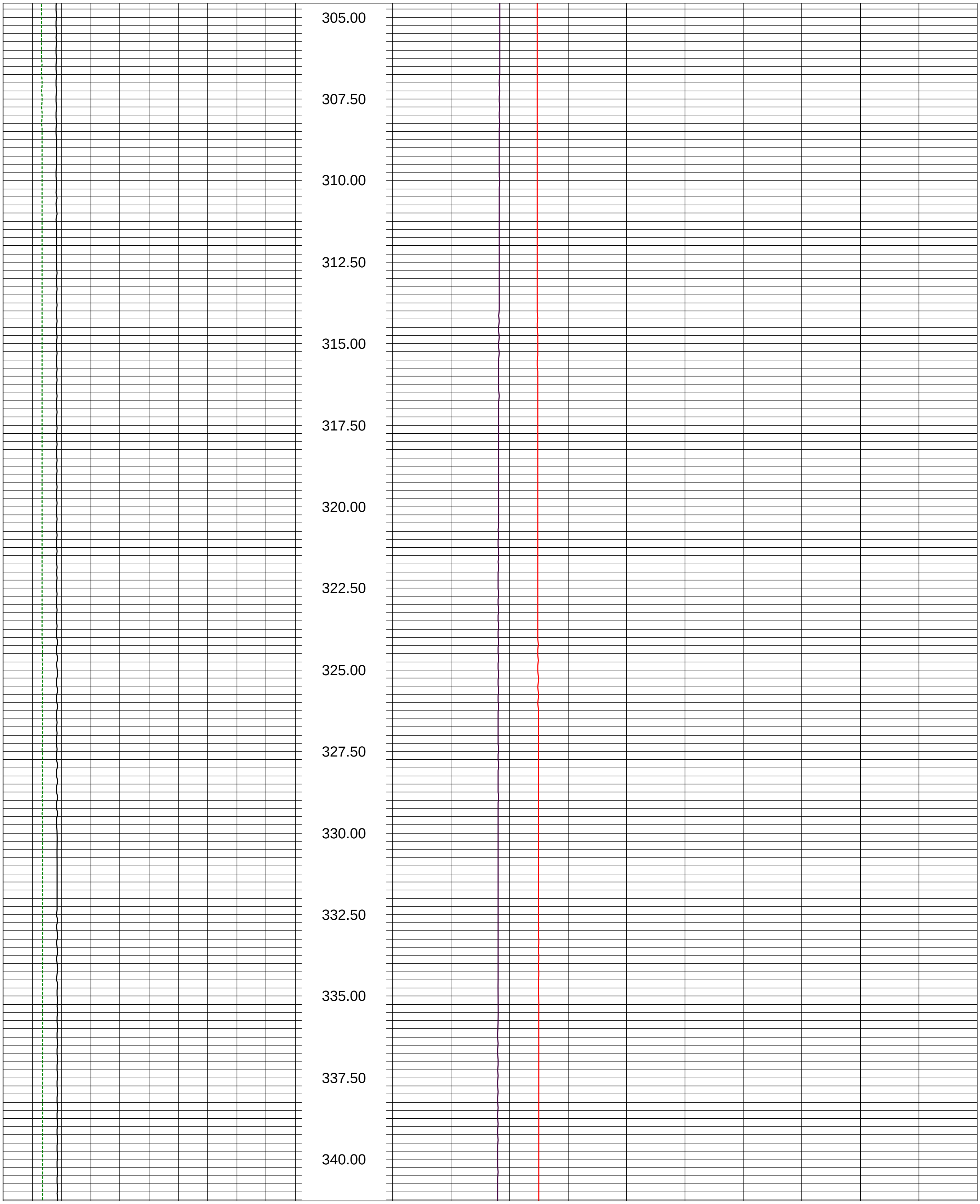
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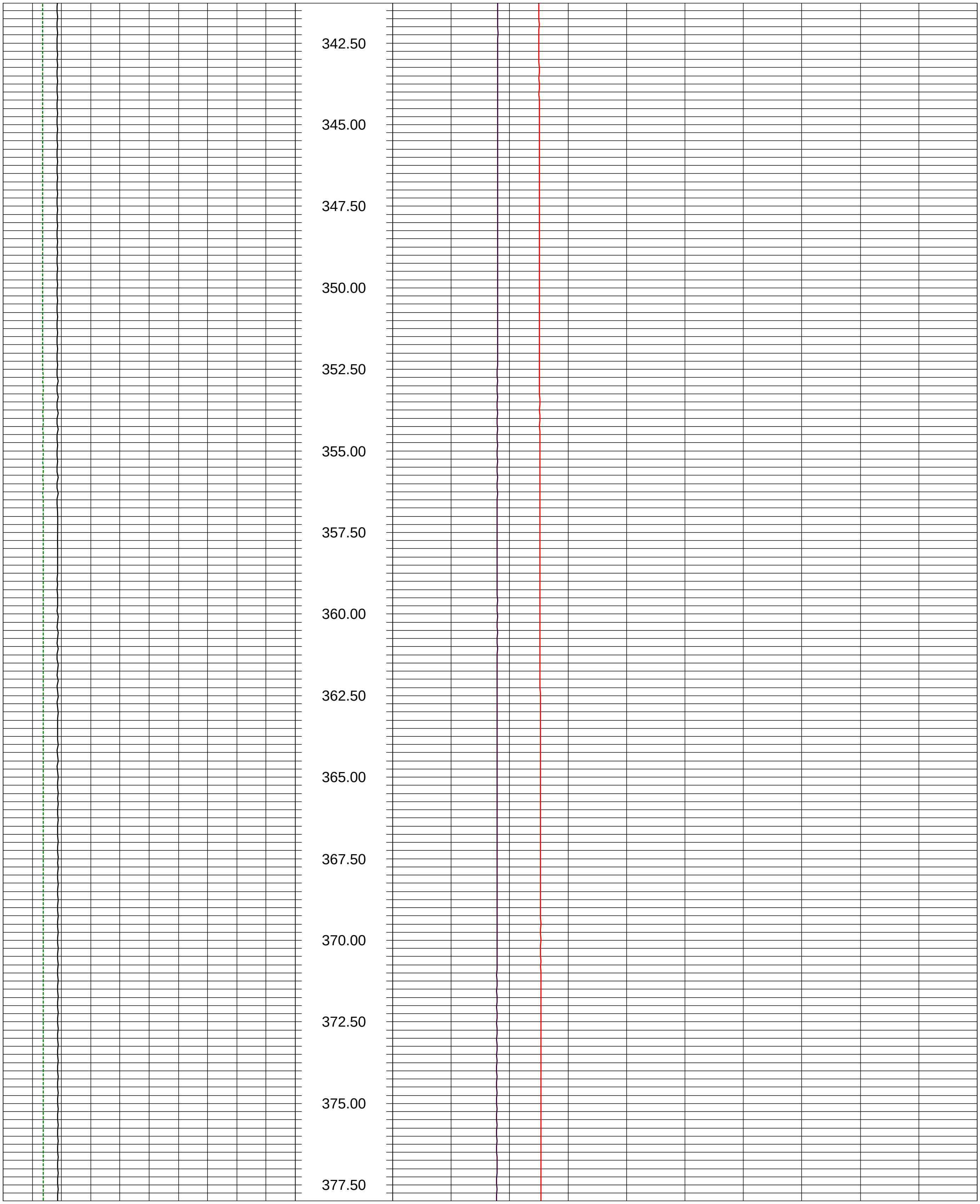
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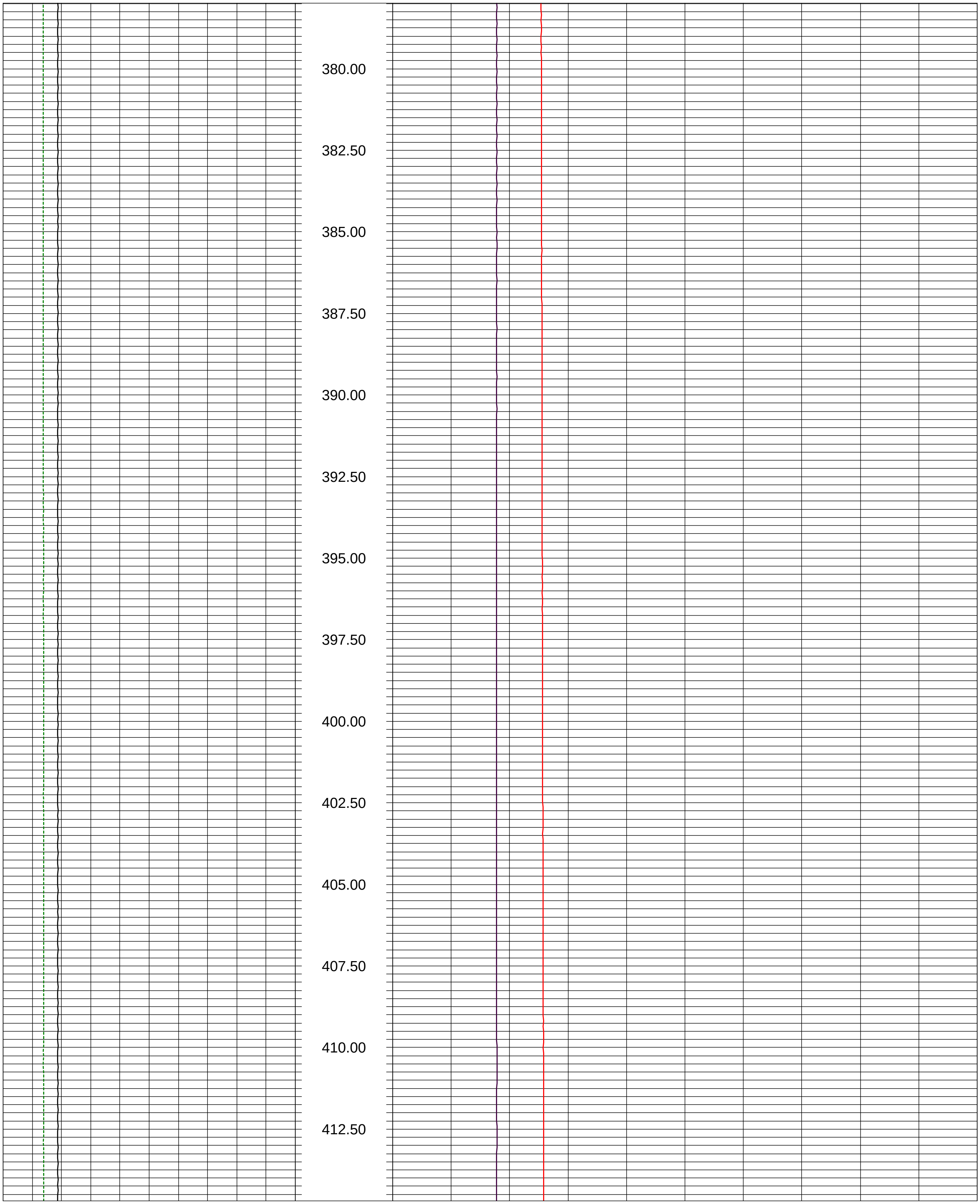
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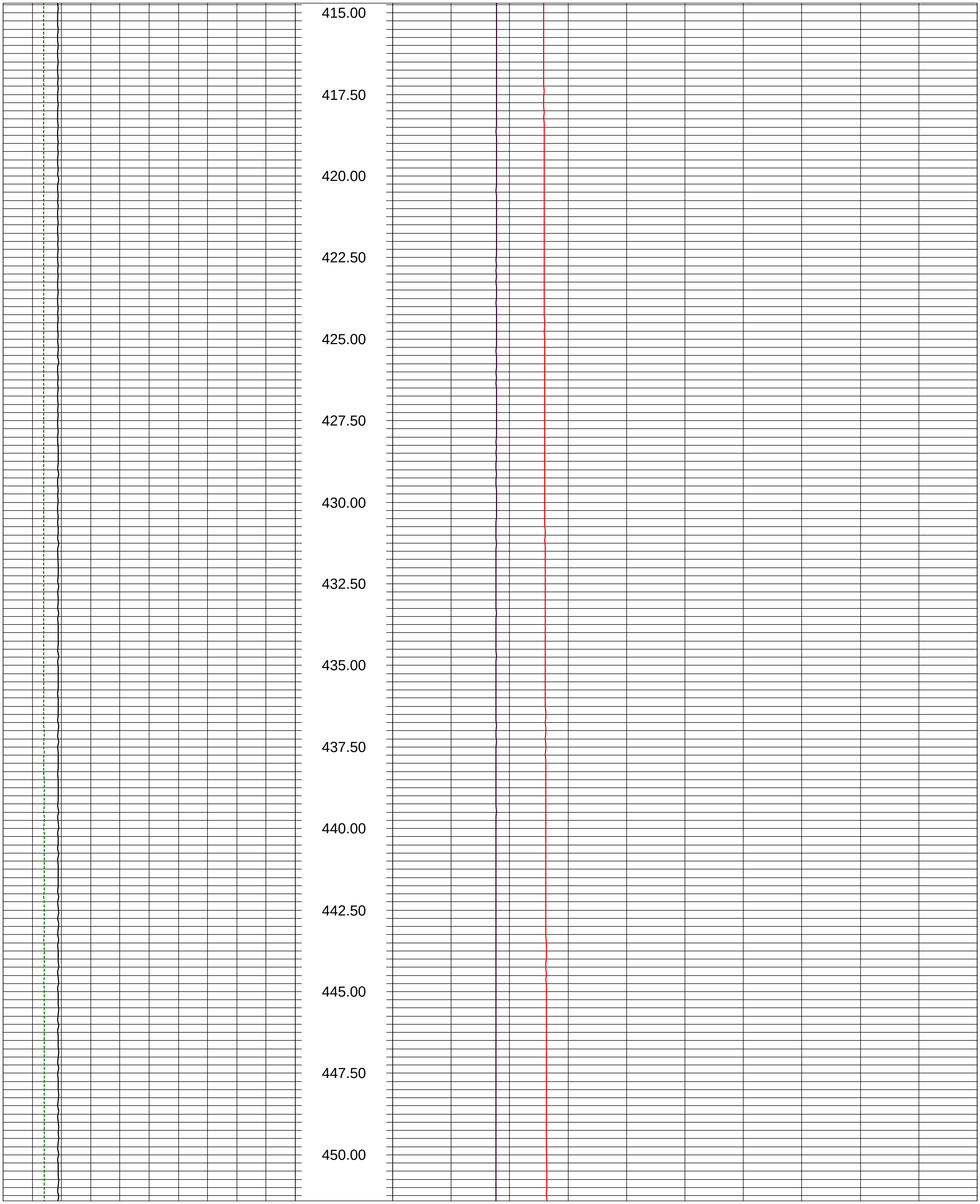
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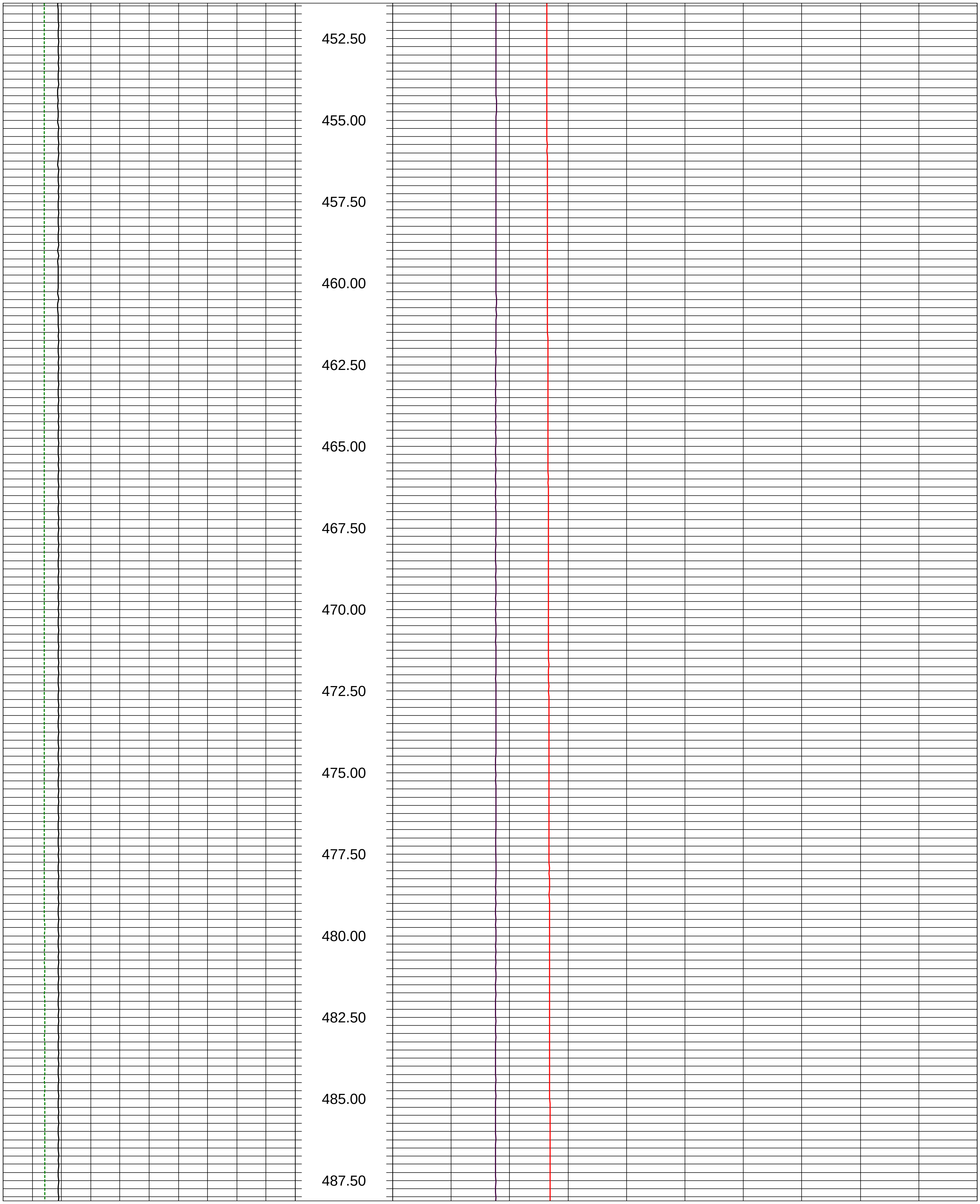
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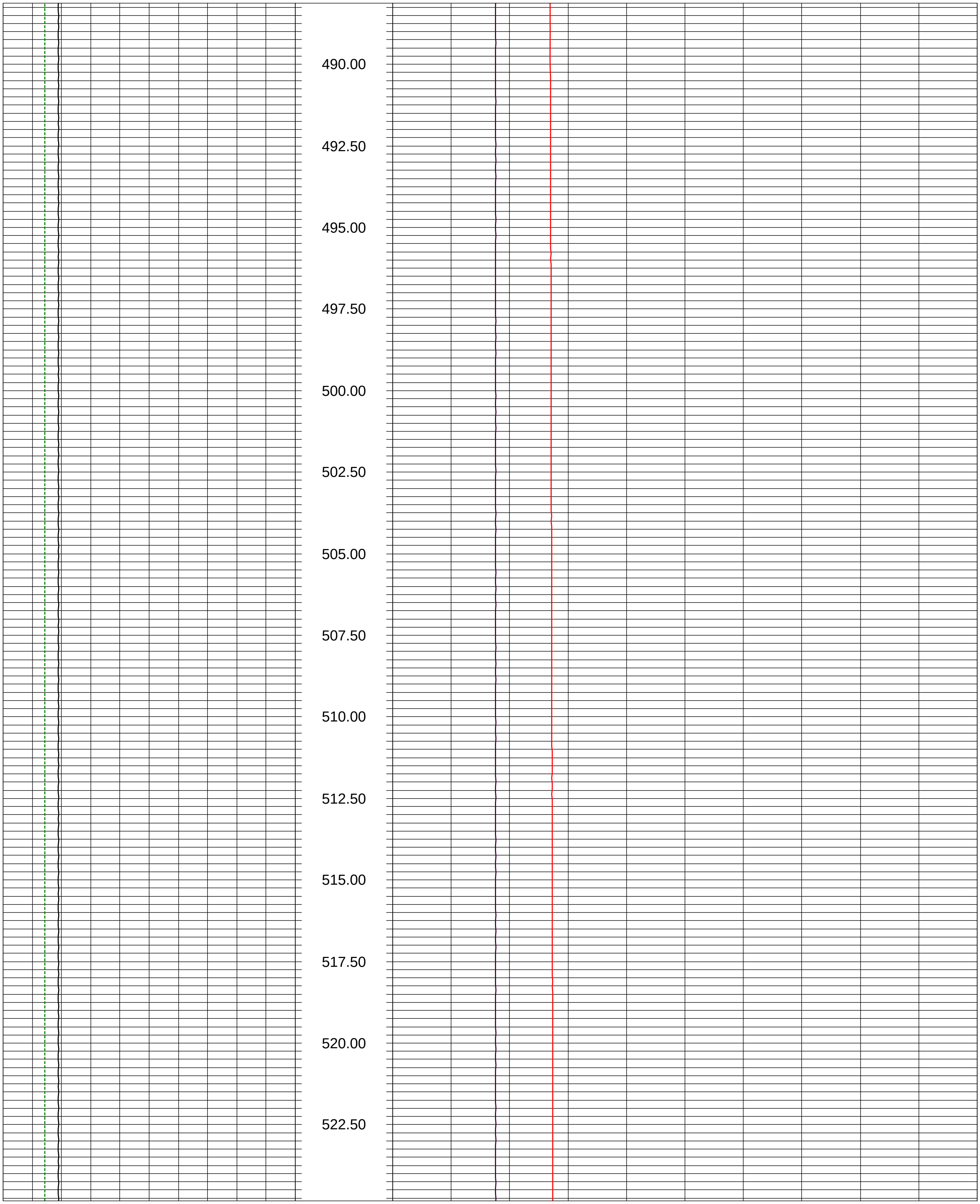
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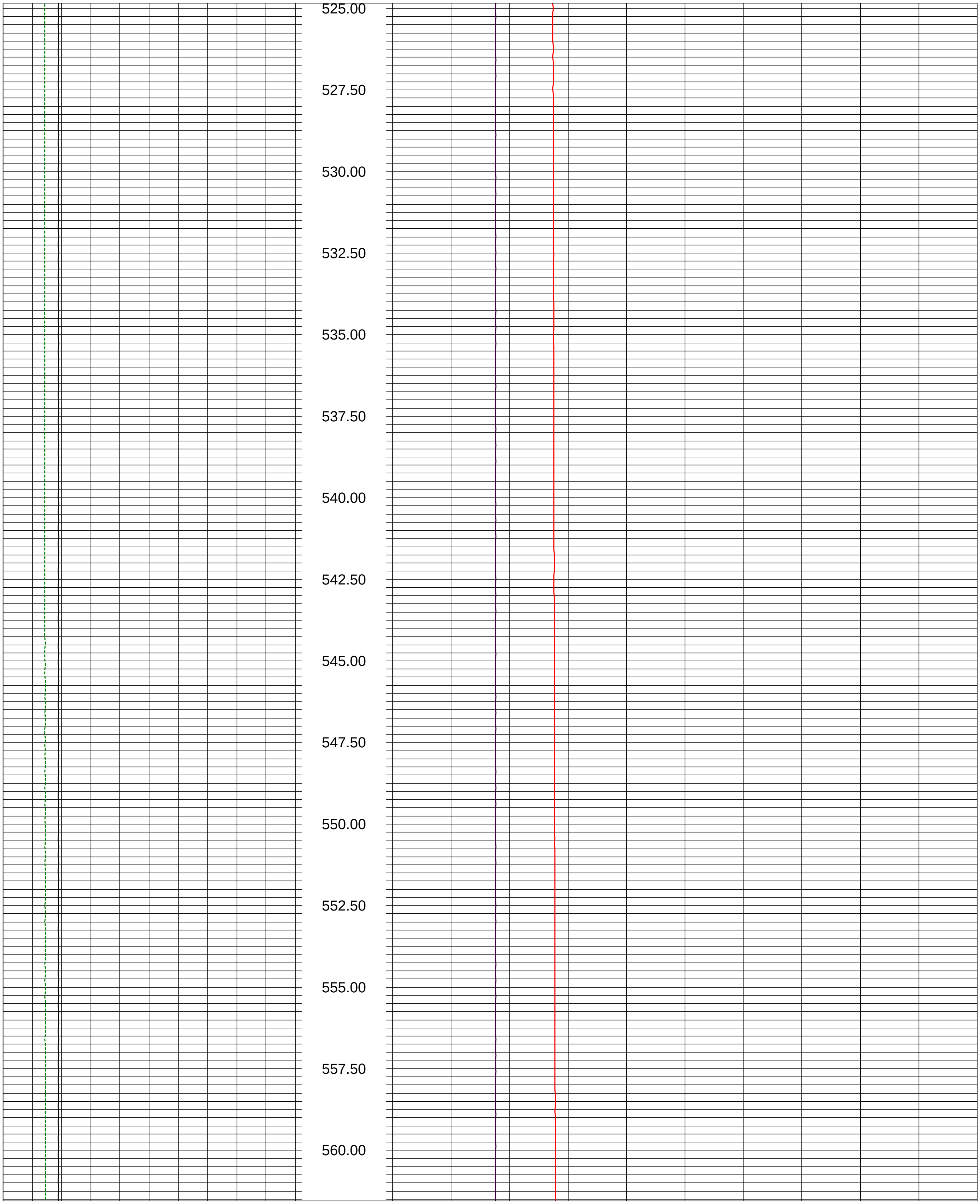
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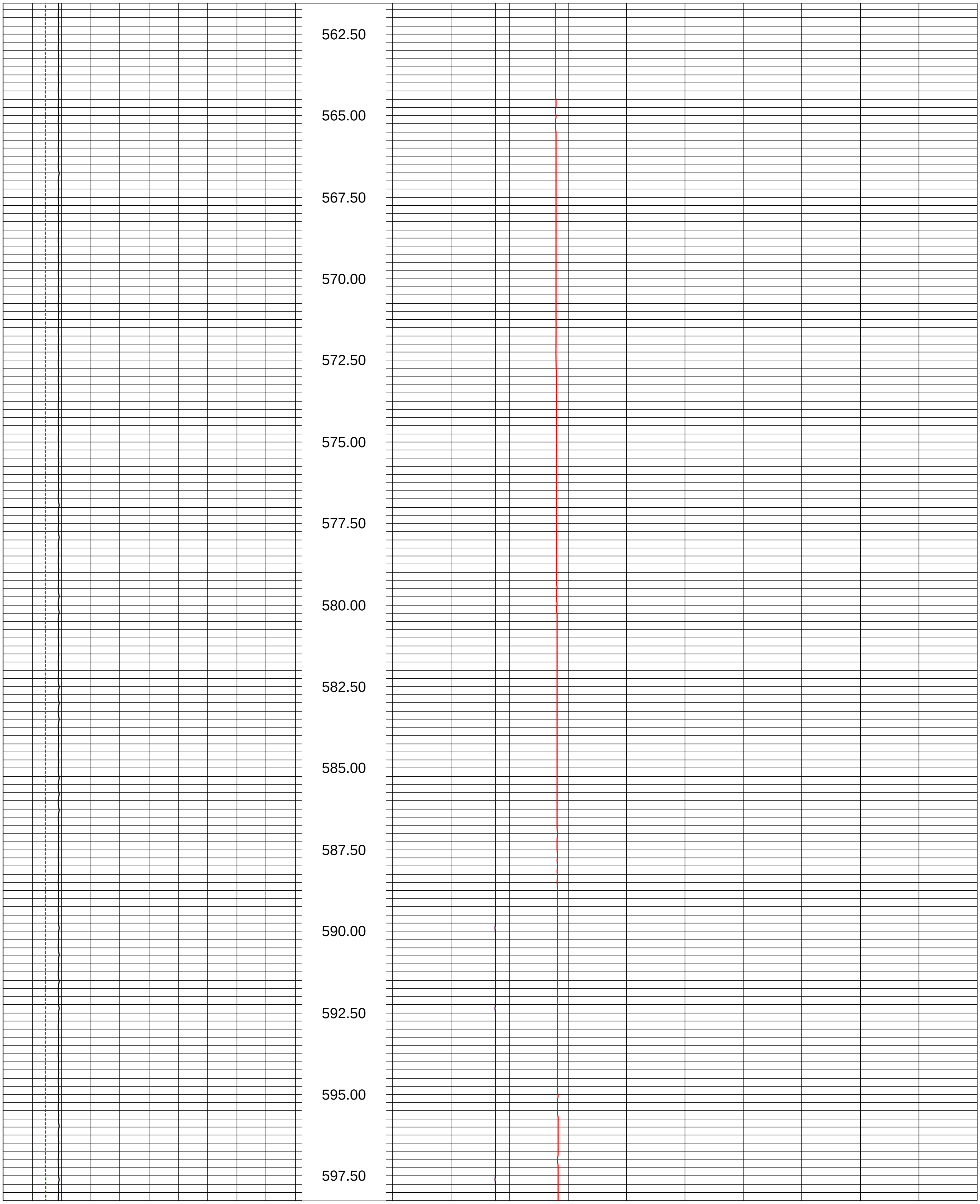
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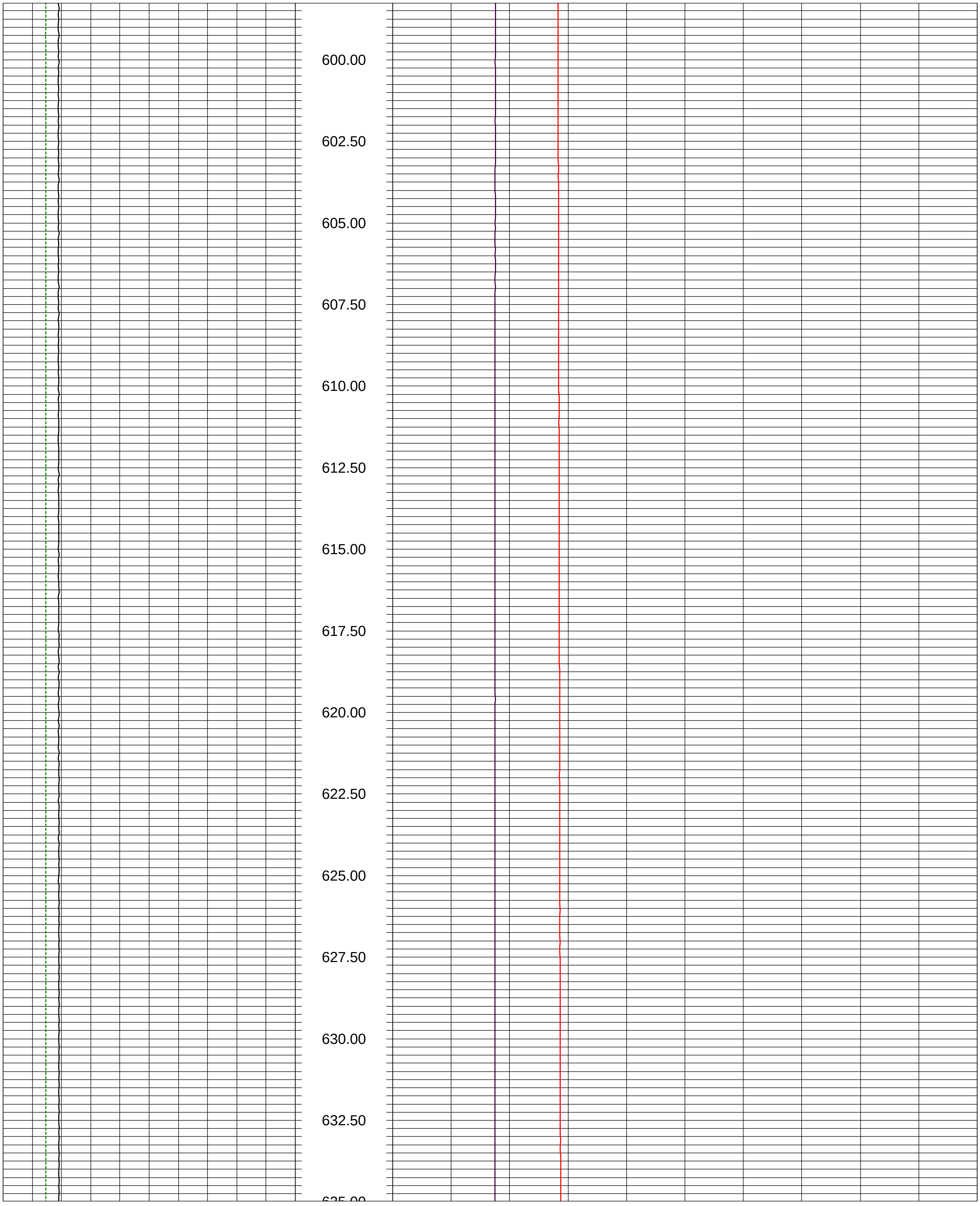
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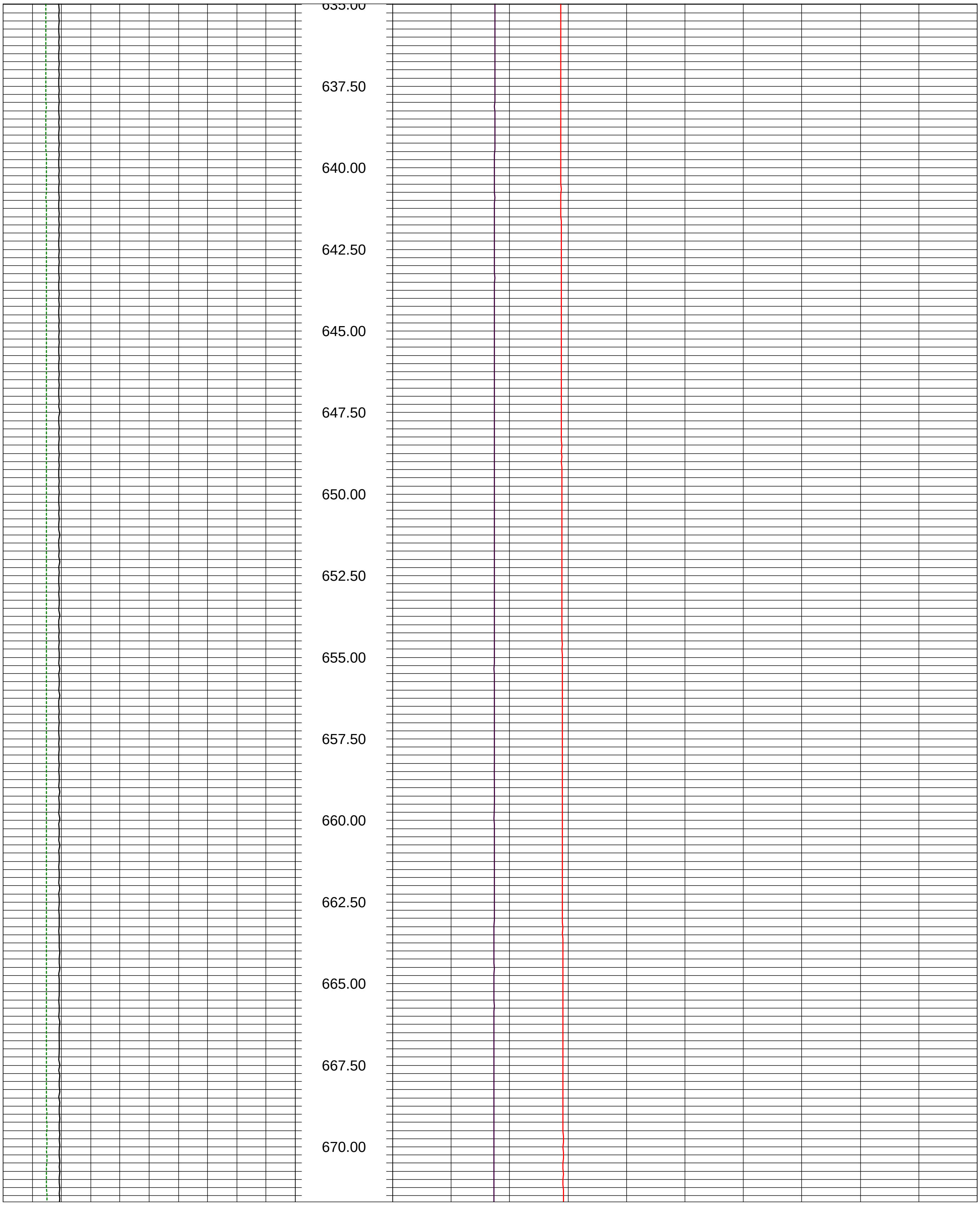
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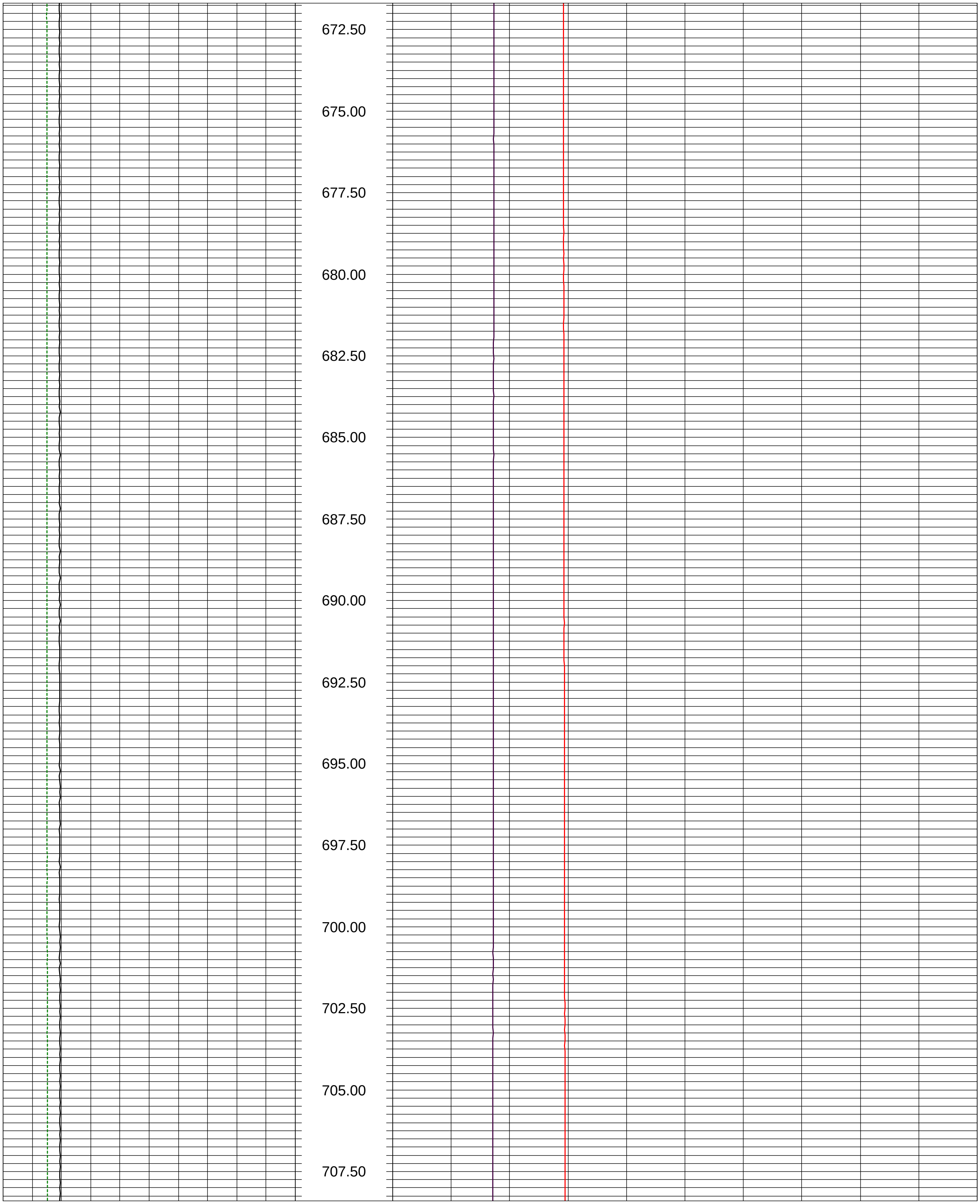
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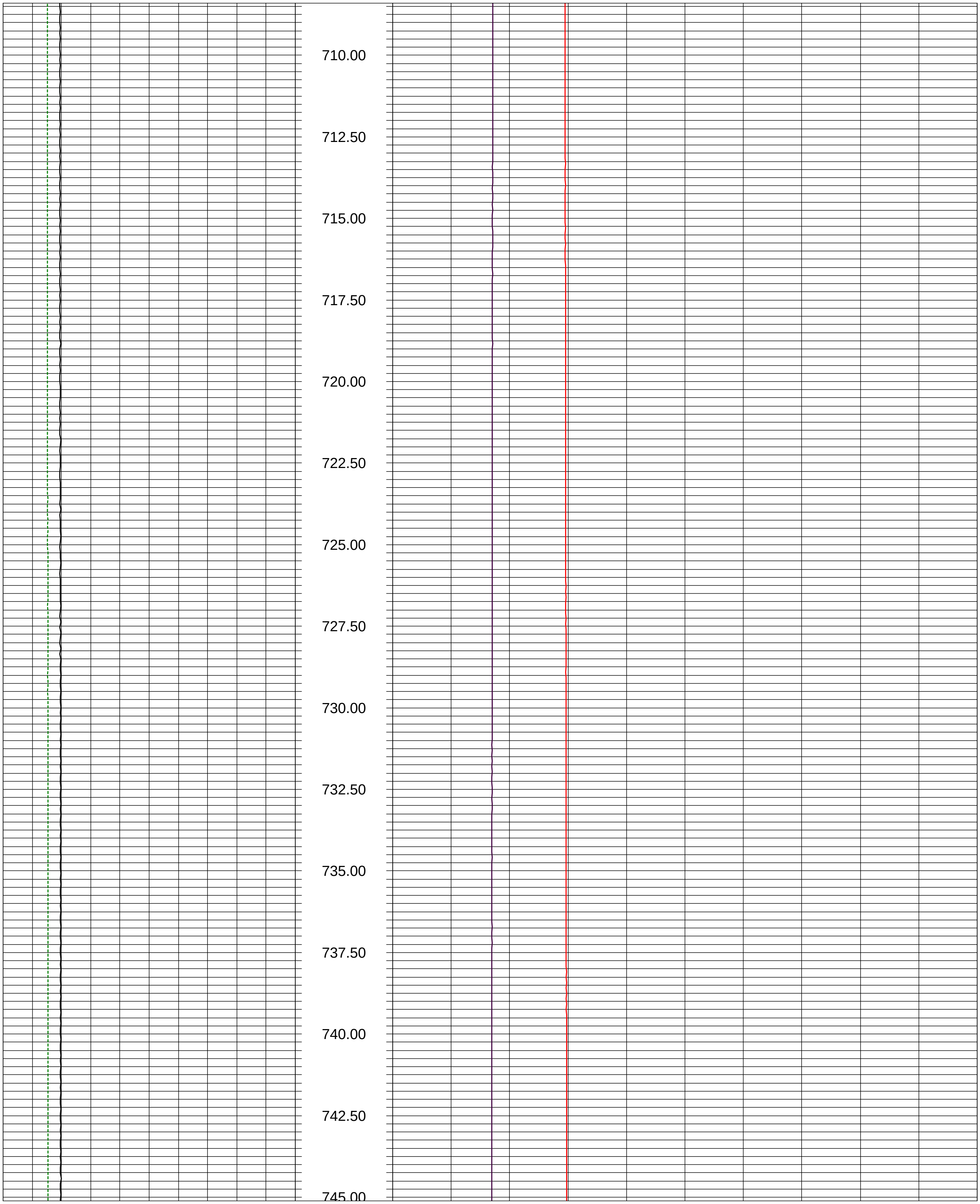
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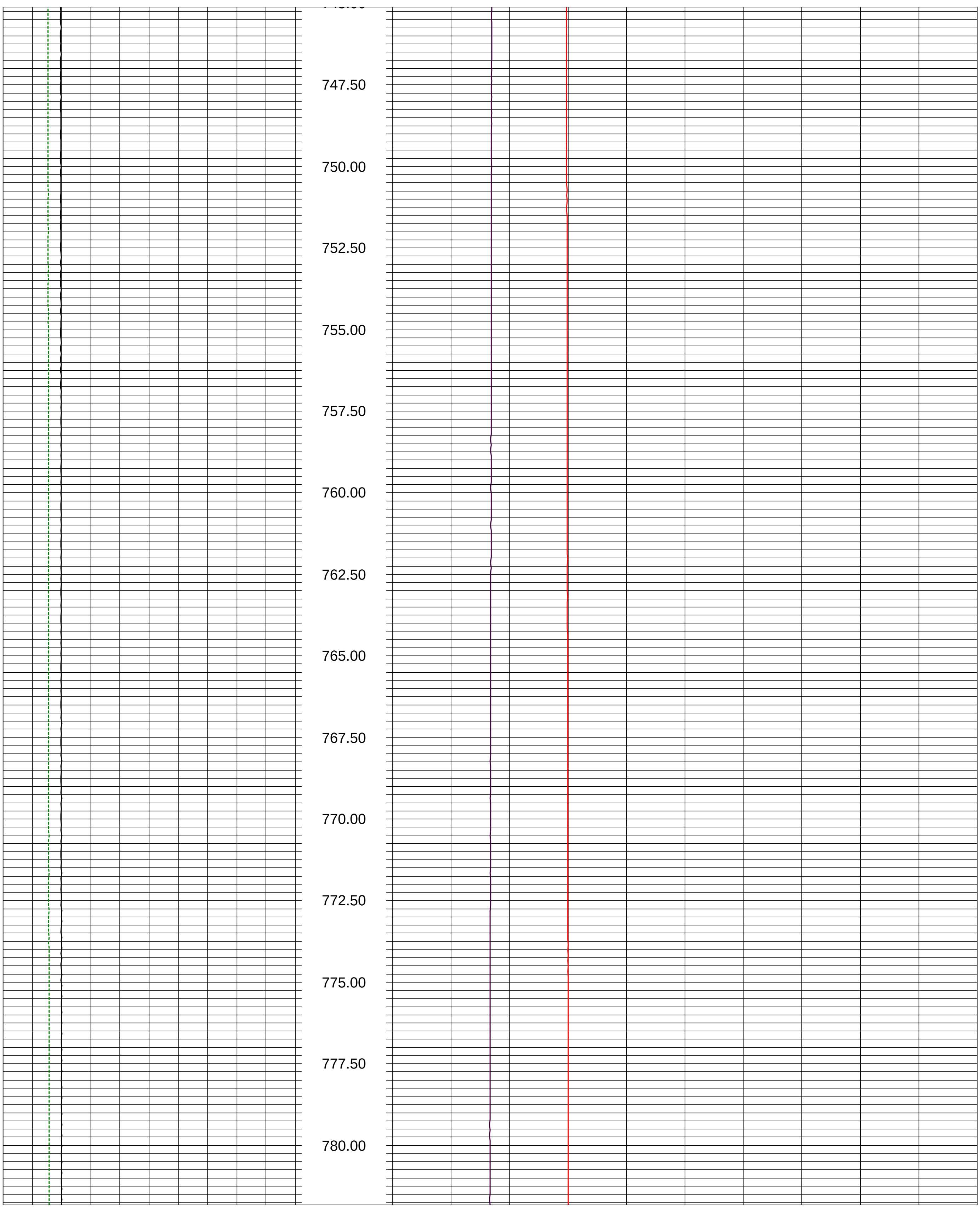
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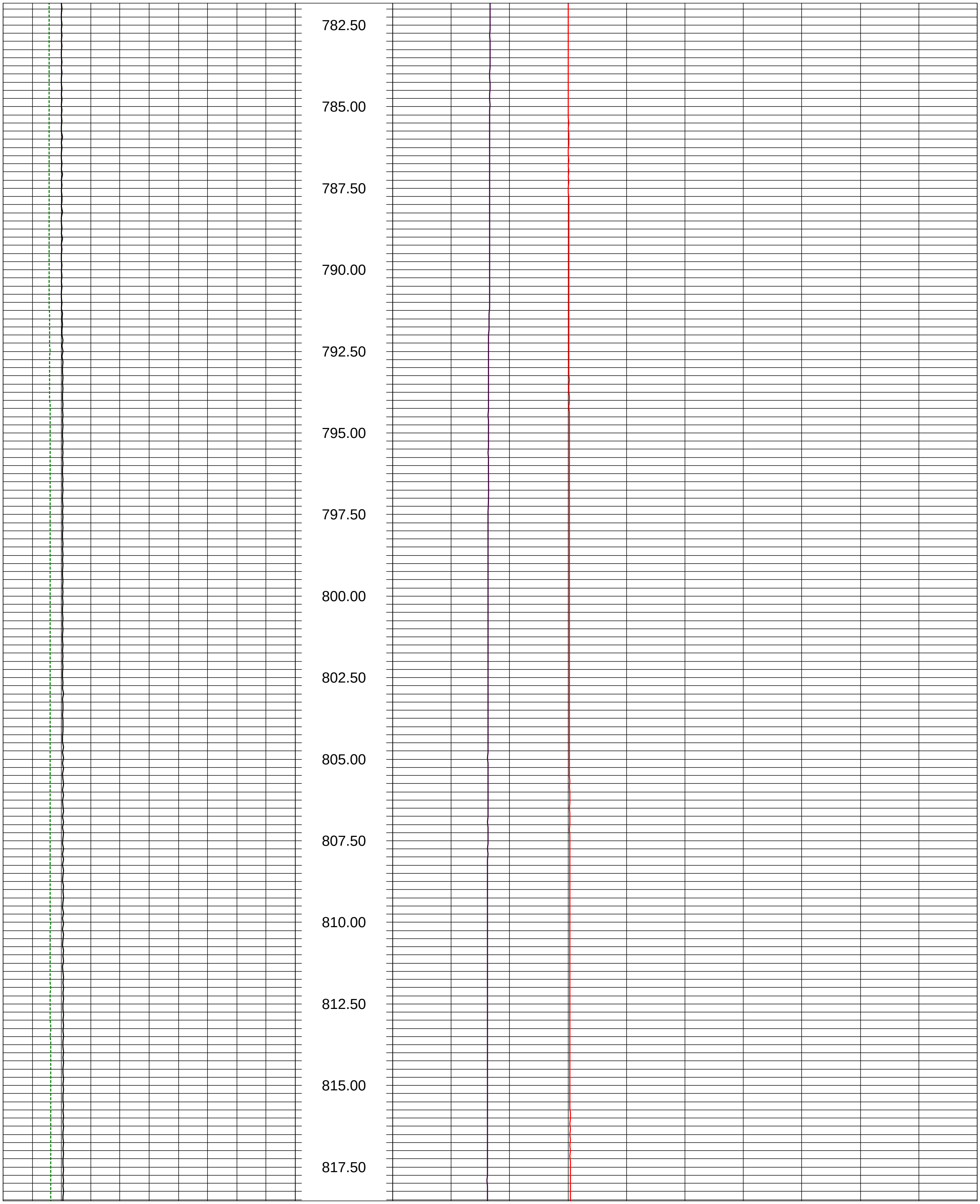
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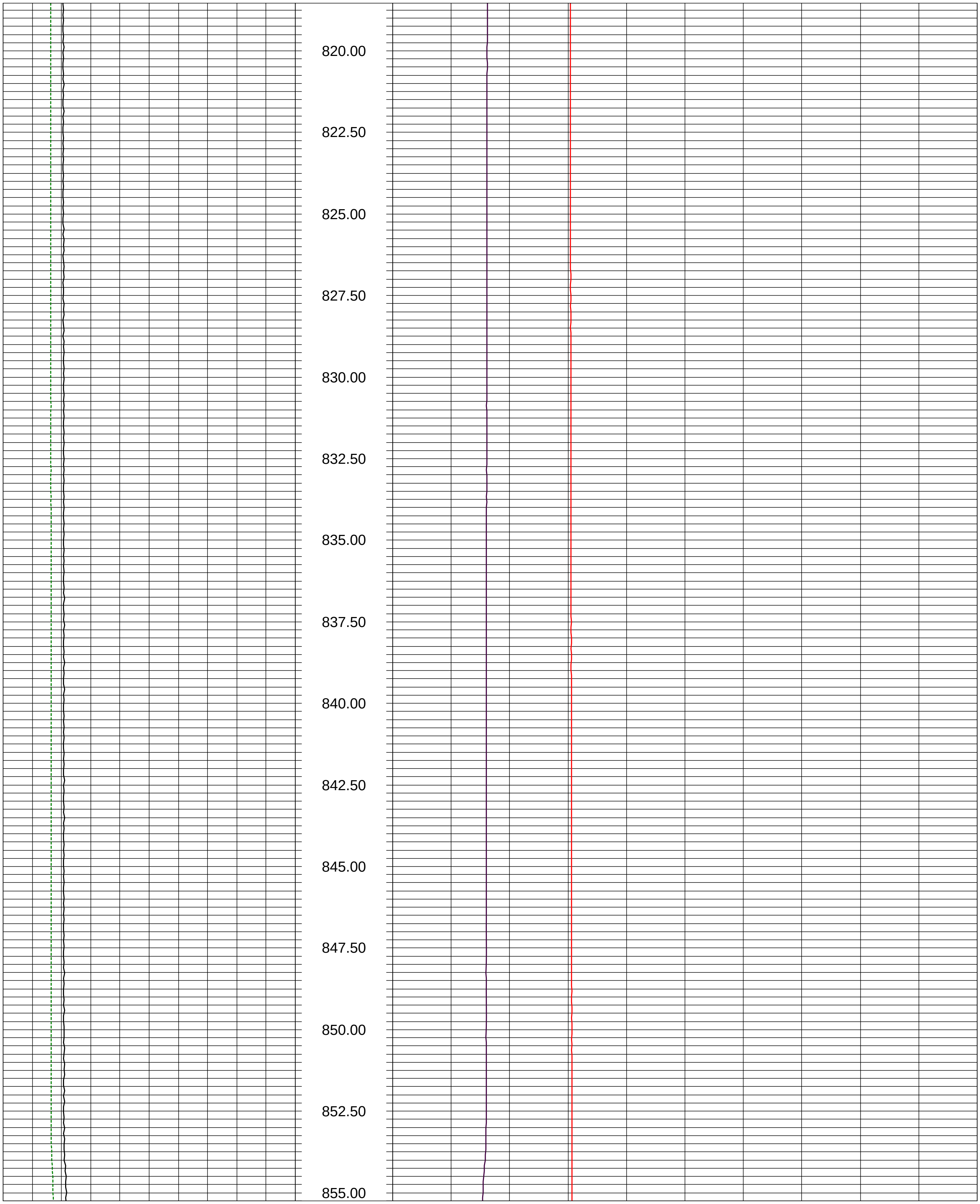
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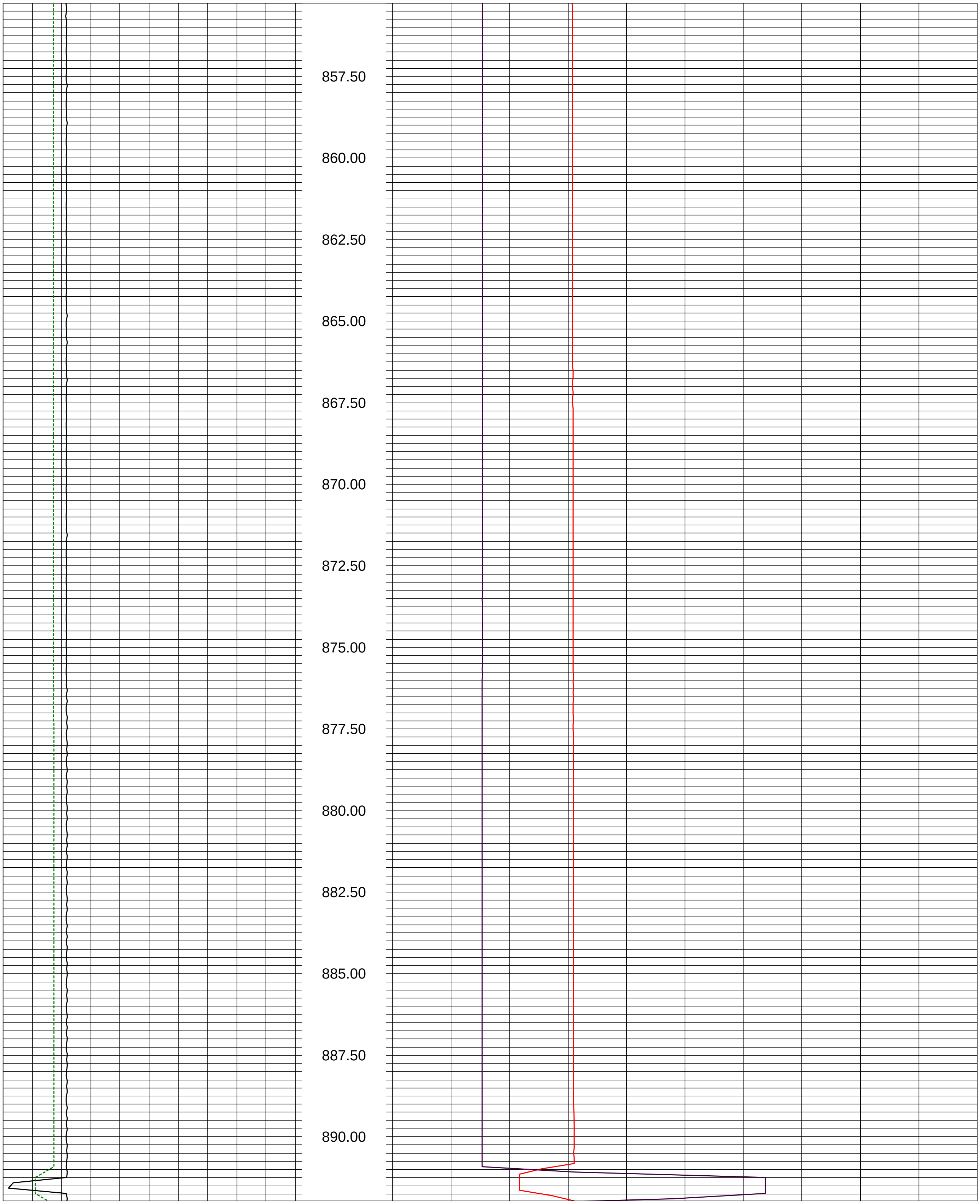
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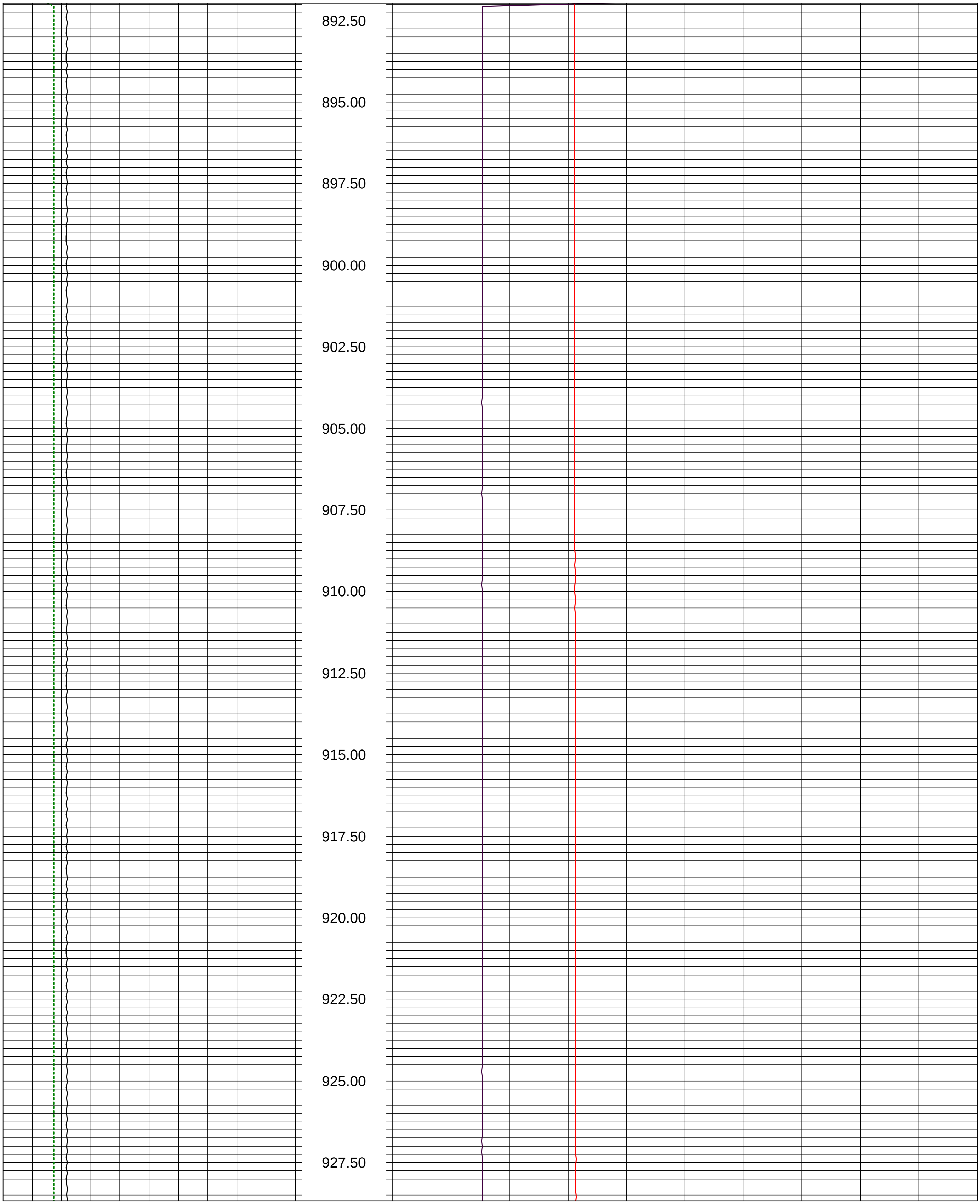
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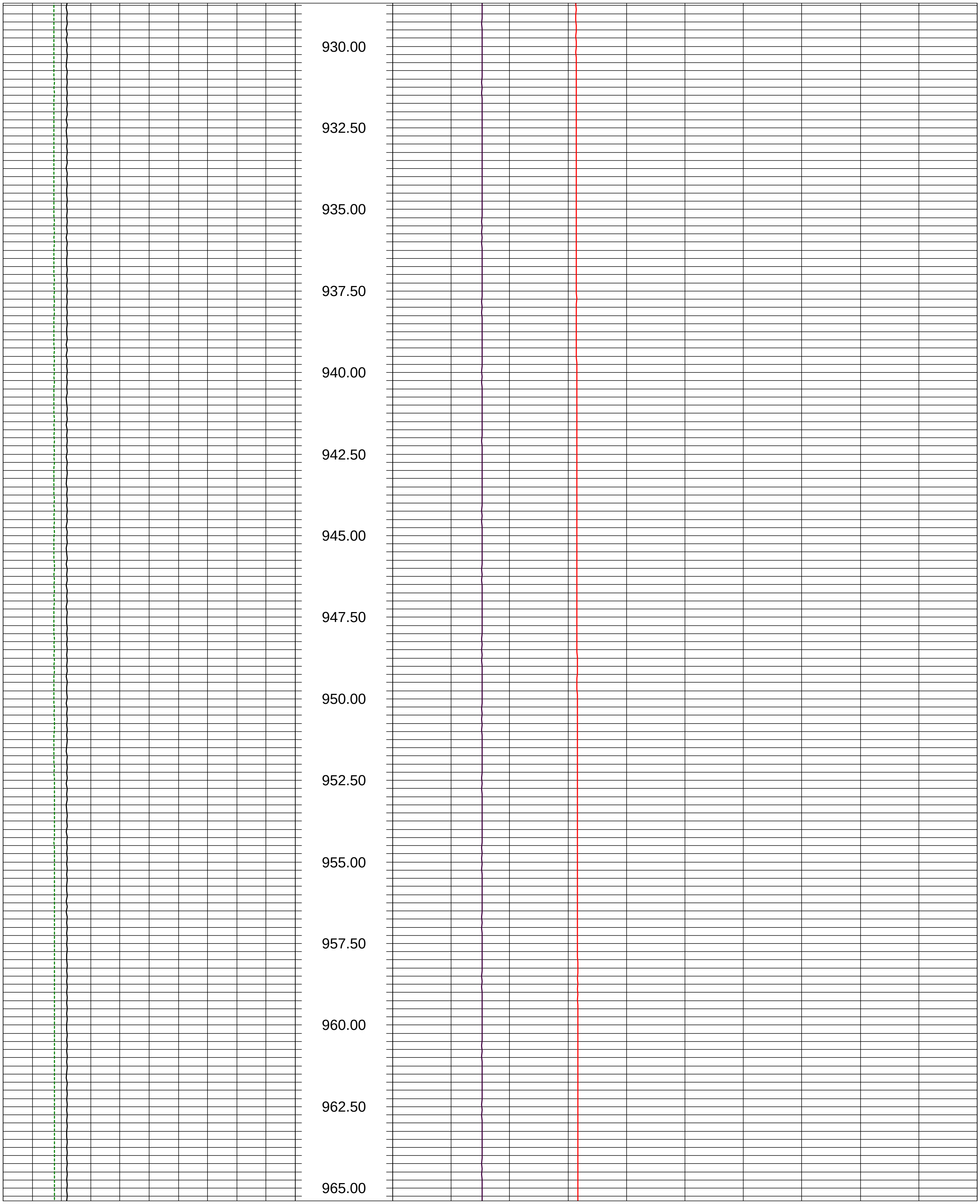
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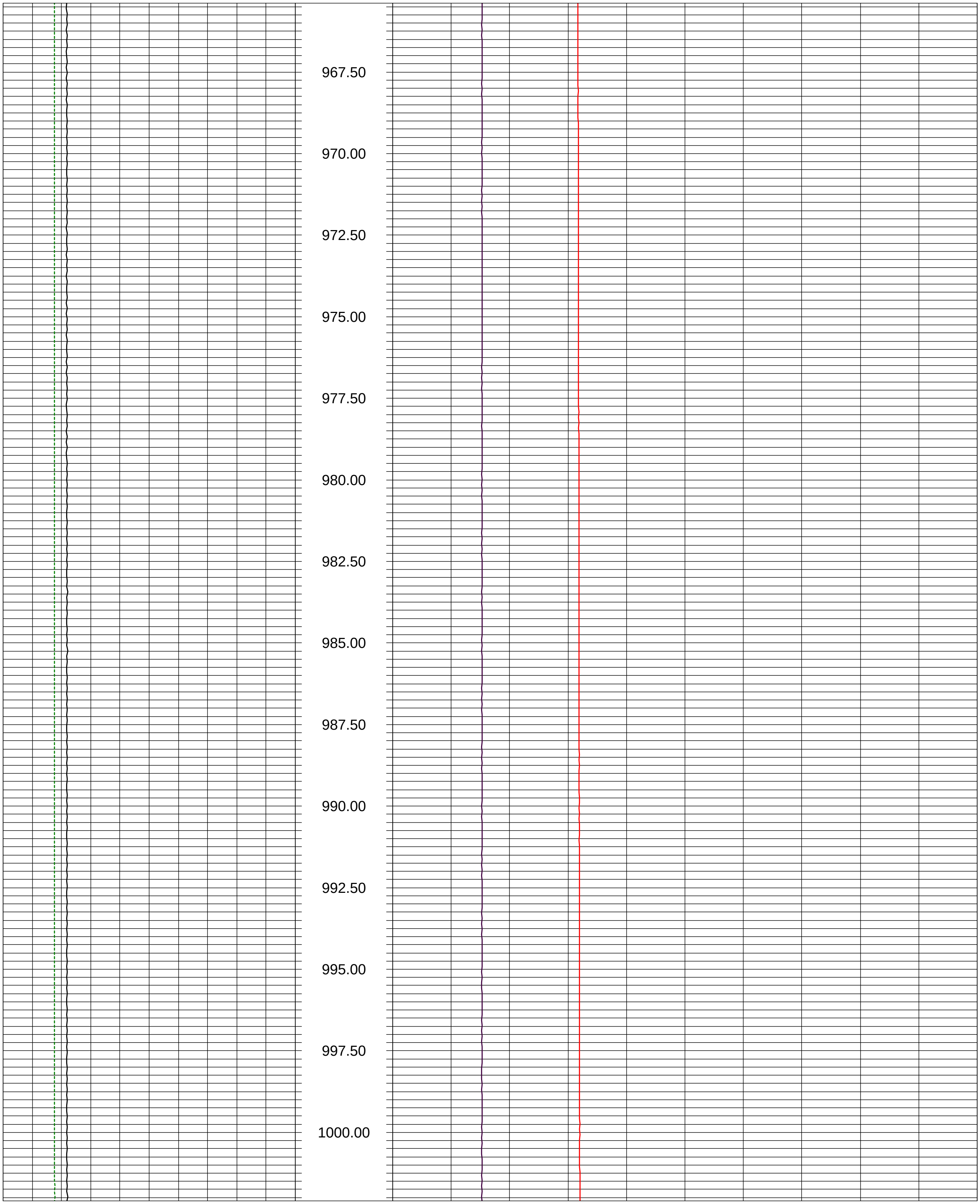
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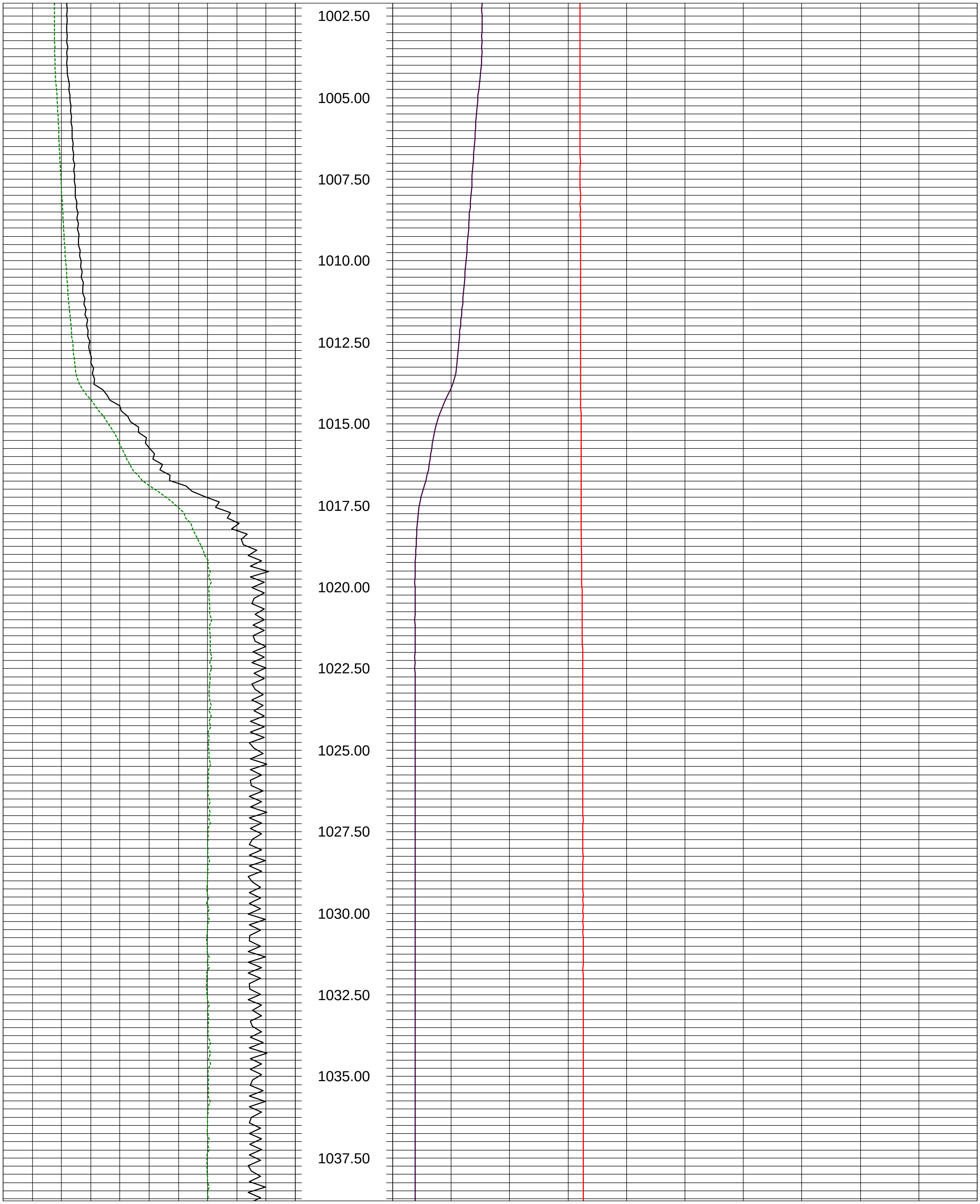
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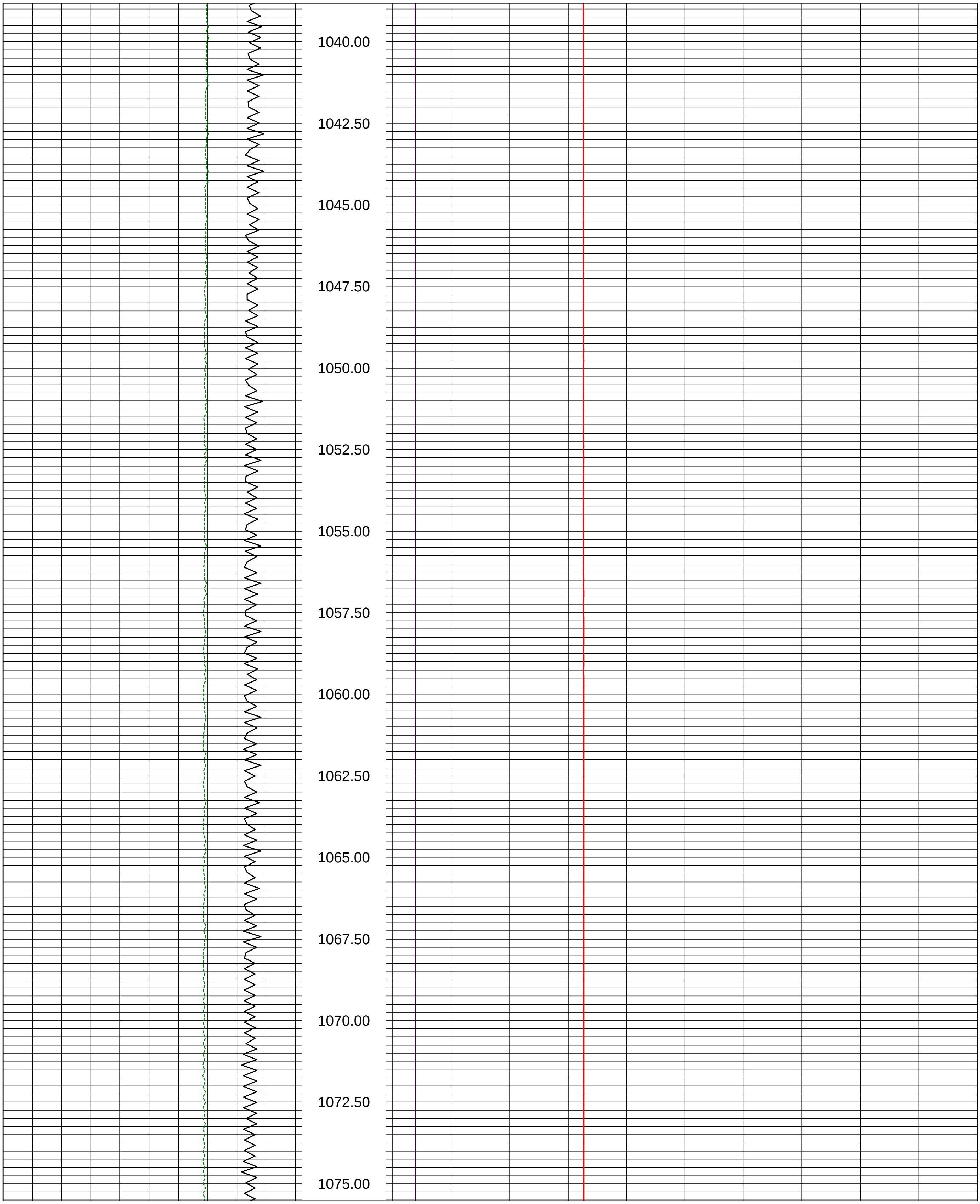
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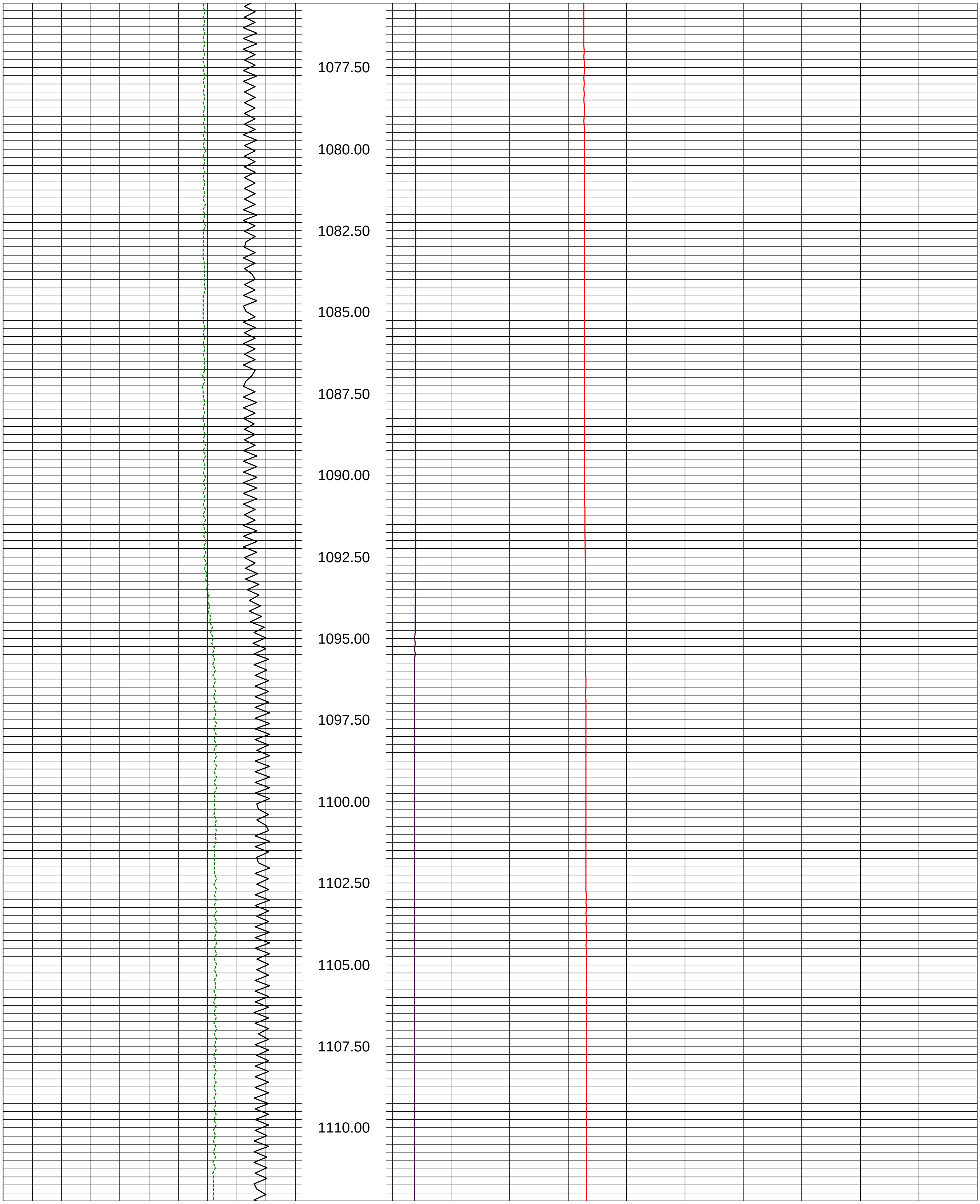
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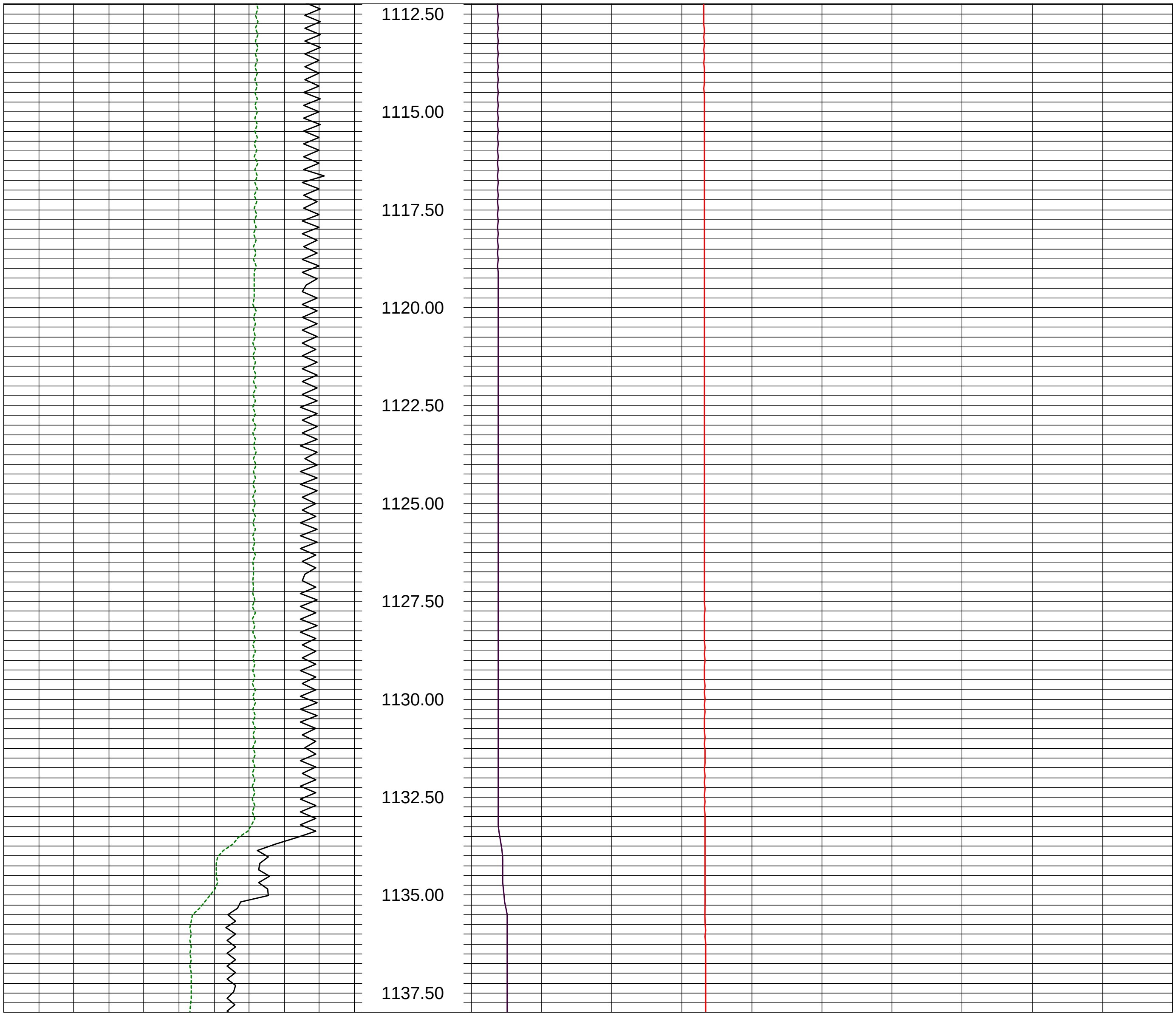
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APPENDIX 3.F - DESCRIPTIVE STRATIGRAPHIC LOG OF EXPLORATORY BOREHOLE #3 AT THE IATAN GENERATING STATION, PLATTE COUNTY, MISSOURI

STRATIGRAPHIC DESCRIPTION

No Sample (0-97 (feet depth)

Pennsylvania System (93-1,170 feet depth): This unit contains intervals of thick to thin layers of dark gray to light gray to buff to light brown, fine grained, limestones, black to dark gray to greenish gray to brownish, fissile, shales to silty sand shales, and white to light brown, cemented to friable, quartz sands.

Meramecian Series (1,170-1,250 feet depth): This unit contains buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale.

Burlington-Keokuk Limestone (1,250-1,325 feet depth): This unit contains light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale also was found.

Slough (1,325-2,090 feet depth): This unit contains slough possibly from Pennsylvania System which is a black to dark gray to greenish gray, shale. Possibly 0.1% is from the formation at depth. Complications from drilling made interpretation of strata from cuttings collected from a drilling depth below 1,325 feet impractical.

APPENDIX 3.G EXPLORATORY BOREHOLE #3 WELL LOG

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Divison of Geology and Land Survey
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Project: Shallow Carbon Sequestration Demonstration Project

Site: Iatan Generating Station

Hole Exploratory Borehole #3

Driller's Information

Drilling Company: Lanye Christensen

Driller: Rusty Bowles

Equipment Description: Atlas Copco

Contractor's Information

Primary Contractor:

P C Represetative:

Sub-Contractor:

S C Representative:

Site Location Information

County: Platte County

Quadrangle:

Land Grant:

Section:

Additional description:

Well longitude: 94° 57’ 27.2” W

Well latitude: 39° 26’ 25.3” N

Logged by: John Pate

Alias well ID:

Date drilled: Started 01/08/13 **; Ended** 03/01/13

Additional location description:

Elevation	Depth	Formation	Member			Lithologic Description	Samples Interval	Comments
778.72						0-97: No Sample		
773.72	5'							
768.72	10'							
763.72	15'							
758.72	20'							
753.72	25'							
748.72	30'							

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project

Site: Iatan Generating Station

Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
743.72	35'					
738.72	40'					
733.72	45'					
728.72	50'					
723.72	55'					
718.72	60'					
713.72	65'					
708.72	70'					

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project

Site: Iatan Generating Station

Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
703.72	75'					
698.72	80'					
693.72	85'					
688.72	90'					
				93-97: **Pennsylvanian System:** Bedrock at 93' No Sample		
683.72	95'					
				97-100: Dark gray, medium grained, limestone.	S-1	
678.72	100'			100-105: Light gray to buff, fine grained, limestone with dark to gray, medium grained limestone.	S-2	
673.72	105'			105-110: Light gray to buff, fine grained to microcrystalline, limestone with dark gray, medium grained, limestone. Black fissile shale.	S-3	
668.72	110'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				110-115: Light gray to buff, fine grained to microcrystalline, limestone with dark gray, medium grained, limestone. Black fissile shale.	S-4	
663.72	115'			115-120: Buff, fine grained limestone with green shale.	S-5	
658.72	120'			120-125: Gray to green shale.	S-6	
653.72	125'			125-130: Dark gray, fissile, shale.	S-7	
648.72	130'			130-135: Buff to brown, fine to medium grained, limestone with dark gray, fissile shale.	S-8	
643.72	135'			135-140: Buff to brown, fine to medium grained, limestone, slightly brecciated.	S-9	
638.72	140'			140-145: Buff to brown, fine to medium grained, limestone, slightly brecciated.	S-10	
633.72	145'			145-150: Dark gray, fissile shale to silty sandy shale.	S-11	
628.72	150'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				150-155: Dark gray, fissile shale to silty sandy shale.	S-12	
623.72	155'			155-160: Dark gray, fissile shale to silty sandy shale.	S-13	
618.72	160'			160-165: Dark gray, fissile shale to silty sandy shale.	S-14	
613.72	165'			165-170: Dark gray, fissile shale to silty sandy shale.	S-15	
608.72	170'			170-175: Dark gray, fissile shale to silty sandy shale.	S-16	
603.72	175'			175-180: Dark gray, fissile shale to silty sandy shale.	S-17	
598.72	180'			180-185: Dark gray, fissile shale to silty sandy shale.	S-18	
593.72	185'			185-190: Dark gray, fissile shale to silty sandy shale.	S-19	
588.72	190'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				190-195: Dark gray, fissile shale to silty sandy shale.	S-20	
583.72	195'			195-200: Dark brown, fine grained, limestone with dark gray shale.	S-21	
578.72	200'			200-205: Dark brown, fine grained, limestone with dark gray shale.	S-22	
573.72	205'			205-210: Dark gray , fine grained, limestone.	S-23	
568.72	210'			210-215: Dark gray, fissile, shale.	S-24	
563.72	215'			215-220: Dark gray, fissile, shale.	S-25	
558.72	220'			220-225: Dark gray, fissile, shale.	S-26	
553.72	225'			225-230: Brown to gray, fine grained, limestone with bluish green shale.	S-27	
548.72	230'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				230-235: Brown to buff, fine grained, limestone.	S-28	
543.72	235’			235-240: Brown to buff, fine grained, limestone with dark gray shale.	S-29	
538.72	240’			240-245: Dark gray, fissile, shale.	S-30	
533.72	245’			245-250: Light brown and light gray, limestone with bluish green shale.	S-31	
528.72	250’			250-255: Light brown, fine grained, limestone with dark gray, fissile, shale.	S-32	
523.72	255’			255-260 Dark gray, fissile, shale.	S-33	
518.72	260’			260-265: Light brown to buff, fine grained, limestone	S-34	
513.72	265’			265-270: Black, fissile, shale.	S-35	
508.72	270’					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				270-275: Black, fissile, shale.	S-36	
503.72	275'			275-280: Black, fissile, shale.	S-37	
498.72	280'			280-285: Brown to buff to dark gray, fine grained, limestone with black shale.	S-38	
493.72	285'			285-290: Black to dark gray, shale	S-39	
488.72	290'			290-295: Brown to buff, fine grained, limestone with bluish green shale	S-40	
483.72	295'			295-300: Light gray, fine grained, limestone with slight amounts of black shale.	S-41	
478.72	300'			300-305: Light gray to gray, fine grained, limestone	S-42	
473.72	305'			305-310: Light brown to buff, fine grained, limestone	S-43	
468.72	310'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				310-315: Light brown to buff, fine grained, limestone with dark gray to black shale	S-44	
463.72	315'			315-320: Light brown to buff, fine grained, limestone with dark gray to black shale	S-45	
458.72	320'			320-325: Light brown to buff, fine grained, limestone with dark gray to black shale	S-46	
453.72	325'			325-330: Buff to light brown, fine grained, limestone with greenish gray shale	S-47	
448.72	330'			330-335: Buff to light brown, fine grained, limestone with greenish gray shale	S-48	
443.72	335'			335-340: Light gray, fine grained, limestone	S-49	
438.72	340'			340-345: Light gray, fine grained, limestone	S-50	
433.72	345'			345-350: Light gray, fine grained, limestone with black shale	S-51	
428.72	350'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project

Site: Iatan Generating Station

Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				350-355: Light gray, fine grained, limestone with black shale.	S-52	
423.72	355'					
				355-360: Light gray to buff, fine grained, limestone with black shale.	S-53	
418.72	360'					
				360-365: Light gray to buff, fine grained, limestone	S-54	
413.72	365'					
				365-370: Light gray to buff, fine grained, limestone with bluish green to black shale.	S-55	
408.72	370'					
				370-375: Light gray to buff, fine grained, limestone with bluish green to black shale.	S-56	
403.72	375'					
				375-380: Dark gray, fissile, shale.	S-57	
398.72	380'					
				380-385: Dark gray, fissile, shale	S-58	
393.72	385'					
				385-390: Bluish green shale.	S-59	
388.72	390'					

Notes/Comments:

Missouri Department of Natural Resources
Divison of Geology and Land Survey
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Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				390-395: Bluish green to black, fissile shale	S-60	
383.72	395'			395-400: Bluish green to black, shale	S-61	
378.72	400'			400-405: Dark gray to black, fissile shale	S-62	
373.72	405'			405-410: Dark gray to black, fissile shale	S-63	
368.72	410'			410-415: Dark gray to black , fissile shale	S-64	
363.72	415'			415-420: Dark gray to black , fissile shale	S-65	
358.72	420'			420-425: Dark gray, fissile shale with slight amounts of buff fine grained limestone	S-66	
353.72	425'			425-430: Dark gray, fissile shale with slight amounts of buff fine grained limestone	S-67	
348.72	430'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				430-435: Dark gray, fissile, shale	S-68	
343.72	435’			435-440: Dark gray, fissile, shale	S-69	
338.72	440’			440-445: Dark gray, fissile, shale	S-70	
333.72	445’			445-450: Dark gray, fissile, shale	S-71	
328.72	450’			450-455: Dark gray, fissile, shale	S-72	
323.72	455’			455-460: Dark gray, fissile, shale	S-73	
318.72	460’			460-465: Dark gray, fissile, shale	S-74	
313.72	465’			465-470: Dark gray, fissile, shale	S-75	
308.72	470’					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				470-475: Dark gray, fissile, shale	S-76	
303.72	475'			475-480: Dark gray, fissile, shale	S-77	Oil
298.72	480'			480-485: Dark gray, fissile, shale with light brown, fine grained, limestone	S-78	
293.72	485'			485-490: Dark gray, fine grained, limestone with dark gray to greenish gray, shale	S-79	
288.72	490'			490-495: Dark gray, fine grained, limestone with dark gray to greenish gray, fissile, shale	S-80	
283.72	495'			495-500: Dark gray, fissile, shale	S-81	
278.72	500'			500-505: Dark gray to black, shale	S-82	
273.72	505'			505-510: Black, dark gray to bluish green fissile, shale with buff, fine grained, limestone	S-83	
268.72	510'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				510-515: Dark gray to black, fissile shale	S-84	
263.72	515'			515-520: Buff to light brown, fine grained, limestone with dark gray to bluish green to black, fissile, shale	S-85	
258.72	520'			520-525: Buff to light brown, fine grained, limestone with dark gray to bluish green to black, fissile, shale	S-86	
253.72	525'			525-530: Buff to light brown, fine grained, limestone with dark gray to bluish green to black, fissile, shale	S-87	
248.72	530'			530-535: Buff to light brown, fine grained, limestone with dark gray to bluish green to black, fissile, shale	S-88	
243.72	535'			535-540: Dark gray to greenish to black, fissile, shale	S-89	
238.72	540'			540-545: Dark gray to greenish to black, fissile, shale with slight amount of buff, fine grained, limestone	S-90	
233.72	545'			545-550: Dark gray to greenish to black, fissile, shale with slight amount of buff, fine grained, limestone	S-91	
228.72	500'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project

Site: Iatan Generating Station

Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				550-555: Greenish, sandy silty shale, with black, fissile, shale	S-92	
223.72	555'			555-560: Black to dark gray, fissile, shale	S-93	
218.72	560'			560-565: Black, fissile, shale	S-94	
213.72	565'			565-570: Black, fissile, shale	S-95	
208.72	570'			570-575: Black, fissile, shale with coal	S-96	
203.72	575'			575-580: Green to black, fissile, shale	S-97	
198.72	580'			580-585: Light gray to buff, fine grained, limestone	S-98	
193.72	585'			585-590: Light gray to buff, fine grained, limestone with green shale	S-99	
188.72	590'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				590-595: Black, fissile, shale	S-100	
183.72	595'			595-600: Black, fissile, shale	S-101	
178.72	600'			600-605: Light gray to buff, fine grained, limestone with black, fissile shale	S-102	
173.72	605'			605-610: Light gray to buff, fine grained, limestone with black, fissile shale	S-103	
168.72	610'			610-615: Black, fissile, shale, with slight amount of limestone	S-104	
163.72	615'			615-620: Black to gray, fissile, shale	S-105	
158.72	620'			620-625: Light gray, fine grained, limestone with bluish green to black, fissile, shale	S-106	
153.72	625'			625-630: Light gray to gray, silty shale	S-107	
148.72	630'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				630-635: Light gray to gray, silty shale	S-108	
143.72	635'			635-640: Light gray to buff, fine grained, limestone with light gray to gray, silty shale	S-109	
138.72	640'			640-645: Gray to black, fissile, shale	S-110	
133.72	645'			645-650: Black, fissile, shale	S-111	
128.72	650'			650-655: Black, fissile, shale	S-112	
123.72	655'			655-660: Black, fissile, shale	S-113	
118.72	660'			660-665: Black, fissile, shale	S-114	
113.72	665'			665-670: Black, fissile, shale with light gray to buff, fine grained, limestone	S-115	
108.72	670'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				670-675: Black, fissile, shale	S-116	
103.72	675'			675-680: Black to gray, fissile, shale	S-117	
98.72	680'			680-685: Black to gray, fissile, shale	S-118	
93.72	685'			685-690: Black to gray, fissile, shale	S-119	
88.72	690'			690-695: Black to gray, fissile, shale	S-120	
83.72	695'			695-700: Black to gray, fissile, shale	S-121	
78.72	700'			700-705: Black to gray, fissile, shale	S-122	
73.72	705'			705-710: Black to gray, fissile, shale	S-123	
68.72	710'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				710-715: Buff to light gray, fine grained, limestone with black, fissile, shale	S-124	
63.72	715'			715-720: Buff to light gray, fine grained, limestone with black, fissile, shale	S-125	
58.72	720'			720-725: Gray, fissile, shale	S-126	
53.72	725'			725-730: Gray to black, fissile, shale with light gray to buff, fine grained, limestone	S-127	
48.72	730'			730-735: Gray to black to brown, fissile, shale	S-128	
43.72	735'			735-740: Gray to black, fissile, shale	S-129	
38.72	740'			740-745: Gray to black, fissile, shale	S-130	
33.72	745'			745-750: Gray to black to brown, fissile shale to silty shale	S-131	
28.72	750'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				750-755: Gray to black, fissile, shale	S-132	
23.72	755'			755-760: Gray to black, fissile, shale	S-133	
18.72	760'			760-765: Gray to black, fissile, shale	S-134	
13.72	765'			765-770: Gray to black, fissile, shale	S-135	
8.72	770'			770-775: Gray to black, fissile, shale	S-136	
3.72	775'			775-780: Gray to black, fissile, shale	S-137	
-1.28	780'			780-785: Gray to black, fissile, shale	S-138	
-6.28	785'			785-790: Gray to black, fissile, shale	S-139	
-11.28	790'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				790-795: Gray to black, fissile, shale	S-140	
-16.28	795'			795-800: Gray to black, fissile, shale	S-141	
-21.28	800'			800-805: Gray to black, fissile, shale	S-142	
-26.28	805'			805-810: Gray to black, fissile, shale	S-143	
-31.28	810'			810-815: Dark gray to brownish to yellow to black, fissile, shale to silty shale	S-144	
-36.28	815'			815-820: Dark gray to greenish gray to black, fissile, shale	S-145	
-41.28	820'			820-825: Dark gray to greenish gray to black, fissile, shale	S-146	
-46.28	825'			825-830: Dark gray to greenish gray to black, fissile, shale	S-147	
-51.28	830'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				830-835: Black, fissile, shale	S-148	
-56.28	835'			835-840: Black to dark gray, fissile, shale	S-149	
-61.28	840'			840-845: Black to dark gray, fissile, shale	S-150	
-66.28	845'			845-850: Black to dark gray, fissile, shale	S-151	
-71.28	850'			850-855: Black to dark gray, fissile, shale	S-152	
-76.28	855'			855-860: Black to dark gray, fissile, shale	S-153	
-81.28	860'			860-865: Black to dark gray, fissile, shale	S-154	
-86.28	865'			865-870: Black to dark gray, fissile, shale	S-155	
-91.28	870'					

Notes/Comments:

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Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				870-875: Black to dark gray, fissile, shale	S-156	
-96.28	875'			875-880: Black to dark gray, fissile, shale	S-157	
-101.28	880'			880-885: Black to dark gray, fissile, shale	S-158	
-106.28	885'			885-890: Black to dark gray, fissile, shale	S-159	
-111.28	890'			890-895: Black to dark gray, fissile, shale	S-160	
-116.28	895'			895-900: Black to dark gray, fissile, shale	S-161	
-121.28	900'			900-905: Black to dark gray, fissile, shale	S-162	
-126.28	905'			905-910: Black to dark gray, fissile, shale	S-163	
-131.28	910'					

Notes/Comments:

Missouri Department of Natural Resources
Divison of Geology and Land Survey
Geological Survey Program

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				910-915: Black to dark gray, fissile, shale	S-164	
-136.28	915'					
				915-920: Black to dark gray, fissile, shale	S-165	
-141.28	920'					
				920-925: Black to dark gray, fissile, shale	S-166	
-146.28	925'					
				925-930: Black to dark gray, fissile, shale	S-167	
-151.28	930'					
				930-935: Black to dark gray, fissile, shale	S-168	
-156.28	935'					
				935-940: Greenish gray to black to brown to dark gray, fissile, shale	S-169	
-161.28	940'					
				940-945: Greenish gray to black to brown to dark gray, fissile, shale	S-170	
-166.28	945'					
				945-950: Greenish gray to black to brown to dark gray, fissile, shale	S-171	
-171.28	950'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				950-955: Gray to black , fissile shale with gray to white, cemented to friable, quartz sand	S-172	
-176.28	955'			955-960: Gray to black , fissile shale with gray to white, cemented to friable, quartz sand	S-173	
-181.28	960'			960-965: Gray to black , fissile shale with gray to white, cemented to friable, quartz sand	S-174	
-186.28	965'			965-970: Gray to black , fissile shale with gray to white, cemented to friable, quartz sand	S-175	
-191.28	970'			970-975: Gray to black , fissile shale with gray to white, cemented to friable, quartz sand	S-176	
-196.28	975'			975-980: Gray to black , fissile shale with gray to white, cemented to friable, quartz sand	S-177	
-201.28	980'			980-985: Gray to black , fissile shale with gray to white, cemented to friable, quartz sand	S-178	
-206.28	985'			985-990: Gray to black , fissile shale with gray to white, cemented to friable, quartz sand	S-179	
-211.28	990'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				990-995: Gray to black , fissile shale with gray to white, cemented to friable, quartz sand -pyrite crystals on shale	S-180	
-216.28	995'			995-1000: Black to dark gray, fissile, shale	S-181	
-221.28	1000'			1000-1005: Dark gray to black, fissile, shale with gray to white, quartz sand	S-182	
-226.28	1005'			1005-1010: Dark gray to black, fissile, shale with gray to white, quartz sand	S-183	
-231.28	1010'			1010-1015: Dark gray to black, fissile, shale with gray to white, quartz sand	S-184	
-236.28	1015'			1015-1020: Dark gray to black, fissile, shale with gray to white, quartz sand	S-185	
-241.28	1020'			1020-1025: Dark gray to black, fissile, shale with gray to white, quartz sand	S-186	
-246.28	1025'			1025-1030: Dark gray to black, fissile, shale	S-187	
-251.28	1030'					

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1030-1035: Dark gray to black, fissile, shale	S-188	
-256.28	1035'			1035-1040: Dark gray to black, fissile, shale	S-189	
-261.28	1040'			1040-1045: Dark gray to black, fissile, shale	S-190	
-266.28	1045'			1045-1050: Dark gray to black, fissile, shale	S-191	
-271.28	1050'			1050-1055: Dark gray to black, fissile, shale	S-192	
-276.28	1055'			1055-1060: Dark gray to black, fissile, shale	S-193	
-281.28	1060'			1060-1065: Dark gray to black, fissile, shale	S-194	
-286.28	1065'			1065-1070: Dark gray to black, fissile, shale	S-195	
-291.28	1070'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1070-1075: Gray to dark gray to black, fissile, shale	S-196	
-296.28	1075'			1075-1080: Gray to dark gray to black, fissile shale with white to gray cemented to friable, quartz sand	S-197	
-301.28	1080'			1080-1085: Gray to dark gray to black, fissile shale with white to gray cemented to friable, quartz sand	S-198	
-306.28	1085'			1085-1090: Gray to dark gray to black, fissile shale with white to gray cemented to friable, quartz sand	S-199	
-311.28	1090'			1090-1095: Gray to dark gray to greenish gray to black, fissile shale	S-200	
-316.28	1095'			1095-1100: Gray to dark gray to greenish gray to black, fissile shale	S-201	
-321.28	1100'			1100-1105: Gray to dark gray to greenish gray to black, fissile shale	S-202	
-326.28	1105'			1105-1110: Gray to dark gray to greenish gray to black, fissile shale	S-203	
-331.28	1110'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1110-1115: Gray to dark gray to greenish gray to black, fissile shale	S-204	
-336.28	1115'			1115-1120: Gray to dark gray to greenish gray to black, fissile shale	S-205	
-341.28	1120'			1120-1125: Gray to dark gray to greenish gray to black, fissile shale	S-206	
-346.28	1125'			1125-1130: Gray to dark gray to greenish gray to black, fissile shale	S-207	
-351.28	1130'			1130-1135: Dark gray to greenish gray to black shale with white to gray, fine grained, cemented to friable, quartz sand	S-208	
-356.28	1135'			1135-1140: Dark gray to greenish gray to black shale with white to gray, fine grained, cemented to friable, quartz sand	S-209	
-361.28	1140'			1140-1145: Dark gray to greenish gray to black shale with white to gray, fine grained, cemented to friable, quartz sand	S-210	
-366.28	1145'			1145-1150: Dark gray to greenish gray to black shale with white to gray, fine grained, cemented to friable, quartz sand	S-211	
-371.28	1150'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1150-1155: Dark gray to greenish gray to black shale with white to gray, fine grained, cemented to friable, quartz sand	S-212	
-376.28	1155'			1155-1160: Dark gray to greenish gray to black shale with white to gray, fine grained, cemented to friable, quartz sand	S-213	
-381.28	1160'			1160-1165: Dark gray to greenish gray to black shale with white to gray, fine grained, cemented to friable, quartz sand	S-214	
-386.28	1165'			1165-1170: Dark gray to greenish gray to black shale with white to gray, fine grained, cemented to friable, quartz sand	S-215	
-391.28	1170'			1170-1175: **Meramecian Series** Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-216	
-396.28	1175'			1175-1180: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-217	
-401.28	1180'			1180-1185: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-218	
-406.28	1185'			1185-1190: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-219	
-411.28	1190'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1190-1195: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-220	
-416.28	1195'			1195-1200: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-221	
-421.28	1200'			1200-1205: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-222	
-426.28	1205'			1205-1210: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-223	
-431.28	1210'			1210-1215: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-224	
-436.28	1215'			1215-1220: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-225	
-441.28	1220'			1220-1225: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-226	
-446.28	1225'			1225-1230: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-227	
-451.28	1230'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1230-1235: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-228	
-456.28	1235'			1235-1240: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-229	
-461.28	1240'			1240-1245: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-230	
-466.28	1245'			1245-1250: Buff to light brown, microcrystalline to fine grained, limestone with greenish gray to black, fissile shale	S-231	
-471.28	1250'			1250-1255: **Burlington-Keokuk Limestone** Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-232	
-476.28	1255'			1255-1260: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-233	
-481.28	1260'			1260-1265: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-234	
-486.28	1265'			1265-1270: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-235	
-491.28	1270'					

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project
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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1270-1275: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-236	
-496.28	1275'			1275-1280: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-237	
-501.28	1280'			1280-1285: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-238	
-506.28	1285'			1285-1290: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-239	
-511.28	1290'			1290-1295: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-240	
-516.28	1295'			1295-1300: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-241	
-521.28	1300'			1300-1305: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-242	
-526.28	1305'			1305-1310: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-243	
-531.28	1310'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1310-1315: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-244	
-536.28	1315'			1315-1320: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-245	
-541.28	1320'			1320-1325: Light gray to buff, fine grained, limestone with white to gray fossiliferious chert to chert. Greenish gray to black, fissile shale	S-246	
-546.28	1325'			1325-1330: **Slough possibly from Pennsylvania System** Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-247	Complications from drilling made interpretation of strata from cuttings collected from a drilling depth below 1325 feet impractical.
-551.28	1330'			1330-1335: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-248	
-556.28	1335'			1335-1340: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-249	
-561.28	1340'			1340-1345: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-250	
-566.28	1345'			1345-1350: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-251	
-571.28	1350'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1350-1355: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-252	
-576.28	1355'			1355-1360: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-253	
-581.28	1360'			1360-1365: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-254	
-586.28	1365'			1365-1370: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-255	
-591.28	1370'			1370-1375: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-256	
-596.28	1375'			1375-1380: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-257	
-601.28	1380'			1380-1385: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-258	
-606.28	1385'			1385-1390: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-259	
-611.28	1390'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1390-1395: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-260	
-616.28	1395'			1395-1400: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-261	
-621.28	1400'			1400-1405: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-262	
-626.28	1405'			1405-1410: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-263	
-631.28	1410'			1410-1415: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-264	
-636.28	1415'			1415-1420: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-265	
-641.28	1420'			1420-1425: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-266	
-646.28	1425'			1425-1430: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-267	
-651.28	1430'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1430-1435: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-268	
-656.28	1435'			1435-1440: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-269	
-661.28	1440'			1440-1445: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-270	
-666.28	1445'			1445-1450: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-271	
-671.28	1450'			1450-1455: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-272	
-676.28	1455'			1455-1460: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-273	
-681.28	1460'			1460-1465: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-274	
-686.28	1465'			1465-1470: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-275	
-691.28	1470'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1470-1475: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-276	
-696.28	1475'			1475-1480: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-277	
-701.28	1480'			1480-1485: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-278	
-706.28	1485'			1485-1490: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-279	
-711.28	1490'			1490-1495: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-280	
-716.28	1495'			1495-1500: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-281	
-721.28	1500'			1500-1505: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-282	
-726.28	1505'			1505-1510: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-283	
-731.28	1510'					

Notes/Comments:

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1510-1515: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-284	
-736.28	1515'			1515-1520: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-285	
-741.28	1520'			1520-1525: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-286	
-746.28	1525'			1525-1530: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-287	
-751.28	1530'			1530-1535: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-288	
-756.28	1535'			1535-1540: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-289	
-761.28	1540'			1540-1545: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-290	
-766.28	1545'			1545-1550: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-291	
-771.28	1550'					

Notes/Comments:

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Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1550-1555: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-292	
-776.28	1555'			1555-1560: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-293	
-781.28	1560'			1560-1565: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-294	
-786.28	1565'			1565-1570: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-295	
-791.28	1570'			1570-1575: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-296	
-796.28	1575'			1575-1580: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-297	
-801.28	1580'			1580-1585: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-298	
-806.28	1585'			1585-1590: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-299	
-811.28	1590'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1590-1595: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-300	
-816.28	1595'			1595-1600: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-301	
-821.28	1600'			1600-1605: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-302	
-826.28	1605'			1605-1610: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-303	
-831.28	1610'			1610-1615: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-304	
-836.28	1615'			1615-1620: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-305	
-841.28	1620'			1620-1625: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-306	
-846.28	1625'			1625-1630: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-307	
-851.28	1630'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1630-1635: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-308	
-856.28	1635'			1635-1640: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-309	
-861.28	1640'			1640-1645: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-310	
-866.28	1645'			1645-1650: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-311	
-871.28	1650'			1650-1655: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-312	
-876.28	1655'			1655-1660: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-313	
-881.28	1660'			1660-1665: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-314	
-886.28	1665'			1665-1670: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-315	
-891.28	1670'					

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1670-1675: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-316	
-896.28	1675'			1675-1680: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-317	
-901.28	1680'			1680-1685: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-318	
-906.28	1685'			1685-1690: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-319	
-911.28	1690'			1690-1695: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-320	
-916.28	1695'			1695-1700: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-321	
-921.28	1700'			1700-1705: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-322	
-926.28	1705'			1705-1710: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-323	
-931.28	1710'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1710-1715: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-324	
-936.28	1715'			1715-1720: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-325	
-941.28	1720'			1720-1725: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-326	
-946.28	1725'			1725-1730: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-327	
-951.28	1730'			1730-1735: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-328	
-956.28	1735'			1735-1740: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-329	
-961.28	1740'			1740-1745: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-330	
-966.28	1745'			1745-1750: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-331	
-971.28	1750'					

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project

Site: Iatan Generating Station

Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1750-1755: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-332	
-976.28	1755'			1755-1760: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-333	
-981.28	1760'			1760-1765: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-334	
-986.28	1765'			1765-1770: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-335	
-991.28	1770'			1770-1775: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-336	
-996.28	1775'			1775-1780: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-337	
-1001.28	1780'			1780-1785: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-338	
-1006.28	1785'			1785-1790: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-339	
-1011.28	1790'					

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1790-1795: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-340	
-1016.28	1795'			1795-1800: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-341	
-1021.28	1800'			1800-1805: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-342	
-1026.28	1805'			1805-1810: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-343	
-1031.28	1810'			1810-1815: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-344	
-1036.28	1815'			1815-1820: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-345	
-1041.28	1820'			1820-1825: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-346	
-1046.28	1825'			1825-1830: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-347	
-1051.28	1830'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1830-1835: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-348	
-1056.28	1835'			1835-1840: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-349	
-1061.28	1840'			1840-1845: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-350	
-1066.28	1845'			1845-1850: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-351	
-1071.28	1850'			1850-1855: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-352	
-1076.28	1855'			1855-1860: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-353	
-1081.28	1860'			1860-1865: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-354	
-1086.28	1865'			1865-1870: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-355	
-1091.28	1870'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1870-1875: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-356	
-1096.28	1875'			1875-1880: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-357	
-1101.28	1880'			1880-1885: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-358	
-1106.28	1885'			1885-1890: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-359	
-1111.28	1890'			1890-1895: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-360	
-1116.28	1895'			1895-1900: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-361	
-1121.28	1900'			1900-1905: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-362	
-1126.28	1905'			1905-1910: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-363	
-1131.28	1910'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1910-1915: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-364	
-1136.28	1915'			1915-1920: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-365	
-1141.28	1920'			1920-1925: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-366	
-1146.28	1925'			1925-1930: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-367	
-1151.28	1930'			1930-1935: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-368	
-1156.28	1935'			1935-1940: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-369	
-1161.28	1940'			1940-1945: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-370	
-1166.28	1945'			1945-1950: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-371	
-1171.28	1950'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1950-1955: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-372	
-1176.28	1955'			1955-1960: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-373	
-1181.28	1960'			1960-1965: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-374	
-1186.28	1965'			1965-1970: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-375	
-1191.28	1970'			1970-1975: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-376	
-1196.28	1975'			1975-1980: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-377	
-1201.28	1980'			1980-1985: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-378	
-1206.28	1985'			1985-1990: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-379	
-1211.28	1990'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				1990-1995: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-380	
-1216.28	1995'					
				1995-2000: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-381	
-1221.28	2000'					
				2000-2005: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-382	
-1226.28	2005'					
				2005-2010: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-383	
-1231.28	2010'					
				2010-2015: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-384	
-1236.28	2015'					
				2015-2020: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-385	
-1241.28	2020'					
				2020-2025: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-386	
-1246.28	2025'					
				2025-2030: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-387	
-1251.28	2030'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				2030-2035: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-388	
-1256.28	2035'			2035-2040: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-389	
-1261.28	2040'			2040-2045: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-390	
-1266.28	2045'			2045-2050: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-391	
-1271.28	2050'			2050-2055: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-392	
-1276.28	2055'			2055-2060: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-393	
-1281.28	2060'			2060-2065: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-394	
-1286.28	2065'			2065-2070: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-395	
-1291.28	2070'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Iatan Generating Station
Hole Exploratory Borehole #3

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				2070-2075: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-396	
-1296.28	2075'			2075-2080: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-397	
-1301.28	2080'			2080-2085: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-398	
-1306.28	2085'			2085-2090: Slough is black to dark gray to greenish gray, shale. Possibly 1/10th of a percent is from the formation at depth.	S-399	
-1311.28	2090'			Bottom of EXP#3		
-1316.28	2095'					
-1321.28	2100'					
-1326.28	2105'					
-1331.28	2110'					

Notes/Comments:

APPENDIX 3.H - DESCRIPTIVE STRATIGRAPHIC LOG OF EXPLORATORY BOREHOLE #4 AT THE SIOUX POWER PLANT SITE IN FLORISSANT, ST. LOUIS COUNTY, MISSOURI

STRATIGRAPHIC DESCRIPTION

Fill Material (0-2 feet depth): This unit contains approximately two feet of limestone gravel (Drilling Pad).

Alluvium Material (2-91 feet depth): This unit contains light brown to yellowish brown silty clays to light gray to gray, fine to coarse grained, well rounded to sub rounded to angular, calcite to quartz sands. Minor amounts of black organic fragments were found throughout.

St. Louis Formation/Salem Formation (91-205 feet depth): This unit contains light gray to white, microcrystalline to fine grained, limestone to light gray to buff, fine to medium grained, limestone with white to black chert.

Warsaw Formation (205-340 feet depth): This unit contains intervals of gray to dark gray, medium to coarse grained limestone and dark gray, fine grained limey shale.

Burlington/Keokuk Formation (340-500 feet depth): This unit contains light gray to buff, fine to medium to coarse grained, limestone to cherty limestone. White to gray cherts to white to gray cherts with crinoid fragments also was found. Secondary minerals include glauconite.

Fern Glen Formation (500-615 feet depth): This unit contains light gray to dark gray to dark greenish gray, fine to medium grained, limestone with light gray to dark gray cherts. Intervals of dark greenish gray to dark gray, fine grained, limey shale. Minor fragments of crinoids and other fossils were found.

Chouteau Group (615-645 feet depth): This unit contains gray to dark gray, microcrystalline to fine to medium grained, limestone.

Grassy Creek Shale (645- 690 feet depth): This unit contains dark gray to gray, fissile, limey shale.

Bowling Green Dolomite (690-805 feet depth): This unit contains light gray to gray to buff, fine grained, and pitted dolomite.

Maquoketa Formation (805-965 feet depth): This unit contains dark gray to olive gray, fissile shale.

Kimmswick Limestone (965-1,060 feet depth): This unit contains buff to tan to dark gray, fine to medium to coarse grained, limestone.

Decorah Group (1,060-1,095 feet depth): This unit contains gray to dark gray, fine grained, limestone.

Plattin Group (1,095-1,260 feet depth): This unit contains light gray, fine grained, limestone. Minor amounts of bluish green shale and light gray chert.

Joachim Dolomite (1,260-1,345 feet depth): This unit contains gray to brown, fine grained, limestone with slight amounts of dark gray fine grained dolomite. White to light gray, well sorted, friable fine grained, rounded frosted quartz sand also were found, as well as minor amounts of bluish green shale.

St. Peter Sandstone (1,345-1,525 feet depth): This unit contains white to light gray to gray, well-sorted, friable, fine grained, rounded frosted quartz sand to fine grained, rounded to sub rounded, and calcite cemented quartz sand. Minor amounts of white chert and greenish gray shale also were found.

Cotter Dolomite (1,525-1,770 feet depth): This unit contains light gray, fine to medium to coarse, dolomite, with bluish green to dark gray shale, slight amounts of gray to white oolitic chert to gray to white chert. Minor amounts of white, friable, fine grained, rounded quartz sand were found. Secondary mineral present is pyrite.

Jefferson City Dolomite (1,770-2,020 feet depth): This unit contains buff to light gray to dark gray, fine to medium grained, dolomite with bluish green shale, slight amounts of white oolitic chert to white chert. Minor amounts of white, friable, fine grained, rounded quartz sand also were found.

Roubidoux Formation (2,020-2,105 feet depth): This unit contains light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. Light gray, fine to medium grained, dolomite were found, as well as, minor amounts of bluish green to grayish green shale and white chert.

Gasconade Dolomite (2,105-2,340 feet depth): This unit contains light gray, fine to medium grained, dolomite with white chert. Minor amounts of bluish green to green shale also were found.

Eminence Dolomite (2,340-2,595 feet depth): This unit contains light gray, fine to medium-grained dolomite to pitted to vuggy dolomite. Vugs filled with quartz druse and pyrite cubes also were found.

Potosi Dolomite (2,595-2,775.4 feet depth): This unit contains light gray, fine to medium grained, dolomite to vuggy dolomite mottled with bioturbation and laminations. Vugs filled with quartz druse and pyrite cubes also were found.

Derby-Doerun Dolomite (2,775.4-2,932.2 feet depth): This unit contains light gray to light tan to light brown, fine to medium grained, thin to massive bedded, dolomite. Interbeds of tan and light brown argillaceous fine grained dolomite also were found.

Davis Formation (2,932.2-3,061.6 feet depth): This unit contains intertwined (Transitional zone) variably glauconitic, very fine-grained sandstone, siltstone, and carbonate shale: interbedded carbonate facies ranging from packstone to mudstone. Interbedded within the entire sequence are debris flow beds represented by edgewise flat pebble conglomerates.

Bonneterre Formation (3,061.6-3,229 feet depth): This unit contains gray to dark gray, fine to medium grained, oolitic limestone to dolomite, variably glauconitic. Gray mottled dolomite with grainstones, and laminated, shaly dolomite were found, as well as, laminated limestones and dolomites with dark shales.

Eau Claire Formation (3,229-3,480.9 feet depth): This unit contains light gray to gray to brown to pink, fine to medium to coarse grained, interbedded siliciclastic carbonate containing dolomites, sandy dolomites, silts, shales and sandstones. Variably glauconitic and oolitic also were found.

Lamotte Sandstone (3,480.9-3,625 feet depth): The Lamotte Sandstone is comprised of two distinct sand bodies that gradually grade upwards from an alluvium fan facies into a fluvial plain or marine sequence. The upper sand body (3,480.9 – 2,597 feet depth) predominately consists of thin and thick sections that vary in colors of white, tan, brown, red, and gray, with grain size ranging from very fine to medium, rounded to sub-rounded, weakly friable to well cemented, quartz sand.

The basal sand body (3,597-3,625 feet depth) consists predominately of red to pink, with very fine to coarse-grained, rounded to angular, weakly friable arkosic sand containing quartz and feldspar pebbles. Cross bedding is mostly observed in the basal portion of this formation.

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Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Driller's Information

Drilling Company: Lanye Christensen
Driller:
Equipment Description: Atlas Copco RD -20

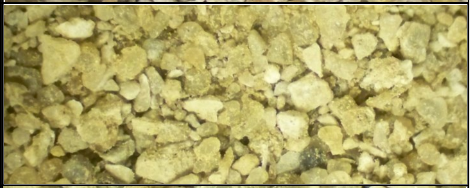
Contractor's Information

Primary Contractor:
P C Represetative:
Sub-Contractor:
S C Representative:

Site Location Information

County: St. Louis County
Quadrangle:
Land Grant:
Section:
Additional description:

Well longitude: 90° 20′ 15.8″ N
Well latitude: 38° 52′ 09.4″ W
Logged by: John Pate
Alias well ID:
Date drilled: Started 09/01/12 **; Ended** 6/23/12
Additional location description:

Elevation	Depth / Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
450.61′			0-2 : Gravel Fill: Drilling Pad		
			2-5: **Alluvium** Light brown to yellowish brown silty clays with light gray, fine grained limestone and quartz sands.		
445.61	5'		5-10: Light brown silty clays with light gray to brown, angular to sub angular calcite sands with minor amounts of well rounded quartz sands.		
440.61	10'		10-15 Light brown to light gray, well rounded, quartz and angular to sub-angular, calcite sands. ● Black coal fragments		
435.61	15'		15-20: Light brown to light gray, well rounded, quartz and angular to sub-angular, calcite sands. ● Black coal fragments		
430.61	20'		20-25: Light brown to light gray, well rounded, quartz and angular to sub-angular, calcite sands.		
425.61	25'		25-30: Light gray to gray, coarse, calcite sands with minor amounts of well rounded, quartz sands.		
420.61	30'				

Notes/Comments:

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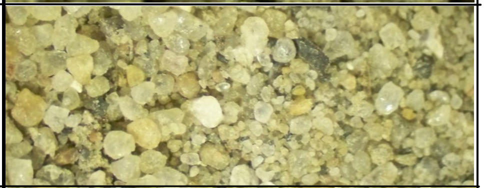
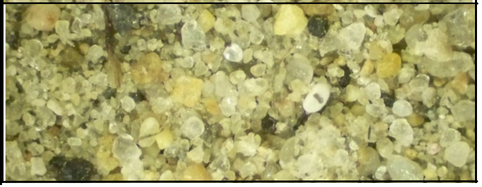
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
415.61	35'			30-35: Light gray to gray, angular to sub angular, coarse calcite sands with minor amounts of well round, quartz sands.	S-7	
410.61	40'			35-40: Light gray to gray, angular to sub angular, coarse calcite sands with well round, quartz sands.	S-8	
405.61	45'			40-45: Light gray to gray, angular to sub angular, coarse calcite sands with well round, quartz sands.	S-9	
400.61	50'			45-50: Light gray to gray, angular to sub angular, coarse calcite sands with well round, quartz sands.	S-10	
395.61	55'			50-55: Light gray to gray, angular to sub angular, coarse calcite sands with well rounded, quartz sands.	S-11	
390.61	60'			55-60: Light gray to gray, rounded to sub angular, fine grained, calcite sands with well rounded, quartz sands.	S-12	
385.61	65'			60-65: Light gray to gray, rounded to sub angular, fine grained, calcite sands with well rounded, quartz sands.	S-13	
380.61	70'			65-70: Light gray to gray, rounded to sub angular, fine grained, calcite sands with well rounded to sub angular, quartz sands.	S-14	

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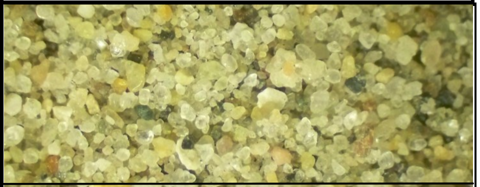
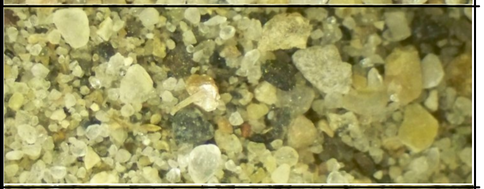
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				70-75: Light brown to light gray, well rounded to sub rounded, fine grained, quartz sand with minor amounts of well rounded calcite sand.	S-15	
375.61	75'			75-80: Light brown to light gray, well rounded to sub rounded, fine grained, quartz sand. ● Black organic fragments	S-16	
370.61	80'			80-85: Light brown to light gray, well rounded to sub rounded, fine grained, quartz sand. ● Black organic fragments	S-17	
365.61	85'			85-90: Light brown to light gray, well rounded to sub rounded, fine grained, quartz sand ● Black organic fragments	S-18	
360.61	90'			90-95: **St. Louis Formation/Salem Formation** Light brown to light gray, well rounded to sub rounded, fine grained, quartz sand with light gray, fine grained limestone fragments. ● Bedrock at 91 ft.	S-19	
355.61	95'			95-100: 100% light gray to white, microcrystalline to fine grained, limestone.	S-20	
350.61	100'			100-105: 100% light gray to white, microcrystalline to fine grained, limestone.	S-21	
345.61	105'			105-110: 100% light gray to white, microcrystalline to fine grained, limestone.	S-22	
340.61	110'					

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Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				110-115: 100% light gray to white, fine to coarse grained, limestone. • 114-116: Void	S-23	
335.61	115'			115-120: 97% light brown to brown to red, rounded to well rounded, coarse quartz to calcite sands, 3% light gray, fine grained, limestone. • 116-118: Void	S-24	
330.61	120'			120-125: 100% light gray, microcrystalline to fine grained, limestone • 124-125: Void	S-25	
325.61	125'			125-130: 95% light gray to white, microcrystalline to fine grained, limestone. 5% light brown to brown to red, rounded to well rounded, coarse quartz to calcite sands. • 125-129: Void	S-26	
320.61	130'			130-135: 97% light gray to white, fine grained, limestone. 3% brown calcite fragments	S-27	
315.61	135'			135-140: 99% light gray to white, fine grained, limestone. 1% brown calcite fragments	S-28	
310.61	140'			140-145: 99% light gray to white, fine grained, limestone. 1% brown calcite fragments	S-29	
305.61	145'			145-150: 100% light gray to buff to white, fine to medium grained, limestone	S-30	
300.61	150'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
295.61	155'			150-155: 100% light gray to buff to white, fine to medium grained, limestone	S-31	
290.61	160'			155-160: 100% light gray to buff to white, fine to medium grained, limestone.	S-32	
285.61	165'			160-165: 100% light gray to white, fine to medium grained, limestone.	S-33	
280.61	170'			165-170: 100% light gray , fine to medium grained, limestone.	S-34	
275.61	175'			170-175: 100% light gray , fine to medium grained, limestone.	S-35	
270.61	180'			175-180: 100% light gray, medium to coarse, limestone.	S-36	
265.61	185'			180-185: Salem Formation? 95% light gray to buff , fine grained, limestone. 5% light gray to white chert.	S-37	
260.61	190'			185-190: 95% light gray to buff, fine grained, limestone. 5% light gray to white chert.	S-38	

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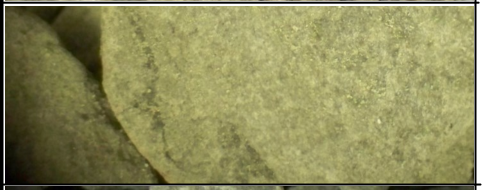
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				190-195: 97% light gray to buff, fine grained, limestone. 3% light gray to white chert.	S-39	
255.61	195'			195-200: 99% light gray to buff, fine to medium grained, limestone. 1% molted white to black chert.	S-40	
250.61	200'			200-205: 100% light gray to buff, medium grained, limestone.	S-41	
245.61	205'			205-210: **Warsaw Formation** 100% gray to dark gray, medium to coarse grained, limestone.	S-42	
240.61	210'			210-215: 100% gray to dark gray, medium to coarse grained, limestone.	S-43	
235.61	215'			215-220: 100% dark gray, fine grained, shaley to silty limestone.	S-44	
230.61	220'			220-225: 100% dark gray, fine grained, limey shale.	S-45	
225.61	225'			225-230: 100% dark gray, fine grained, limey shale.	S-46	
220.61	230'					

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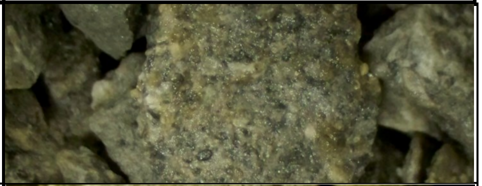
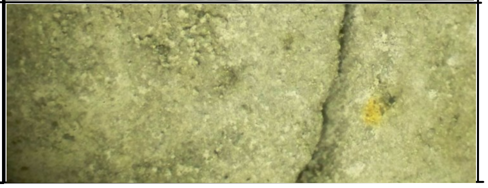
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				230-235 : 100% dark gray, coarse grained, limestone with intervals of dark gray limey shale.	S-47	
215.61	235'			235-240: 100% dark gray, coarse grained, limestone.	S-48	
210.61	240'			240-245: 100% dark gray, coarse grained, limestone.	S-49	
205.61	245'			245-250: 100% gray to dark gray, fine to coarse grained, limestone.	S-50	
200.61	250'			250-255: 100% gray, fine grained, limestone to silty limestone.	S-51	
195.61	255'			255-260: 100% gray, coarse grained, limestone with crinoid fragments.	S-52	
190.61	260'			260-265: 100% dark gray limey shale.	S-53	
185.61	265'			265-270: 100% dark gray limey shale.	S-54	
180.61	270'					

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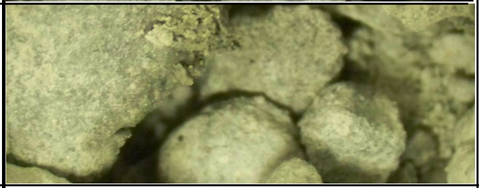
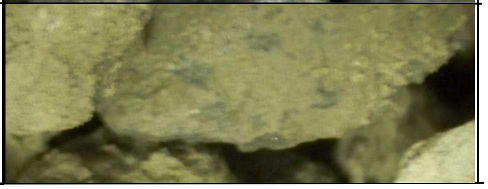
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				270-275: 100% dark gray limey shale.	S-55	
175.61	275'			275-280: 100% dark gray limey shale.	S-56	
170.61	280'			280-285: 100% dark gray limey shale.	S-57	
165.61	285'			285-290: 100% dark gray limey shale.	S-58	
160.61	290'			290-295: 100% dark gray limey shale.	S-59	
155.61	295'			295-300: 99% dark gray limey shale. 1% pyrite	S-60	
150.61	300'			300-305: 100% dark gray, fine grained limestone with intervals of dark gray shale.	S-61	
145.61	305'			305-310: 95% dark gray, fine grained limestone to shaly limestone. 5% dark gray shale.	S-62	
140.61	310'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				310-315: 95% dark gray, fine grained limestone to shaly limestone. 5% dark gray shale.	S-63	
135.61	315'			315-320: 95% gray to dark gray, fine to coarse grained, limestone to shaley limestone. 5% dark gray shale.	S-64	
130.61	320'			320-325 98% gray to dark gray, fine to coarse grain, limestone to shaley limestone. 2% dark gray shale.	S-65	
125.61	325'			325-330: 100% gray, fine to medium grained, limestone.	S-66	
120.61	330'			330-335: 100% gray, fine to coarse grain, limestone.	S-67	
115.61	335'			335-340: 99% gray, fine to coarse grained, limestone with fossil fragments. 1% white to gray chert	S-68	
110.61	340'			340-345: **Burlington/Keokuk Formation** 75% light gray, fine to coarse grained, limestone. 25% white to milky gray chert.	S-69	
105.61	345'			345-350: 50% buff to light gray, fine grained, limestone. 50% white to milky gray chert.	S-70	
1166.32	350'					

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Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				350-355: 75% white to light gray, coarse grained, limestone. 25% white to milky gray chert to fossiliferious chert.	S-71	
100.61	355'			355-360: 100% light gray, fine grained, limestone interbedded with white chert.	S-72	
95.61	360'			360-365: 10% light gray, fine grained, limestone. 90% white chert.	S-73	
90.61	365'			365-370: 15% light gray, fine to coarse grained, limestone. 85% white to milky chert.	S-74	
85.61	370'			370-375: 50% light gray, fine to coarse grained, limestone. 50% white to milky chert.	S-75	
80.61	375'			375-380: 50% light gray, fine to coarse grained, limestone. 50% white to milky chert.	S-76	
75.61	380'			380-385: 25% buff to light gray, fine to coarse grained, limestone to peppered with glauconitic. 75% white to milky chert to peppered with glauconitic chert.	S-77	
70.61	385'			385-390: 50% buff to light gray, fine to coarse grained, limestone. 50% white to milky chert.	S-78	
65.61	390'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				390-395 75% light gray, coarse grained, limestone. 25% white chert	S-79	
60.61	395'			395-400: 95% white to light gray, coarse grained, limestone. 5% white to gray chert.	S-80	
55.61	400'			400-405: 95% white to light gray, coarse grained, limestone. 5% white to gray chert.	S-81	
50.61	405'			405-410: 50% buff light gray, fine to coarse grained, limestone. 50% white chert	S-82	
45.61	410'			410-415: 90% light gray, medium to coarse grained, limestone. 10% gray to white chert to fossiliferious chert.	S-83	
40.61	415'			415-420: 90% light gray, medium to coarse grained, limestone. 10% gray to white chert to fossiliferious chert.	S-84	
35.61	420'			420-425: 90% light gray, medium to coarse grained, limestone. 10% gray to white chert.	S-85	
30.61	425'			425-430: 50% light gray, microcrystalline to fine grained, limestone. 50% gray to white chert	S-86	
25.61	430'					

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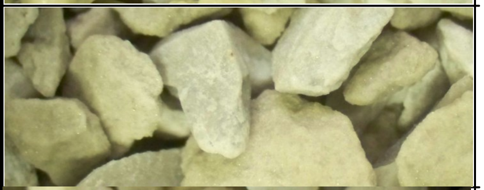
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
20.61	435’			430-435: 50% buff to light gray, coarse grained, limestone. 50% gray to white chert	S-87	
15.61	440’			435-440: 50% buff to light gray, coarse grained, limestone. 50% gray to white chert	S-88	
10.61	445’			440-445: 50% buff to light gray, fine grained, limestone. 50% gray to white chert	S-89	
5.61	450’			445-450: 74% buff to light gray, fine grained, limestone. 25% gray to white chert. 1% calcite crystals	S-90	
0.61	455’			450-455: 75% buff to light gray, fine grained, limestone. 25% gray to white chert.	S-91	
-4.39	460’			455-460: 80% buff to light gray, fine to coarse grained, limestone. 20% gray to white chert.	S-92	
-9.39	465’			460-465: 90%buff to light gray, fine to coarse grained, limestone. 10% gray to white chert to fossiliferious chert.	S-93	
-14.39	470’			465-470: 90%buff to light gray, fine to coarse grained, limestone. 10% gray to white chert.	S-94	

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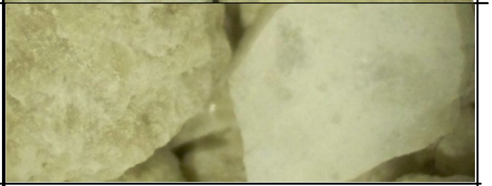
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				470-475: 93% buff to light gray, coarse grained, limestone. 7% gray to white chert.	S-95	
-19.39	475'			475-480: 75% buff to light gray, fine to coarse grained, limestone. 25% gray to white chert to fossiliferious chert.	S-96	
-24.39	480'			480-485: 25% buff to light gray, fine to coarse grained, limestone. 75% gray to white chert to fossiliferious chert.	S-97	
-29.39	485'			485-490: 50% buff to light gray, fine to coarse grained, limestone. 50% gray to white chert to fossiliferious chert.	S-98	
-34.39	490'			490-495: 99% light gray, coarse grained, limestone. 1% white chert.	S-99	
-39.39	495'			495-500 90% light gray, fine grained, limestone, 10% white chert.	S-100	
-44.39	500'			500-505: **Fern Glen Formation** 93% light gray to greenish gray, fine grained to coarse grained, limestone. 7% white chert.	S-101	
-49.39	505'			505-510: 93% light gray to greenish gray, fine to coarse grained, limestone. 7% white chert.	S-102	
-54.39	510'					

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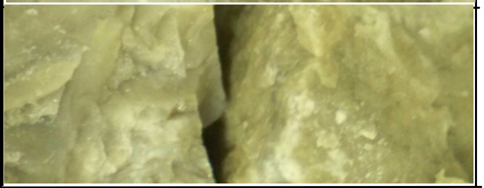
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				510-515: 75% buff to light gray, fine to coarse grained, limestone. 25% white chert.	S-103	
-59.39	515'			515-520: 90% buff to light gray to gray, fine to coarse grained, limestone. 10% white chert.	S-104	
-64.39	520'			520-525: 75% buff to light gray, fine grained , limestone. 25% white chert.	S-105	
-69.39	525'			525-530: 75% buff to dark gray, fine grained, limestone. 25% white to gray chert.	S-106	
-74.39	530'			530-535: 95% buff to dark gray, fine to coarse grained, limestone. 5% white to light gray to dark gray chert.	S-107	
-79.39	535'			535-540: 95% light gray to dark gray, fine grained, limestone. 5% light gray to dark gray chert	S-108	
-84.39	540'			540-545: 95% light gray to dark gray, fine grained, limestone. 5% light gray to dark gray chert	S-109	
-89.39	545'			545-550: 95% light gray to dark gray, fine grained, limestone. 5% light gray to dark gray chert	S-110	
-94.39	500’					

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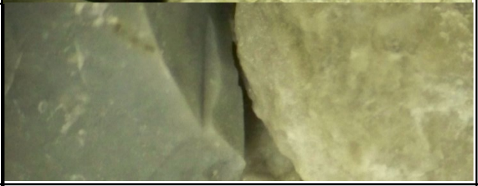
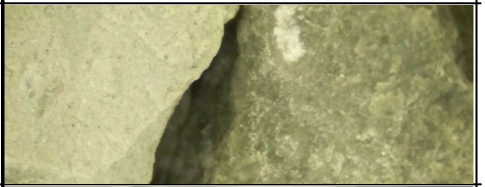
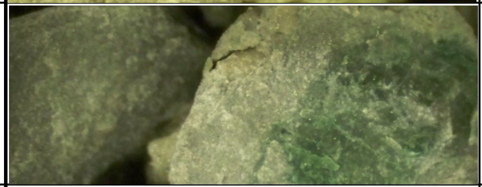
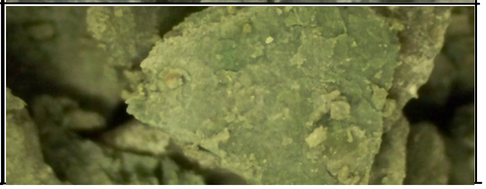
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				550-555: 90% light gray to dark gray, fine grained, limestone. 10% light gray to dark gray chert.	S-111	
-99.39	555'			555-560: 90% light gray to dark gray to dark greenish gray, fine grained, limestone. 10% light gray to dark gray chert.	S-112	
-104.39	560'			560-565: 95% dark gray to dark greenish gray, fine grained, limestone. 5% light gray to dark gray chert.	S-113	
-109.39	565'			565-570: 100% dark gray to dark greenish gray, limestone.	S-114	
-114.39	570'			570-575: 100% dark gray to dark greenish gray to dark red, fine grained, limestone.	S-115	
-119.39	575'			575-580: 50% light gray to dark gray to dark greenish gray, fine grained, limestone. 50% dark greenish gray to dark gray limey shale.	S-116	
-124.39	580'			580-585: 50% light gray to dark gray to dark greenish gray, fine grained, limestone. 50% dark greenish gray to dark gray limey shale. • Crinoid fragments	S-117	
-129.39	585'			585-590: 100% dark greenish gray to dark gray limey shale.	S-118	
-134.39	590'					

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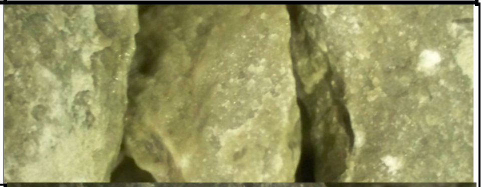
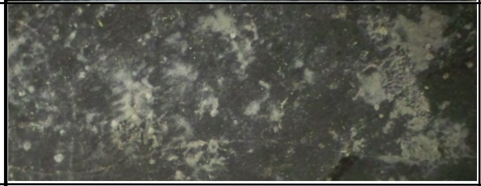
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				590-595: 10% light gray, fine grained, limestone. 90% dark greenish gray to dark gray limey shale. ● Crinoid fragments	S-119	
-139.39	595'			595-600: 50% brownish red to gray to dark gray, fine grained, limestone. 50% dark greenish gray limey shale.	S-120	
-144.39	600'			600-605: 50% brownish red to gray to dark gray, fine grained, limestone. 50% dark greenish gray limey shale.	S-121	
-149.39	605'			605-610: 100% brownish red to dark greenish gray to green, fine grained limestone.	S-122	
-154.39	610'			610-615: 100% light gray to greenish gray to dark gray, fine grained, limestone.	S-123	
-159.39	615'			615-620: **Chouteau Group** 100% gray, microcrystalline, limestone	S-124	
-164.39	620'			620-625: 100% gray to dark gray, microcrystalline to fine grained, limestone	S-125	
-169.39	625'			625-630: 100% gray to dark gray, microcrystalline to fine grained, limestone	S-126	
-174.39	630'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
-179.39	635'			630-635: 100% gray to dark gray, fine grained, limestone.	S-127	
-184.39	640'			635-640 100% gray to dark gray, fine to medium grained, limestone.	S-128	
-189.39	645'			640-645: 100% gray to dark gray, fine to medium grained, limestone.	S-129	
-194.39	650'			645-650: **Grassy Creek Formation** 50% gray to dark gray, fine to medium grained, limestone. 50% dark gray, fissile limey shale.	S-130	
-199.39	655'			650-655: 100% dark gray to black, fissile limey shale.	S-131	
-204.39	660'			655-660: 100% dark gray to black, fissile limey shale.	S-132	
-209.39	665'			660-665: 100% dark gray to black, fissile limey shale.	S-133	
-214.39	670'			665-670: No Sample Same As Above	S-134	

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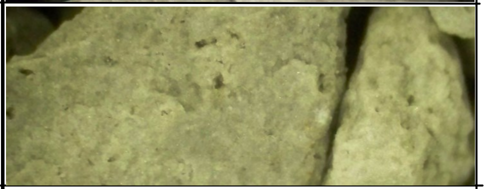
Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				670-675: 100% dark gray to black, fissile limey shale.	S-135	
-219.39	675'			675-680: 100% dark gray to black, fissile limey shale.	S-136	
-224.39	680'			680-685: 100% dark gray to black, fissile limey shale.	S-137	
-229.39	685'			685-690: 100% dark gray to black, fissile limey shale.	S-138	
-234.39	690'			690-695: **Bowling Green Dolomite** 90% light gray, fine grained, pitted dolomite to dolomite.10% black fissile shale.	S-139	
-239.39	695'			695-700: 100% light gray to gray, fine grained, pitted dolomite.	S-140	
-244.39	700'			700-705: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-141	
-249.39	705'			705-710: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-142	
-254.39	710'					

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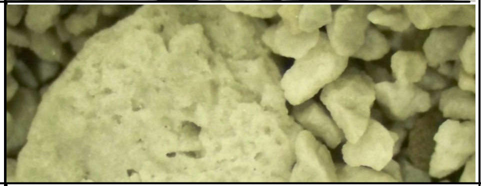
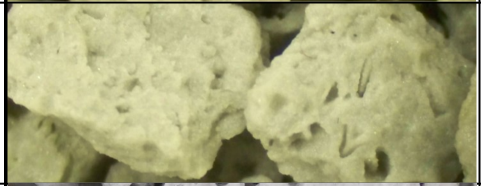
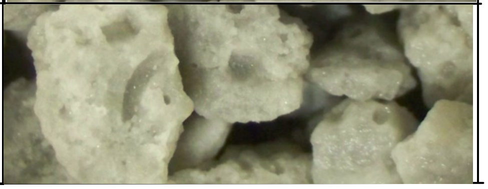
Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				710-715: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-143	
-259.39	715'			715-720: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-144	
-264.39	720'			720-725: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-145	
-269.39	725'			725-730: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-146	
-274.39	730'			730-735: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-147	
-279.39	735'			735-740: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-148	
-284.39	740'			740-745: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-149	
-289.39	745'			745-750: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-150	
-294.39	750'					

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Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				750-755: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-151	
-299.39	755'			755-760: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-152	
-304.39	760'			760-765: 100% light gray to gray, fine grained, pitted dolomite to dolomite.	S-153	
-309.39	765'			765-770: 100% light gray to greenish gray, fine grained, dolomite to glauconitic.	S-154	
-314.39	770'			770-775: 97% light gray to gray, fine grained, dolomite. 3% white chert.	S-155	
-319.39	775'			775-780: 100% buff to light gray, fine grained, pitted dolomite to dolomite.	S-156	
-324.39	780'			780-785: 100% buff to light gray, fine grained, pitted dolomite to dolomite.	S-157	
-329.39	785'			785-790: 100% buff to light gray, fine grained, pitted dolomite to dolomite.	S-158	
-334.39	790'					

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Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				790-795: 100% buff to light gray, fine grained, pitted dolomite to dolomite.	S-159	
-339.39	795'			795-800: 100% buff to light gray, fine grained, pitted dolomite to dolomite.	S-160	
-344.39	800'			800-805: 100% buff to light gray, fine grained, pitted dolomite to dolomite.	S-161	
-349.39	805'			805-810: **Maquoketa Formation** 50% buff to light gray, fine grained, pitted dolomite to dolomite. 50% dark gray to olive gray, fissile shale.	S-162	
-354.39	810'			810-815: 100% dark gray to olive gray, fissile shale.	S-163	
-359.39	815'			815-820: 100% dark gray to olive gray, fissile shale.	S-164	
-364.39	820'			820-825: 100% dark gray to olive gray, fissile shale.	S-165	
-369.39	825'			825-830: 100% dark gray to olive gray, fissile shale.	S-166	
-374.39	830'					

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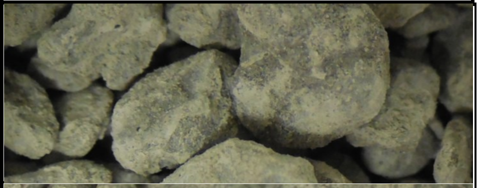
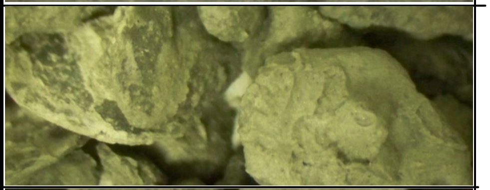
Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				830-835:	S-167	
-379.39	835'			835-840: 100% dark gray , fissile shale	S-168	
-384.39	840'			840-845: 100% dark gray , fissile shale	S-169	
-389.39	845'			845-850: 100% dark gray , fissile shale	S-170	
-394.39	850'			850-855: 100% dark gray , fissile shale	S-171	
-399.39	855'			855-860: 100% dark gray , fissile shale	S-172	
-404.39	860'			860-865: 100% dark gray , fissile shale	S-173	
-409.39	865'			865-870: 100% dark gray , fissile shale	S-174	
-414.39	870'					

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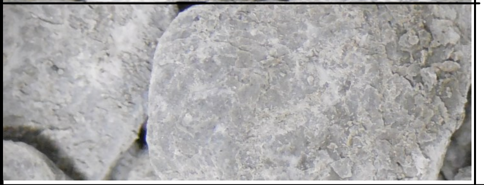
Project: Shallow Carbon Sequestration Demonstration Project

Site: Luecke Site

Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				870-875: 100% dark gray , fissile shale. Pyrite.	S-175	
-419.39	875'			875-880: 100% dark gray , fissile shale	S-176	
-424.39	880'			880-885: 100% dark gray , fissile shale	S-177	
-429.39	885'			885-890: 100% dark gray , fissile shale	S-178	
-434.39	890'			890-895: 100% dark gray , fissile shale	S-179	
-439.39	895'			895-900: 100% dark gray , fissile shale	S-180	
-444.39	900'			900-905: 100% dark gray , fissile shale	S-181	
-449.39	905'			905-910: 100% dark gray , fissile shale	S-182	
-454.39	910'					

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Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				910-915: 100% dark gray , fissile shale	S-183	
-459.39	915'			915-920: 100% dark gray , fissile shale	S-184	
-464.39	920'			920-925: 100% dark gray , fissile shale	S-185	
-469.39	925'			925-930: 100% dark gray , fissile shale	S-186	
-474.39	930'			930-935: 100% dark gray , fissile shale	S-187	
-479.39	935'			935-940: 100% dark gray , fissile shale	S-188	
-484.39	940'			940-945: 100% dark gray , fissile shale	S-189	
-489.39	945'			945-950: 100% dark gray , fissile shale	S-190	
-494.39	950'					

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Project:	Shallow Carbon Sequestration Demonstration Project
Site:	Luecke Site
Hole	Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				950-955: Transition Zone 100% dark gray, fine grained, shaley dolomite to dolomite.	S-191	
-499.39	955'			955-960: Transition Zone 50% buff to tan, fine to medium grained, limestone.50% dark gray, fine grained, shaley dolomite to dolomite.	S-192	
-504.39	960'			960-965: 75% buff to tan, fine to medium grained, limestone.25% dark gray, fine grained, shaley dolomite to dolomite.	S-193	
-509.39	965'			965-970: **Kimmswick Formation** 100% buff to tan , fine to medium grained, limestone.	S-194	
-514.39	970'			970-975: 100% buff to tan , fine to medium grained, limestone.	S-195	
-519.39	975'			975-980: 100% buff to tan , fine to medium grained, limestone.	S-196	
-524.39	980'			980-985: 100% buff to tan , medium grained, limestone.	S-197	
-529.39	985'			985-990: 100% buff to tan , medium grained to coarsely crystalline, limestone.	S-198	
-534.39	990'					

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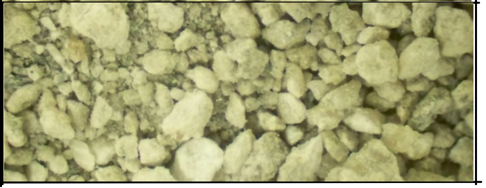
Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				990-995: 90% dark gray shale. 10% buff to tan, fine grained, limestone	S-199	
-539.39	995'			995-1000: 95% buff to tan, fine grained, limestone. 5% dark gray shale	S-200	
-544.39	1000'			1000-1005: 100% buff to tan, fine grained, limestone.	S-201	
-549.39	1005'			1005-1010: 100% buff to tan, fine grained, limestone.	S-202	
-554.39	1010'			1010-1015: Same As Above. No Sample.	S-203	
-559.39	1015'			1015-1020: 100% buff to tan, fine grained, limestone.	S-204	
-564.39	1020'			1020-1025: 70% buff to tan, fine grained, limestone. 30% dark gray shale	S-205	
-569.39	1025'			1025-1030: 95% buff to tan, fine grained, limestone. 5% dark gray shale	S-206	
-574.39	1030'					

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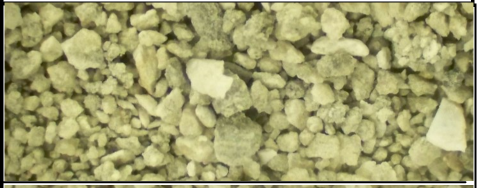
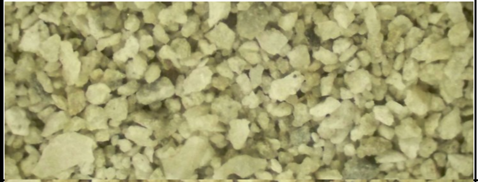
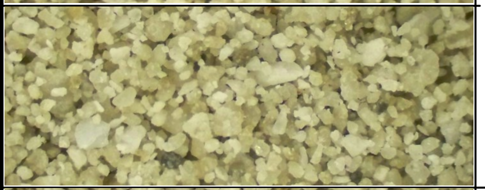
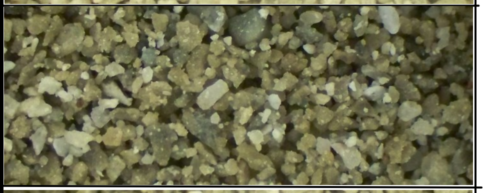
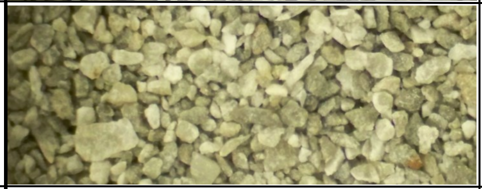
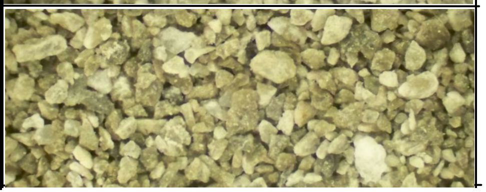
Project: Shallow Carbon Sequestration Demonstration Project

Site: Luecke Site

Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1030-1035: 100% gray, fine grained, limestone.	S-207	
-579.39	1035'			1035-1040: 100% buff to tan, fine grained, limestone.	S-208	
-584.39	1040'			1040-1045: 100% buff to tan, fine grained, limestone.	S-209	
-589.39	1045'			1045-1050: 100% buff to tan, fine grained, limestone.	S-210	
-594.39	1050'			1050-1055: 100% buff to gray, fine grained, limestone.	S-211	
-599.39	1055'			1055-1060: Transition Zone 100% buff to dark gray, fine grained, limestone.	S-212	
-604.39	1060'			1060-1065: **Decorah Group** 100% gray to dark gray, fine grained, limestone.	S-213	
-609.39	1065'			1065-1070: 100% gray to dark gray, fine grained, limestone.	S-214	
-614.39	1070'					

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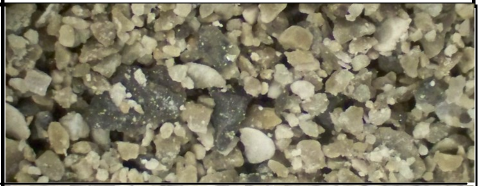
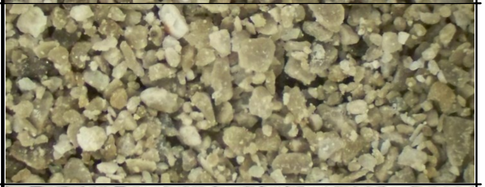
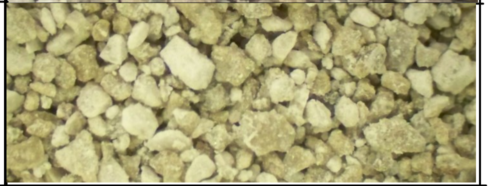
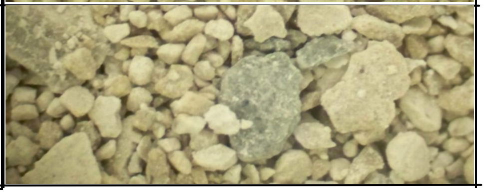
Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1070-1075: 100% gray to dark gray, fine grained, limestone.	S-215	
-619.39	1075'			1075-1080: 100% buff to gray, fine grained, limestone.	S-216	
-624.39	1080'			1080-1085: 100% buff to gray, fine grained, limestone.	S-217	
-629.39	1085'			1085-1090: 100% gray, fine grained, limestone.	S-218	
-634.39	1090'			1090-1095: 100% buff to gray, fine grained, limestone.	S-219	
-639.39	1095'			1095-1100: **Plattin Group** 100% light gray, fine grained, limestone.	S-220	
-644.39	1100'			1100-1105: 100% light gray, fine grained, limestone.	S-221	
-649.39	1105'			1105-1110: 99% light gray, fine grained, limestone. 1% bluish green shale.	S-222	
-654.39	1110'					

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Project: Shallow Carbon Sequestration Demonstration Project

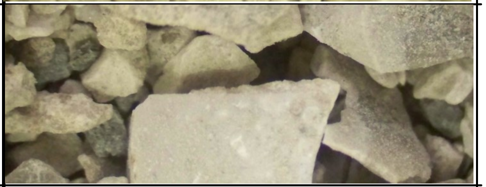
Site: Luecke Site

Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
-659.39	1115'			1110-1115: 100% light gray, fine grained, limestone	S-223	
-664.39	1120'			1115-1120: 100% light gray, fine grained, limestone	S-224	
-669.39	1125'			1120-1125: 100% light gray, fine grained, limestone	S-225	
-674.39	1130'			1125-1130: 100% light gray, fine grained, limestone	S-226	
-679.39	1135'			1130-1135: 100% light gray, fine grained, limestone	S-227	
-684.39	1140'			1135-1140: 100% light gray to gray, fine grained, limestone	S-228	
-689.39	1145'			1140-1145: 100% light gray to gray, fine grained, limestone	S-229	
-694.39	1150'			1145-1150: 100% buff to light gray, fine grained, limestone	S-230	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1150-1155: 100% buff to light gray, fine grained, limestone.	S-231	
-699.39	1155'			1155-1160: 100% light gray, fine grained, limestone.	S-232	
-704.39	1160'			1160-1165: 98% light gray, fine grained, limestone. 1% light gray chert. 1% bluish green shale.	S-233	
-709.39	1165'			1165-1170: 99% light gray, fine grained, limestone. 1% light gray chert.	S-234	
-714.39	1170'			1170-1175: 99% light, microcrystalline to fine grained, limestone. 1% light gray chert.	S-235	
-719.39	1175'			1175-1180: 97% light gray, fine grained, limestone. 2% bluish green shale, 1% light gray chert.	S-236	
-724.39	1180'			1180-1185: 100% light, fine grained, limestone.	S-237	
-729.39	1185'			1185-1190: 99% light, fine grained, limestone.	S-238	
-734.39	1190'					

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Project: Shallow Carbon Sequestration Demonstration Project
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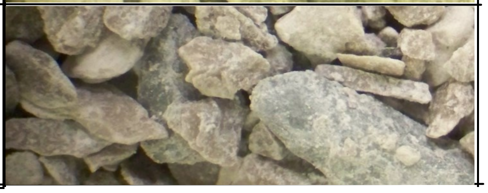
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1190-1195: 99% light gray to gray, fine grained, limestone. 1% bluish green shale.	S-239	
-739.39	1195'			1195-1200: 99% light gray to gray, fine grained, limestone. 1% bluish green shale.	S-240	
-744.39	1200'			1200-1205: 98% light gray to gray, fine grained, limestone. 2% bluish green shale.	S-241	
-749.39	1205'			1205-1210: 99% light gray to gray, fine grained, limestone. 1% bluish green shale.	S-242	
-754.39	1210'			1210-1215: 99% light gray to gray, fine grained, limestone. 1% bluish green shale.	S-243	
-759.39	1215'			1215-1220: 95% light gray to gray, fine grained, limestone. 5% bluish green shale.	S-244	
-764.39	1220'			1220-1225: 95% light gray to gray, fine grained, limestone. 5% bluish green shale.	S-245	
-769.39	1225'			1225-1230: 97% light gray to gray, fine grained, limestone. 3% bluish green shale.	S-246	
-774.39	1230'					

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Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1230-1235: 99% light gray to gray, fine grained, limestone.1% bluish green shale.	S-247	
-779.39	1235'			1235-1240: 98% light gray to gray, fine grained, limestone.2% bluish green shale.	S-248	
-784.39	1240'			1240-1245: 98% buff to light gray, fine grained, limestone.2% bluish green shale.	S-249	
-789.39	1245'			1245-1250: 95% gray, fine grained, limestone.5% dark green shale.	S-250	
-794.39	1250'			1250-1255: 99% gray, fine grained, limestone. 1% bluish green shale.	S-251	
-799.39	1255'			1255-1260: 100% gray, fine grained, limestone.	S-252	
-804.39	1260'			1260-1265: **Joachim Dolomite** 100% gray to brown, fine grained, limestone.	S-253	
-809.39	1265'			1265-1270: 99% gray to brown, fine grained, limestone. 1% green shale.	S-254	
-814.39	1270'					

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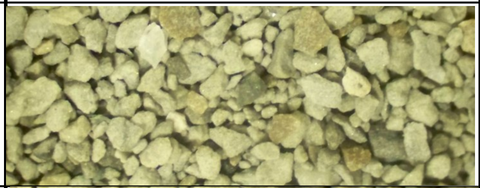
Project: Shallow Carbon Sequestration Demonstration Project

Site: Luecke Site

Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1270-1275: 98% buff to brown, fine grained, limestone. 2% bluish green shale.	S-255	
-819.39	1275'			1275-1280: 98% light gray to buff to brown, fine grained, limestone. 2% bluish green shale.	S-256	
-824.39	1280'			1280-1285: 98% light gray to buff, fine grained, limestone. 2% bluish green shale.	S-257	
-829.39	1285'			1285-1290: 99% light gray to buff, fine grained, limestone. 1% bluish green shale.	S-258	
-834.39	1290'			1290-1295: 94% light gray to buff, fine grained, limestone. 5% dark gray, fine grained, dolomite. 1% bluish green shale.	S-259	
-839.39	1295'			1295-1300: 93% gray to dark gray to buff, fine grained, limestone. 5% dark gray, fine grained, dolomite. 1% white, fine grained, well rounded quartz sand, 1% bluish green shale.	S-260	
-844.39	1300'			1300-1305: 97% gray to buff, fine grained, limestone. 3% dark gray, fine grained, dolomite	S-261	
-849.39	1305'			1305-1310: 99% gray to buff, fine grained, limestone. 1% dark gray, fine grained, dolomite	S-262	
-854.39	1310'					

Notes/Comments:

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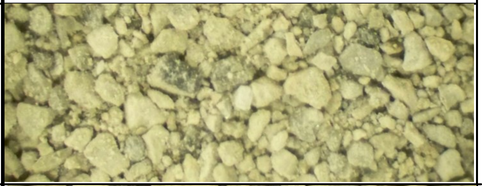
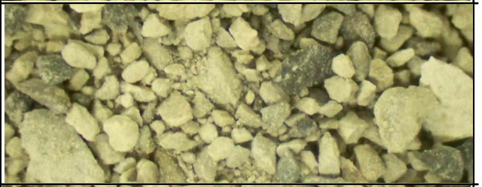
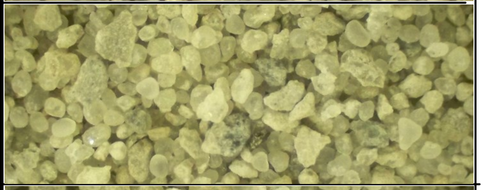
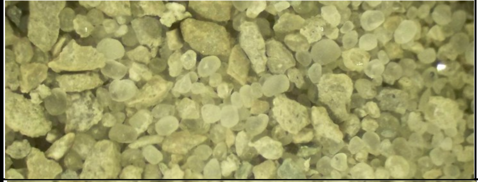
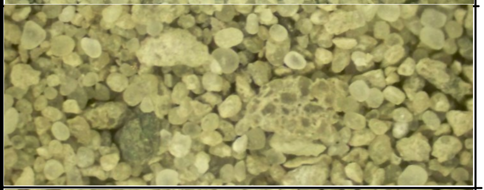
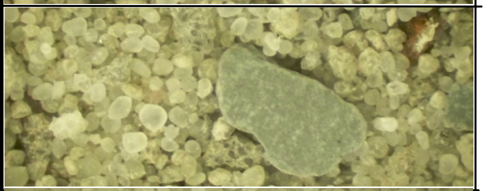
Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
-859.39	1315'			1310-1315: 75% light gray to gray, fine grained, limestone. 25% dark gray, fine grained, dolomite.	S-263	
-864.39	1320'			1315-1320: 95% gray to buff, fine grained, limestone. 5% dark gray, fine grained, dolomite.	S-264	
-869.39	1325'			1320-1325: 95% gray to buff, fine grained, limestone. 5% dark gray, fine grained, dolomite.	S-265	
-874.39	1330'			1325-1330: 93% gray to buff, fine grained, limestone. 7% dark gray, fine grained, dolomite.	S-266	
-879.39	1335'			1330-1335: 99% light gray to gray to buff, fine grained, limestone. 7% dark gray, fine grained, dolomite. • Calcite crystals	S-267	
-884.39	1340'			1335-1340: 99% light gray to gray, fine grained, limestone. 1% dark gray, fine grained, dolomite.	S-268	
-889.39	1345'			1340-1345: 98% light gray to gray, fine grained, limestone. 2% dark gray, fine grained, dolomite.	S-269	
-894.39	1350'			1345-1350: 84% light gray to gray, fine grained, limestone. 15% white, fine grained, friable, rounded frosted quartz sand. 1% dark gray, fine grained, dolomite.	S-270	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
-899.39	1355'			1350-1355: 59% light gray to gray, fine grained, limestone. 40% white to light gray, fine grained, friable, rounded frosted quartz sand. 1% dark gray, fine grained, dolomite.	S-271	
-904.39	1360'			1355-1360: 95% white to light gray, well-sorted, friable fine grained, rounded frosted quartz sand. 5% light gray to gray, fine grained, limestone.	S-272	
-909.39	1365'			1360-1365: 95% white to light gray, well-sorted, friable fine grained, rounded frosted quartz sand. 4% light gray to gray, fine grained, limestone. 1% blueish green shale.	S-273	
-914.39	1370'			1365-1370 95% white to light gray, well-sorted, friable fine grained, rounded frosted quartz sand. 3% light gray to gray, fine grained, limestone. 1% blueish green shale. 1% white chert.	S-274	
-919.39	1375'			1370-1375: 95% white to light gray, well-sorted, friable fine grained, rounded frosted quartz sand. 3% light gray to gray, fine grained, limestone. 1% dark gray, fine grained, dolomite. 1%blueish green shale.	S-275	
-924.39	1380'			1375-1380: 50% white to light gray, well-sorted, friable, fine grained, rounded frosted quartz sand to calcite cemented quartz sand. 50% light gray, fine grained, limestone. ● Pyrite crystals	S-276	
-929.39	1385'			1380-1385: **St. Peter Formation** 99% white to light gray, well-sorted, friable, fine grained, rounded frosted quartz sand to calcite cemented quartz sand. 1% bluish green shale.	S-277	
-934.39	1390'			1385-1390: 100% white, well-sorted, friable, fine grained, rounded frosted quartz sand.	S-278	

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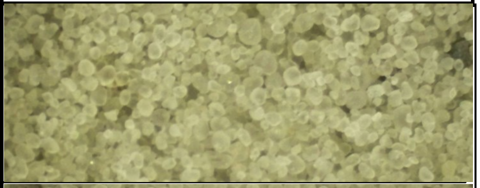
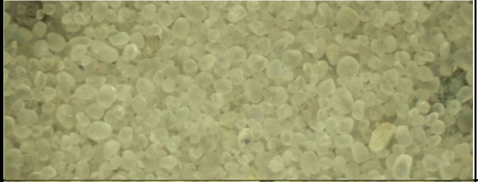
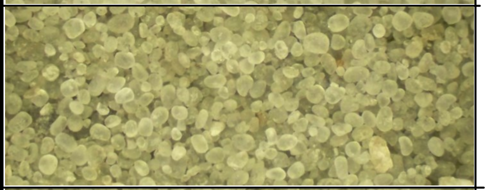
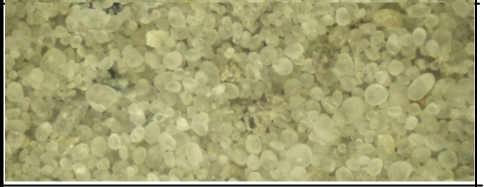
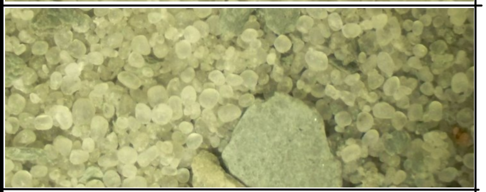
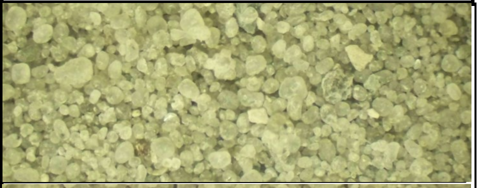
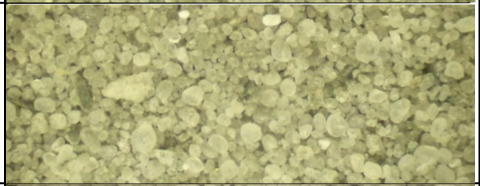
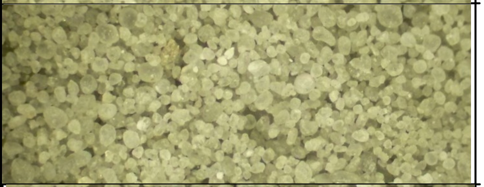
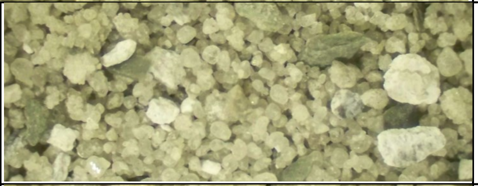
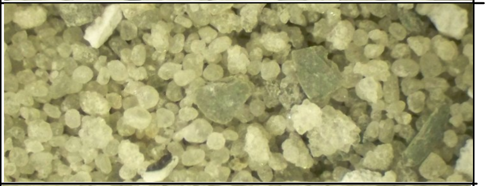
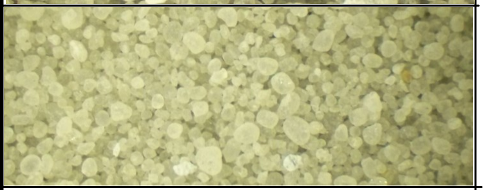
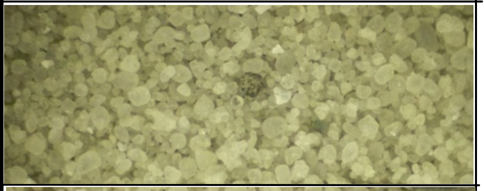
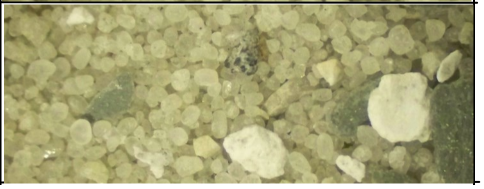
Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1390-1395: 100% white, well-sorted, friable, fine grained, rounded frosted quartz sand.	S-279	
-939.39	1395'			1395-1400: 100% white, well-sorted, friable, fine grained, rounded frosted quartz sand.	S-280	
-944.39	1400'			1400-1405: 100% white, well-sorted, friable, fine grained, rounded frosted quartz sand.	S-281	
-949.39	1405'			1405-1410: 100% white to gray, well-sorted, friable, fine grained, rounded frosted quartz sand.	S-282	
-954.39	1410'			1410-1415: 100% white to gray, well-sorted, friable, fine grained, rounded frosted quartz sand.	S-283	
-959.39	1415'			1415-1420: 100% white to gray, well-sorted, friable, fine grained, rounded frosted quartz sand to calcite cemented quartz sand.	S-284	
-964.39	1420'			1420-1425: 99% white to gray, well-sorted, friable, fine grained, rounded frosted quartz sand. 1% bluish green shale.	S-285	
-969.39	1425'			1425-1430: 100% gray, well-sorted, friable, fine grained, rounded frosted quartz sand.	S-286	
-974.39	1430'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1430-1435: 100% gray, well-sorted, friable, fine grained, rounded frosted quartz sand.	S-287	
-979.39	1435'			1435-1440: 99% gray, well-sorted, friable, fine grained, rounded frosted quartz sand. 1% white chert	S-288	
-984.39	1440'			1440-1445: 99% gray, well-sorted, friable, fine grained, rounded frosted quartz sand. 1% white chert.	S-289	
-989.39	1445'			1445-1450: 98% gray, well-sorted, friable, fine grained, rounded to sub rounded frosted quartz sand. 1% white chert. 1% grayish green shale.	S-290	
-994.39	1450'			1450-1455: 98% gray, well-sorted, friable, fine grained, rounded to sub rounded frosted quartz sand. 1% white chert. 1% grayish green shale.	S-291	
-999.39	1455'			1455-1460: 99% gray to white, well-sorted, friable, fine grained, rounded frosted quartz sand. 1% white chert.	S-292	
-1004.39	1460'			1460-1465: 98% gray, well-sorted, friable, fine grained, rounded frosted quartz sand. 1% black, fined grained, rounded to sub angular, chalcopyrite cemented smoky quartz. 1% white chert.	S-293	
-1009.39	1465'			1465-1470: 94% gray, well-sorted, friable, fine grained, rounded frosted quartz sand. 3% grayish green shale. 2% white chert.1% black, fined grained, rounded to sub angular, chalcopyrite cemented smoky quartz.	S-294	
-1014.39	1470'					

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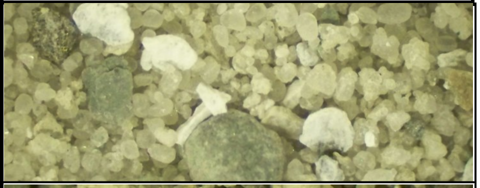
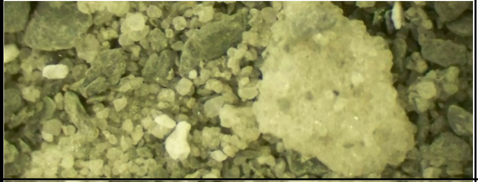
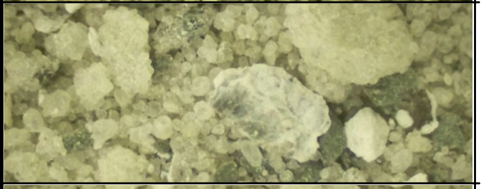
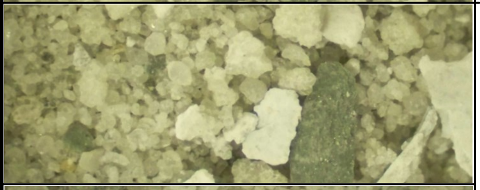
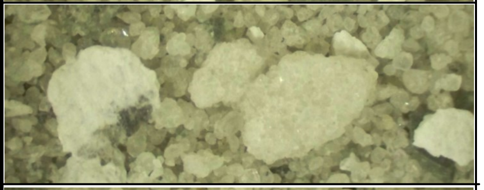
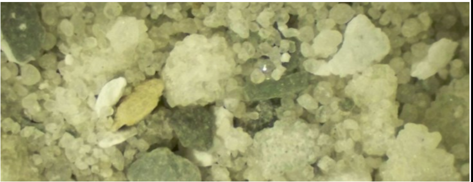
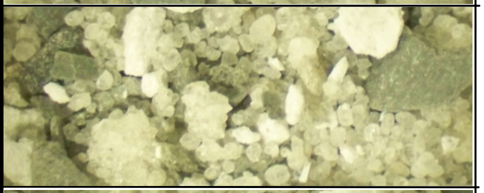
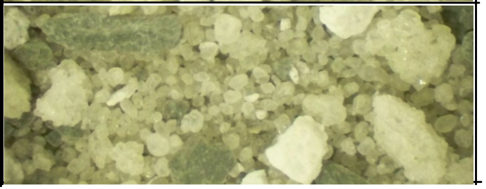
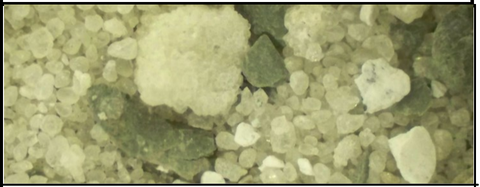
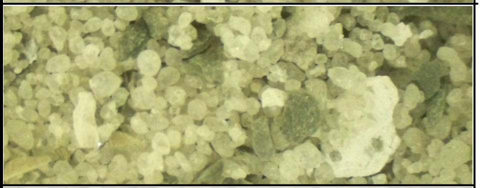
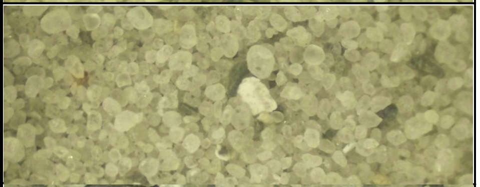
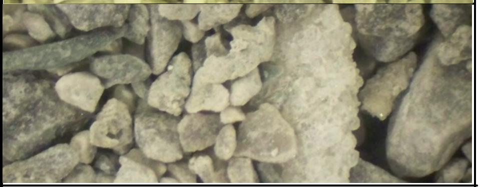
Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1470-1475: 94% gray, well-sorted, friable, fine grained, rounded frosted quartz sand. 3% grayish green shale. 3% white chert.	S-295	
-1019.39	1475'			1475-1480: 50% gray, well-sorted, friable, fine grained, rounded frosted quartz sand to gray, fine grained, calcite cemented quartz sand. 49% grayish green shale. 1% white chert.	S-296	
-1024.39	1480'			1480-1485: 94% gray, well-sorted, friable, fine grained, rounded frosted quartz sand to gray, fine grained, calcite cemented quartz sand. 3% grayish green shale. 3% white chert.	S-297	
-1029.39	1485'			1485-1490: 97% gray, well-sorted, friable, fine grained, rounded frosted quartz sand to gray, fine grained, calcite cemented quartz sand. 3% white chert. 1% greenish gray shale.	S-298	
-1034.39	1490'			1490-1495: 97% gray, well-sorted, friable, fine grained, rounded frosted quartz sand to gray, fine grained, calcite cemented quartz sand. 3% white chert. 1% greenish gray shale.	S-299	
-1039.39	1495'			1495-1500: 86% gray, well-sorted, friable, fine grained, rounded frosted quartz sand to gray, fine grained, calcite cemented quartz sand. 7% white chert. 7% greenish gray shale.	S-300	
-1044.39	1500'			1500-1505: 86% gray, well-sorted, friable, fine grained, rounded frosted quartz sand to gray, fine grained, calcite cemented quartz sand. 7% white chert. 7% greenish gray shale.	S-301	
-1049.39	1505'			1505-1510: 92% gray, well-sorted, friable, fine grained, rounded frosted quartz sand to gray, fine grained, calcite cemented quartz sand. 5% greenish gray shale. 3% white chert.	S-302	
-1054.39	1510'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1510-1515: 92% gray, well-sorted, friable, fine grained, rounded frosted quartz sand to gray, fine grained, calcite cemented quartz sand. 5% greenish gray shale. 3% white chert.	S-303	
-1059.39	1515			1515-1520: 92% gray, well-sorted, friable, fine grained, rounded frosted quartz sand to gray, fine grained, calcite cemented quartz sand. 5% greenish gray shale. 3% white chert.	S-304	
-1064.39	1520			1520-1525: 94% gray, well-sorted, friable, fine grained, rounded frosted quartz sand. 5% greenish gray shale. 1% white chert.	S-305	
-1069.39	1525			1525-1530: **Cotter Dolomite** 81% gray, well-sorted, friable, fine grained, rounded frosted quartz sand. 15% light gray, fine grained, dolomite. 3% greenish gray shale. 1% white chert.	S-306	
-1074.39	1530			1530-1535: Transition Zone 50% gray, well-sorted, friable, fine grained, rounded frosted quartz sand. 46% light gray, fine grained, dolomite. 3% greenish gray shale. 1% white to light gray chert to oolitic chert.	S-307	
-1079.39	1535			1535-1540: 79% light gray to dark gray, fine grained, dolomite. 15% gray, well-sorted, friable, fine grained, rounded frosted quartz sand. 5% bluish green shale. 1% white to light gray chert to oolitic chert.	S-308	
-1084.39	1540			1540-1545: 97% light gray to dark gray, fine grained, dolomite. 1% white to light gray chert. 1% bluish green shale. 1% gray, well-sorted, friable, fine grained, rounded frosted quartz sand.	S-309	
-1089.39	1545			1545-1550: 99% light gray to dark gray, fine grained, dolomite. 1% bluish green shale.	S-310	
-1094.39	1550					

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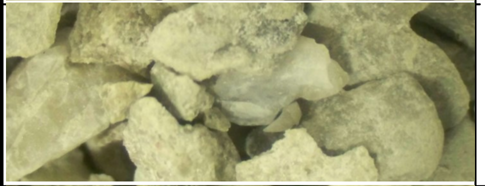
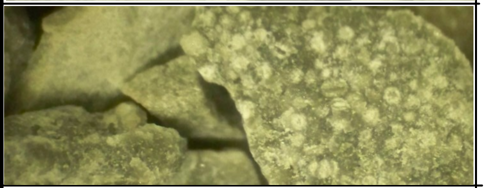
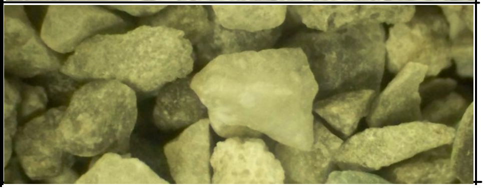
Project: Shallow Carbon Sequestration Demonstration Project

Site: Luecke Site

Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1550-1555: 99% light gray to dark gray, fine to medium grained, dolomite. 1% white, fine grained, rounded to sub rounded, calcite cemented quartz sand	S-311	
-1099.39	1555'			1555-1560: 97% light gray to dark gray, fine to medium grained, dolomite. 2% white to light gray chert. 1% bluish green shale.	S-312	
-1104.39	1560'			1560-1565: 98% light gray to dark gray, fine to medium grained, dolomite. 1% white to light gray chert. 1% bluish green shale.	S-313	
-1109.39	1565'			1565-1570: 98% light gray to dark gray, fine to medium grained, dolomite. 1% white to light gray chert. 1% bluish green shale.	S-314	
-1114.39	1570'			1570-1575: 99% light gray to dark gray, fine to medium grained, dolomite. 1% bluish green shale.	S-315	
-1119.39	1575'			1575-1580: 99% light gray to dark gray, fine to medium grained, dolomite to oolitic dolomite. 1% white to light gray chert. 1% white, fine grained, rounded to sub rounded, calcite cemented quartz sand.	S-316	
-1124.39	1580'			1580-1585: 100% light gray to dark gray, fine to medium grained, dolomite to oolitic dolomite.	S-317	
-1129.39	1585'			1585-1590: 97% light gray to dark gray, fine to medium grained, dolomite to oolitic dolomite. 1% 1% white, fine grained, rounded to sub rounded, calcite cemented quartz sand. 1% white to light gray chert. 1% bluish green shale. • Pyrite crystal	S-318	
-1134.39	1590'					

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Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
-1139.39	1595'			1590-1595: 99% light gray to dark gray, fine to medium grained, dolomite. 1% bluish green shale.	S-319	
-1144.39	1600'			1595-1600: 98% light gray to dark gray, fine to medium grained, dolomite. 1% white, fine grained, rounded to sub rounded, calcite cemented quartz sand. 1% bluish green shale.	S-320	
-1149.39	1605'			1600-1605: 80% light gray, fine grained, dolomite. 20% bluish green shale.	S-321	
-1154.39	1610'			1605-1610: 79% light gray, fine grained, dolomite. 20% grayish green shale. 1% white chert.	S-322	
-1159.39	1615'			1610-1615: 78% light gray, fine grained, dolomite. 20% grayish green shale. 1% white chert. 1% white, friable, fine grained, rounded frosted quartz sand.	S-323	
-1164.39	1620'			1615-1620: 97% light gray to gray, fine to medium grained, dolomite. 1% bluish green shale. 1% white, fine grained, rounded to sub rounded, calcite cemented quartz sand. 1% white to light gray chert.	S-324	
-1169.39	1625'			1620-1625: 96% light gray to gray, fine to medium grained, dolomite to oolitic dolomite. 3% grayish green shale. 1% white to light gray chert.	S-325	
-1174.39	1630'			1625-1630: 83% light gray, fine to medium grained, dolomite. 15% grayish green shale. 1% white chert. 1% white, friable, fine grained, rounded frosted quartz sand to calcite cemented quartz sand.	S-326	

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1630-1635: 88% light gray, fine to medium grained, dolomite. 10% grayish green to bluish green shale. 1% white chert. 1% white, friable, fine grained, rounded frosted quartz.	S-327	
-1179.39	1635'			1635-1640: 91% light gray, fine to medium grained, dolomite. 7% grayish green to bluish green shale. 1% white chert. 1% white, friable, fine grained, rounded frosted quartz to calcite cemented quartz sand.	S-328	
-1184.39	1640'			1640-1645: 91% light gray, fine to medium grained, dolomite . 7% grayish green to bluish green shale. 1% white chert to oolitic chert. 1% white, friable, fine grained, rounded frosted quartz	S-329	
-1189.39	1645'			1645-1650: 98% light gray to gray, fine to medium grained, dolomite . 1% grayish green to bluish green shale. 1% white chert to oolitic chert.	S-330	
-1194.39	1650'			1650-1655: 98% light gray to gray, fine to medium grained, dolomite . 1% grayish green to bluish green shale. 1% white to light gray	S-331	
-1199.39	1655'			1655-1660: 90% light gray to gray, fine to medium grained, dolomite . 7% grayish green to bluish green shale. 3% white to light gray	S-332	
-1204.39	1660'			1660-1665: 82% light gray to gray, fine to medium grained, dolomite . 15% grayish green to bluish green shale. 3% white to light gray	S-333	
-1209.39	1665'			1665-1670: 98% light gray to gray, fine to medium grained, dolomite . 1% grayish green to bluish green shale. 1% white to light gray	S-334	
-1214.39	1670'					

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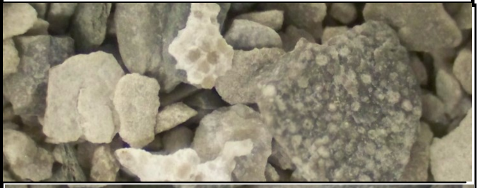
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
-1219.39	1675'			1670-1675: 96% light gray to gray, fine to medium grained, dolomite to oolitic dolomite. 3% grayish green shale. 1% white chert to oolitic chert.	S-335	
-1224.39	1680'			1675-1680: 98% light gray to dark gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert.	S-336	
-1229.39	1685'			1680-1685: 79% light gray, fine to medium grained, dolomite. 15% white, friable, fine grained, rounded to sub rounded frosted quartz sand. 5% bluish green to grayish green shale. 1% white to light gray chert.	S-337	
-1234.39	1690'			1685-1690: 84% light gray, fine to medium grained, dolomite. 10% bluish green to grayish green shale. 5% white, friable, fine grained, rounded frosted quartz sand. 1% white to light gray chert. • Pyrite crystals	S-338	
-1239.39	1695'			1690-1695: 82% light gray, fine to medium grained, dolomite. 10% bluish green to grayish green shale. 7% white, friable, fine grained, rounded frosted quartz sand. 1% white to light gray chert.	S-339	
-1244.39	1700'			1695-1700: 79% light gray, fine to medium grained, dolomite. 10% bluish green to grayish green shale. 10% white, friable, fine grained, rounded frosted quartz sand. 1% white to light gray chert.	S-340	
-1249.39	1705'			1700-1705: 87% light gray to buff, fine to medium grained, dolomite. 7% white, friable, fine grained, rounded frosted quartz sand. 5% bluish green to grayish green shale. 1% white chert to oolitic chert.	S-341	
-1254.39	1710'			1705-1710 79% gray, fine to medium grained, dolomite. 20% grayish green shale. 1% white, friable, fine grained, rounded frosted quartz sand.	S-342	

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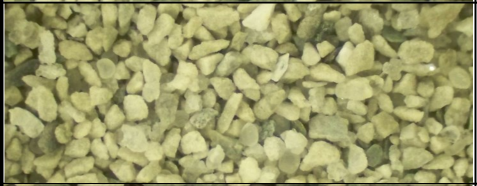
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1710-1715: 93% light gray to gray, fine to medium grained, dolomite. 5% grayish green shale. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white to light gray chert. ● Pyrite crystals	S-343	
-1259.39	1715'			1715-1720: 93% light gray to dark gray, fine to medium grained, dolomite. 5% grayish green shale. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white to light gray chert.	S-344	
-1264.39	1720'			1720-1725: 83% light gray, fine to medium grained, dolomite. 10% white, friable, fine grained, rounded frosted quartz sand. 7% grayish green shale. ● Pyrite crystals	S-345	
-1269.39	1725'			1725-1730: 90% light gray, fine to medium grained, dolomite. 7% grayish green shale. 3% white, friable, fine grained, rounded frosted quartz sand.	S-346	
-1274.39	1730'			1730-1735: 90% light gray, fine to medium grained, dolomite. 3% grayish green shale. 3% white, friable, fine grained, rounded to sub rounded frosted quartz sand. 1% white chert.	S-347	
-1279.39	1735'			1735-1740: 68% light gray, fine to medium grained, dolomite. 30% grayish green shale. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white chert.	S-348	
-1284.39	1740'			1740-1745: 96% light gray, fine to medium grained, dolomite. 3% bluish green to grayish green shale. 1% white chert.	S-349	
-1289.39	1745'			1745-1750: 88% light gray, fine to medium grained, dolomite. 10% bluish green to grayish green shale. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white chert.	S-350	
-1294.39	1750'					

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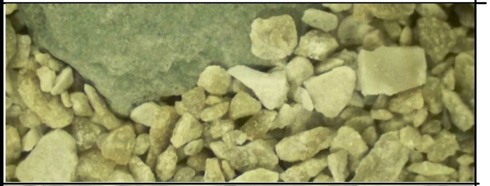
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
-1299.39	1755'			1750-1755: 83% light gray, fine grained, dolomite. 15% bluish green to grayish green shale. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white chert.	S-351	
-1304.39	1760'			1755-1760: 59% light gray, fine grained, dolomite. 25% white, friable, fine grained, rounded frosted quartz sand. 15% bluish green to grayish green shale. 1% white chert.	S-352	
-1309.39	1765'			1760-1765: 59% light gray, fine grained, dolomite. 20% white, friable, fine grained, rounded frosted quartz sand. 20% bluish green to grayish green shale. 1% white chert.	S-353	
-1314.39	1770'			1765-1770: 86% light gray, fine to medium grained, dolomite. 10% bluish green to grayish green shale. 3% white, friable, fine grained, rounded frosted quartz sand. 1% white to light gray chert. • Pyrite crystals	S-354	
-1319.39	1775'			1770-1775: **Jefferson City Dolomite** 93% light brown to buff, medium grained, dolomite. 5% bluish green to grayish green shale. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white chert.	S-355	
-1324.39	1780'			1775-1780: 95% light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white chert.	S-356	
-1329.39	1785'			1780-1785: 79% light gray, fine grained, dolomite. 7% white, friable, fine grained, rounded frosted quartz sand. 7% white chert to oolitic chert. 5% bluish green to grayish green shale.	S-357	
-1334.39	1790'			1785-1790: Light gray to light brown, fine to medium grained, dolomite. 7% white, friable, fine grained, rounded frosted quartz sand. 7% white chert to oolitic chert. 5% bluish green to grayish green shale. • Pyrite chert.	S-358	

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1790-1795: 97% light brown to gray to dark gray, fine grained, dolomite. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white chert. 1% bluish green to grayish green shale.	S-359	
-1339.39	1795'			1795-1800: 94% light gray to dark gray, fine grained, dolomite. 5% bluish green to grayish green shale. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white chert.	S-360	
-1344.39	1800'			1800-1805: 97% light gray to dark gray, fine grained, dolomite. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white chert. 1% bluish green to grayish green shale.	S-361	
-1349.39	1805'			1805-1810: 94% light gray to dark gray, fine grained, dolomite. 5% bluish green to grayish green shale. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white chert.	S-362	
-1354.39	1810'			1810-1815: 97% buff to light gray to dark gray, fine grained, dolomite to oolitic dolomite. 1% white, friable, fine grained, rounded frosted quartz sand. 1% white chert. 1% bluish green to grayish green shale.	S-363	
-1359.39	1815'			1815-1820: 90% light gray to dark gray, fine grained, dolomite. 10% bluish green to grayish green shale.	S-364	
-1364.39	1820'			1820-1825: 90% light gray to dark gray, fine grained, dolomite. 10% bluish green to grayish green shale.	S-365	
-1369.39	1825'			1825-1830: 90% light gray to dark gray, fine grained, dolomite to oolitic dolomite. 10% bluish green to grayish green shale.	S-366	
-1374.39	1830'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
-1379.39	1835'			1830-1835: 96% buff to light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 1% white chert.	S-367	
-1384.39	1840'			1835-1840: 96% buff to light gray, fine grained, dolomite to oolitic dolomite. 3% bluish green to grayish green shale. 1% white chert.	S-368	
-1389.39	1845'			1840-1845: 66% light gray, fine grained, dolomite. 30% white, friable, fine grained, rounded to sub angular, frosted quartz sand. 3% bluish green to grayish green shale. 1% white chert.	S-369	
-1394.39	1850'			1845-1850: 66% light gray, fine grained, dolomite. 20% bluish green to grayish green shale. 9% white, friable, fine grained, rounded to sub rounded, frosted quartz sand to well cemented quartz sand. 1% white chert.	S-370	
-1399.39	1855'			1850-1855: 70% light gray, fine grained, dolomite to oolitic dolomite. 29% dark gray shale. 1% white chert to oolitic chert.	S-371	
-1404.39	1860'			1855-1860: 86% buff to light gray, fine grained, dolomite to oolitic dolomite. 10% white chert to oolitic chert. 3% bluish green to grayish green shale. 1% white, friable, fine grained, rounded, frosted quartz sand	S-372	
-1409.39	1865'			1860-1865 93% Buff to light gray, medium grained, dolomite. 3% white chert to oolitic chert. 3% bluish green to grayish green shale. 1% white, friable, fine grained, rounded, frosted quartz sand	S-373	
-1414.39	1870'			1865-1870: 74% light gray, fine to medium grained, dolomite to oolitic dolomite. 15% white chert to oolitic chert. 10% bluish green to grayish green shale. 1% white, friable, fine grained, rounded, frosted quartz sand.	S-374	

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1870-1875: 91% light gray, fine to medium grained, dolomite. 7% bluish green to grayish green shale. 1% white, friable, fine grained, rounded, frosted quartz sand. 1% white chert to oolitic chert.	S-375	
-1419.39	1875'			1875-1880: 97% light gray, fine grained, dolomite. 3% bluish green to grayish green shale.	S-376	
-1424.39	1880'			1880-1885: 97% light gray, fine grained, dolomite. 5% bluish green to grayish green shale.	S-377	
-1429.39	1885'			1885-1890: 95% light gray, fine to medium grained, dolomite. 3% bluish green to grayish green shale. 1% white, friable, fine grained, rounded, frosted quartz sand. 1% white chert to oolitic chert.	S-378	
-1434.39	1890'			1890-1895: 95% light gray, fine grained, dolomite. 5% bluish green to grayish green shale.	S-379	
-1439.39	1895'			1895-1900: 96% light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 1% white chert to oolitic chert.	S-380	
-1444.39	1900'			1900-1905: 94% light gray, fine grained, dolomite. 5% bluish green to grayish green shale. 1% white chert to oolitic chert.	S-381	
-1449.39	1905'			1905-1910: 94% light gray, fine grained, dolomite. 5% bluish green to grayish green shale. 1% white chert to oolitic chert.	S-382	
-1454.39	1910'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
-1459.39	1915'			1910-1915: 96% light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 1% white, friable, fine grained, rounded, frosted quartz sand.	S-383	
-1464.39	1920'			1915-1920: 95% light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 1% white, friable, fine grained, rounded, frosted quartz sand. 1% white chert.	S-384	
-1469.39	1925'			1920-1925: 95% light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 1% white, friable, fine grained, rounded, frosted quartz sand. 1% white chert.	S-385	
-1474.39	1930'			1925-1930: 93% light gray, fine grained, dolomite. 5% bluish green to grayish green shale. 1% white, friable, fine grained, rounded, frosted quartz sand. 1% white chert.	S-386	
-1479.39	1935'			1930-1935: 93% light gray, fine grained, dolomite. 5% bluish green to grayish green shale. 1% white, friable, fine grained, rounded, frosted quartz sand. 1% white to light gray chert.	S-387	
-1484.39	1940'			1935-1940: 96% light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 1% white chert.	S-388	
-1489.39	1945'			1940-1945: 88% light gray, fine grained, dolomite. 10% bluish green to grayish green shale. 2% white chert to oolitic chert.	S-389	
-1494.39	1950'			1945-1950: 97% buff to light gray, fine to medium grained, dolomite. 2% bluish green to grayish green shale. 1% white chert to oolitic chert.	S-390	

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1950-1955: 96% buff to light gray to dark gray, fine to medium grained, dolomite. 2% bluish green to grayish green shale. 1% white chert. 1% white, friable, fine grained, rounded, frosted quartz sand.	S-391	
-1499.39	1955'					
				1955-1960: 91% light gray to dark gray, fine to medium grained, dolomite. 7% bluish green to grayish green shale. 1% white chert. 1% white, friable, fine grained, rounded, frosted quartz sand.	S-392	
-1504.39	1960'					
				1960-1965: 79% light gray to dark gray, fine to medium grained, dolomite. 20% bluish green to grayish green shale. 1% white chert.	S-393	
-1509.39	1965'					
				1965-1970: 79% light gray to dark gray, fine to medium grained, dolomite. 20% bluish green to grayish green shale. 1% white chert.	S-394	
-1514.39	1970'					
				1970-1975: 70% light gray to dark gray, fine to medium grained, dolomite. 30% bluish green to grayish green shale. • Pyrite crystals	S-395	
-1519.39	1975'					
				1975-1980: 70% light gray to dark gray, fine to medium grained, dolomite. 30% bluish green to grayish green shale. • Pyrite crystals	S-396	
-1524.39	1980'					
				1980-1985: 89% light gray to dark gray, fine to medium grained, dolomite. 10% bluish green to grayish green shale. 1% white chert.	S-397	
-1529.39	1985'					
				1985-1990: 93% buff to light gray, fine grained, dolomite. 7% white chert	S-398	
-1534.39	1990'					

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Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				1990-1995: 89% light gray, fine grained, dolomite. 10% bluish green to grayish green shale. 1% white chert.	S-399	
-1539.39	1995'			1995-2000: 92% light gray, fine grained, dolomite. 7% bluish green to grayish green shale. 1% white chert.	S-400	
-1544.39	2000'			2000-2005: 98% light gray, fine grained, dolomite. 1% bluish green to grayish green shale. 1% white chert.	S-401	
-1549.39	2005'			2005-2010: 97% light gray, fine grained, dolomite. 2% bluish green to grayish green shale. 1% white chert.	S-402	
-1554.39	2010'			2010-2015: 94% light gray, fine grained, dolomite. 5% bluish green to grayish green shale. 1% white chert.	S-403	
-1559.39	2015'			2015-2020: 95% buff to light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 1% white, friable, fine grained, rounded, frosted quartz sand. 1% white chert.	S-404	
-1564.39	2020'			2020-2025: **Roubidoux Formation** 95% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 3% light gray, fine grained, dolomite. 1% bluish green to grayish green shale. 1% white chert.	S-405	
-1569.39	2025'			2025-2030: 98% light gray, fine grained, dolomite. 1%light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% white chert.	S-406	
-1574.39	2030'					

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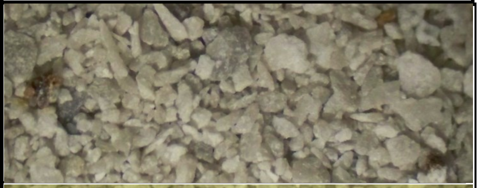
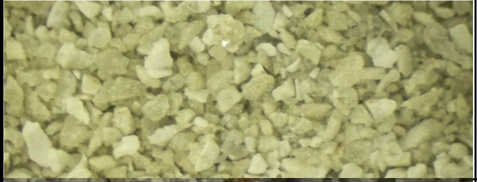
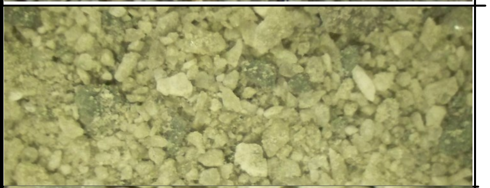
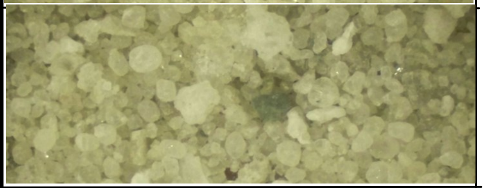
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				2030-2035: 98% light gray, fine grained, dolomite. 1%light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% white chert.	S-407	
-1579.39	2035'			2035-2040: 70% light gray, fine grained, dolomite. 28%l light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 2% white chert.	S-408	
-1584.39	2040'			2040-2045: 98% light gray, fine grained, dolomite. 10% white chert. 3%light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand.	S-409	
-1589.39	2045'			2045-2050: 91% light gray, fine grained, dolomite. 3% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 3% light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 3% white chert.	S-410	
-1594.39	2050'			2050-2055: 91% light gray, fine grained, dolomite. 3% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 3% light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 3% white chert.	S-411	
-1599.39	2055'			2055-2060: 91% light gray, fine to medium grained, dolomite. 5% bluish green to grayish green shale. 3% white chert. 3% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 3% light gray, fine grained, dolomite.	S-412	
-1604.39	2060'			2060-2065: 97% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% light gray, fine grained, dolomite. 1% bluish green to grayish green shale. 1% white chert.	S-413	
-1609.39	2065'			2065-2070: 98% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale. 1% white chert.	S-414	
-1614.39	2070'					

Notes/Comments:

Missouri Department of Natural Resources
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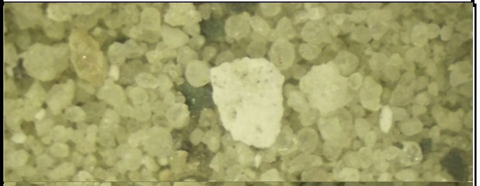
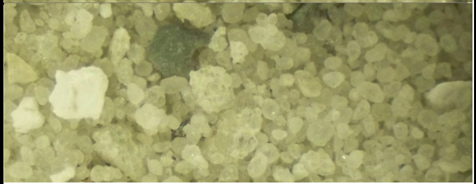
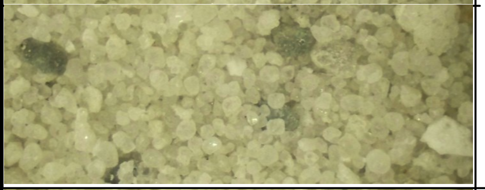
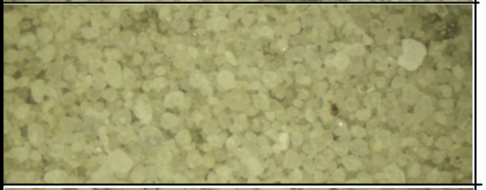
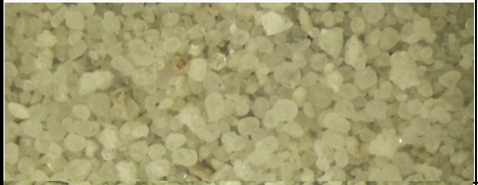
Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				2070-2075; 98% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale. 1% white chert.	S-415	
-1619.39	2075'			2075-2080: 98% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale. 1% white chert.	S-416	
-1624.39	2080'			2080-2085: 98% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale. 1% white chert.	S-417	
-1629.39	2085'			2085-2090: 98% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale. 1% white chert.	S-418	
-1634.39	2090'			2090-2095: 98% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale. 1% white chert.	S-419	
-1639.39	2095'			2095-2100: 98% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale. 1% white chert.	S-420	
-1644.39	2100'			2100-2105: 98% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale. 1% white chert.	S-421	
-1649.39	2105'			2105-2110: **Upper Gasconade** 97% light gray, fine grained, dolomite. 1% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale 1% white chert.	S-422	
-1654.39	2110'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
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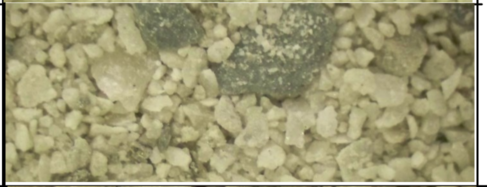
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				2110-2115: 97% light gray, fine grained, dolomite. 1% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale 1% white chert.	S-423	
-1659.39	2115'			2115-2120: 97% light gray, fine grained, dolomite. 1% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale. 1% white chert.	S-424	
-1664.39	2120'			2120-2125: 95% light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 1% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% white chert.	S-425	
-1669.39	2125'			2125-2130: 96% light gray, fine grained, dolomite. 3% bluish green to grayish green shale. 1% white chert.	S-426	
-1674.39	2130'			2130-2135: 96% light gray, fine to medium grained, dolomite. 3% bluish green to grayish green shale. 1% white chert.	S-427	
-1679.39	2135'			2135-2140: 96% light gray, fine to medium grained, dolomite. 3% bluish green to grayish green shale. 1% white chert.	S-428	
-1684.39	2140'			2140-2145: 96% light gray, fine to medium grained, dolomite. 3% bluish green to grayish green shale. 1% white chert.	S-429	
-1689.39	2145'			2145-2150: 50% light gray, fine to medium grained, dolomite. 49% bluish green to grayish green shale. 1% white chert.	S-430	
-1694.39	2150'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				2150-2155: 94% light gray, fine to medium grained, dolomite. 5% bluish green to grayish green shale. 1% white chert.	S-431	
-1699.39	2155'			2155-2160: 94% light gray, fine to medium grained, dolomite. 5% bluish green to grayish green shale. 1% white chert.	S-432	
-1704.39	2160'			2160-2165: 80% light gray, fine to medium grained, dolomite. 15% white chert. 5% bluish green to grayish green shale.	S-433	
-1709.39	2165'			2165-2170: 82% light gray, fine to medium grained, dolomite. 15% white chert. 3% bluish green to grayish green shale.	S-434	
-1714.39	2170'			2170-2175: 94% light gray, fine to medium grained, dolomite. 5% bluish green to grayish green shale. 1% white chert.	S-435	
-1719.39	2175'			2175-2180: 94% light gray, fine to medium grained, dolomite. 3% bluish green to grayish green shale. 3% white chert.	S-436	
-1724.39	2180'			2180-2185: 96% light gray, fine to medium grained, dolomite. 3% bluish green to grayish green shale. 1% white chert.	S-437	
-1729.39	2185'			2185-2190: 97% light gray, fine to medium grained, dolomite. 2% bluish green to grayish green shale. 1% white chert.	S-438	
-1734.39	2190'					

Notes/Comments:

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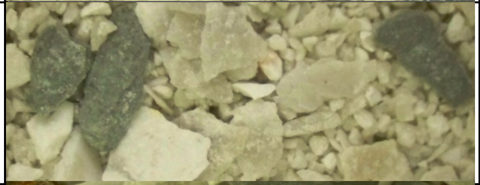
Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
-1739.39	2195'			2190-2195: 97% light gray, fine to medium grained, dolomite. 2% bluish green to grayish green shale. 1% white chert.	S-439	
-1744.39	2200'			2195-2200: 97% light gray, fine to medium grained, dolomite. 5% bluish green to grayish green shale. 1% white chert.	S-440	
-1749.39	2205'			2200-2205: 97% light gray, fine to medium grained, dolomite. 7% bluish green to grayish green shale. 5% white chert.	S-441	
-1754.39	2210'			2205-2210: 92% light gray, fine to medium grained, dolomite. 5% white chert. 3% bluish green to grayish green shale.	S-442	
-1759.39	2215'			2210-2215: 82% light gray, fine to medium grained, dolomite. 15% white chert. 3% bluish green to grayish green shale.	S-443	
-1764.39	2220'			2215-2220: 45% light gray, fine to medium grained, dolomite. 45% bluish green to grayish green shale. 10% white chert.	S-444	
-1769.39	2225'			2220-2225: 45% light gray, fine to medium grained, dolomite. 25% bluish green to grayish green shale. 10% white chert.	S-445	
-1774.39	2230'			2225-2230: 98% light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert.	S-446	

Notes/Comments:

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Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				2230-2235: 96% buff to light gray, fine to medium grained, dolomite. 3% white chert. 1% bluish green to grayish green shale.	S-447	
-1779.39	2235'			2235-2240: 94% light gray, fine to medium grained, dolomite. 3% white chert. 3% bluish green to grayish green shale.	S-448	
-1784.39	2240'			2240-2245: 94% light gray, fine to medium grained, dolomite. 3% white chert. 3% bluish green to grayish green shale.	S-449	
-1789.39	2245'			2245-2250: 94% light gray, fine to medium grained, dolomite. 3% white chert. 3% bluish green to grayish green shale.	S-450	
-1794.39	2250'			2250-2255: 92% light gray, fine to medium grained, dolomite. 5% white chert. 3% bluish green to grayish green shale.	S-451	
-1799.39	2255'			2255-2260: 92% light gray, fine to medium grained, dolomite. 5% white chert. 3% bluish green to grayish green shale.	S-452	
-1804.39	2260'			2260-2265: 92% light gray, fine to medium grained, dolomite. 5% white chert. 3% bluish green to grayish green shale.	S-453	
-1809.39	2265'			2265-2270: **Lower Gasconade?** 77% light gray, fine to medium grained, dolomite. 20% white chert. 3% bluish green to grayish green shale.	S-454	
-1814.39	2270'					

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Project: Shallow Carbon Sequestration Demonstration Project

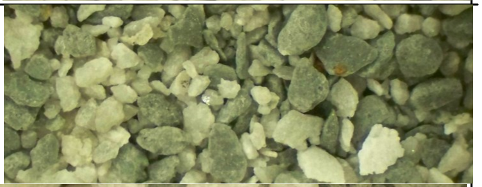
Site: Luecke Site

Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				2270-2275: 89% light gray, fine to medium grained, dolomite. 10% white chert. 1% bluish green to grayish green shale.	S-455	
-1819.39	2275'			2275-2280: 92% light gray, fine to medium grained, dolomite. 7% white chert. 1% bluish green to grayish green shale.	S-456	
-1824.39	2280'			2280-2285: 74% light gray, fine to medium grained, dolomite. 25% white to light gray chert. 1% bluish green to grayish green shale.	S-457	
-1829.39	2285'			2285-2290: 75% light gray, fine to medium grained, dolomite. 25% white to light gray chert.	S-458	
-1834.39	2290'			2290-2295: 96% light gray, fine to medium grained, dolomite. 3% white chert. 1% bluish green to grayish green shale. ● Iron staining	S-459	
-1839.39	2295'			2295-2300: 96% light gray to gray, fine to medium grained, dolomite. 3% white chert. 1% bluish green to grayish green shale. ● Iron staining	S-460	
-1844.39	2300'			2300-2305: 96% light gray, fine to medium grained, dolomite. 2% white chert. 2% bluish green to grayish green shale. ● Iron staining	S-461	
-1849.39	2305'			2305-2310: 94% light gray, fine to medium grained, dolomite. 3% white chert. 3% bluish green to grayish green shale. ● Iron staining	S-462	
-1854.39	2310'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				2310-2315: 82% light gray, fine to medium grained, dolomite. 15% white to light gray chert. 3% bluish green to grayish green shale. • Iron staining	S-463	
-1859.39	2315'			2315-2320: 92% light gray, fine to medium grained, dolomite. 5% white to light gray chert. 3% bluish green to grayish green shale. • Iron staining	S-464	
-1864.39	2320'			2320-2325: **Gunter Sandstone Member?** 92% light gray, fine to medium grained, dolomite. 5% white to light gray chert. 3% bluish green to grayish green shale. • Iron staining	S-465	
-1869.39	2325'			2325-2330: 96% light gray to gray, fine to medium grained, dolomite. 3% white to light gray chert. 1% bluish green to grayish green shale.	S-466	
-1874.39	2330'			2330-2335: 98% light gray to gray, fine to medium grained, dolomite. 1% white chert. 1% bluish green to grayish green shale. • Iron staining	S-467	
-1879.39	2335'			2335-2340: 97% light gray to gray, fine to medium grained, dolomite. 1% white chert. 1% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% bluish green to grayish green shale. • Sponge fragment • Iron staining	S-468	
-1884.39	2340'			2340-2345: **Eminence Dolomite?** 69% light gray to gray, fine to medium grained, dolomite. 30% bluish green to grayish green shale. 1% white chert. • Iron staining	S-469	
-1889.39	2345'			2345-2350: 87% light gray to gray, fine to medium grained, dolomite. 10% bluish green to grayish green shale. 3% white chert.	S-470	
-1894.39	2350'					

Notes/Comments:

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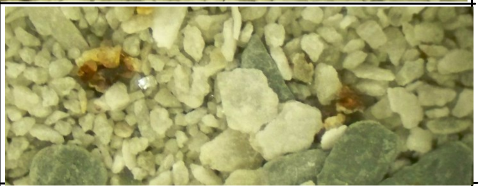
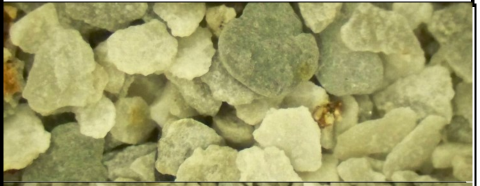
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				2350-2355: 84% light gray to gray, fine to medium grained, dolomite. 15% white chert. 1% bluish green to grayish green shale.	S-471	
-1899.39	2355'					
				2355-2360: 94% light gray to gray, fine to medium grained, dolomite. 5% bluish green to grayish green shale. 1% white chert. ● Iron staining	S-472	
-1904.39	2360'					
				2360-2365: 98% light gray, fine to medium grained, dolomite. 1% white chert. 1% bluish green to grayish green shale. ● Iron staining	S-473	
-1909.39	2365'					
				2365-2370: 94% light gray, fine to medium grained, dolomite. 5% white chert. 1% bluish green to grayish green shale. ● Iron staining	S-474	
-1914.39	2370'					
				2370-2375: 98% light gray, fine to medium grained, dolomite. 1% white chert. 1% bluish green to grayish green shale. ● Iron staining	S-475	
-1919.39	2375'					
				2375-2380: 98% light gray, fine to medium grained, dolomite. 1% white chert. 1% bluish green to grayish green shale. ● Iron staining	S-476	
-1924.39	2380'					
				2380-2385: 96% light gray, fine to medium grained, dolomite. 3% bluish green to grayish green shale. 1% white chert. ● Iron staining	S-477	
-1929.39	2385'					
				2385-2390: 96% light gray, fine to medium grained, dolomite. 3% bluish green to grayish green shale. 1% white chert. ● Iron staining	S-478	
-1934.39	2390'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
-1939.39	2395'			2390-2395: 96% light gray, fine to medium grained, dolomite. 3% bluish green to grayish green shale. 1% white chert. • Iron staining	S-479	
-1944.39	2400'			2395-2400: 98% light gray to dark gray, fine to medium grained, dolomite. % bluish green to grayish green shale. 1% white chert. • Iron staining	S-480	
-1949.39	2405'			2400-2405: 98% light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert. • Iron staining	S-481	
-1954.39	2410'			2405-2410: 98% light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert. • Iron staining	S-482	
-1959.39	2415'			2410-2415: 98% light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert. • Iron staining	S-483	
-1964.39	2420'			2415-2420: 98% light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert. • Iron staining	S-484	
-1969.39	2425'			2420-2425: 96% light gray, fine to medium grained, dolomite. 3% bluish green to grayish green shale. 1% white chert. • Iron staining	S-485	
-1974.39	2430'			2425-2430: 98% light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert. • Iron staining	S-486	

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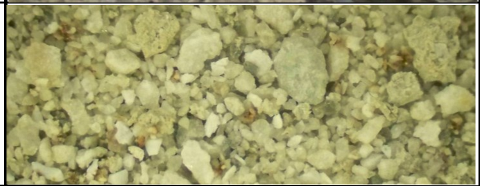
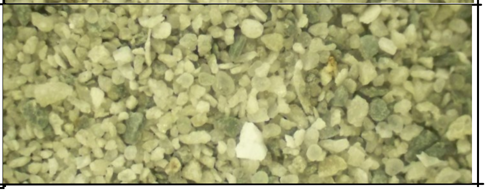
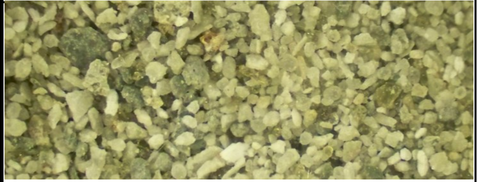
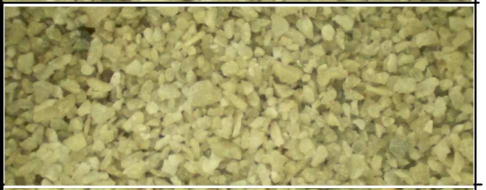
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				2430-2435: 98% light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert. ● Iron staining	S-487	
-1979.39	2435'			2435-2440: 98% light gray to gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert. ● Iron staining	S-488	
-1984.39	2440'			2440-2445: 98% light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert. ● Pyrite crystals ● Iron staining	S-489	
-1989.39	2445'			2445-2450: 98% light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert. ● Iron staining	S-490	
-1994.39	2450'			2450-2455: 100% light gray, fine to medium grained, dolomite.	S-491	
-1999.39	2455'			2455-2460: Drilling mud (N-seal) and cuttings	S-492	
-2004.39	2460'			2460-2465: Gunter? 96% light gray, fine to medium grained, dolomite. 2% white chert. 1% bluish green to grayish green shale. 1% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. ● Iron staining	S-493	
-2009.39	2465'			2465-2470: 69% light gray, fine to medium grained, dolomite. 20% bluish green to grayish green shale. 10% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% white chert. ● Iron staining	S-494	
-2014.39	2470'					

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments 1cm
				2470-2475: 58% bluish green to grayish green shale. 40% light gray, fine to medium grained, dolomite. 1% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% white chert. ● Iron staining ● Drilling fluids	S-495	
-2019.39	2475'			2475-2480: 88% light gray, fine to medium grained, dolomite. 10% bluish green to grayish green shale. 1% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% white chert. ● Iron staining ● Drilling fluids	S-496	
-2024.39	2480'			2480-2485: 97% light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% white chert. ● Iron staining ● Drilling fluids	S-497	
-2029.39	2485'			2485-2490: 97% buff to light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% white chert. ● Iron staining	S-498	
-2034.39	2490'			2490-2495: 97% buff to light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% light gray, friable, fine grained, rounded to sub rounded, frosted quartz sand. 1% white chert. ● Iron staining	S-499	
-2039.39	2495'			2495-2500: 97% buff to light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert. ● Iron staining	S-500	
-2044.39	2500'			2500-2505: 97% buff to light gray, fine to medium grained, dolomite. 1% bluish green to grayish green shale. 1% white chert. ● Iron staining ● Drilling mud.	S-501	
-2049.39	2505'			2505-2510: Same As Above	S-502	
-2054.39	2510'					

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
				2510-2515: Same As Above End of Cuttings		
-2059.39	2515'	Ce		2515-2519: Light gray, fine to medium grained, dolomite to vuggy dolomite. ● Vugs filled with 2 mm dolomite crystals. ● Moderately fractured.	BOX 1 RUN 1	
-2064.39 -2069.39	2520' 2525'	Ce		2519-2529: Light gray, fine to medium grained, dolomite to vuggy dolomite. ● Vugs filled with 2mm dolomite crystals (sub rounded to bladed crystals). ● Moderately fractured.	BOX1 BOX 2 RUN 2	
-2074.39	2530'	Ce		2529-2530.7: Light gray, fine to medium grained, dolomite to vuggy dolomite. * 2529-2529.05: Quartz druse.	BOX2 RUN 3	
-2079.39	2535'	Ce		2530.7-2539: Light gray, fine to medium crystalline, dolomite to vuggy dolomite. ● Vugs filled with euhedral quartz (>5 mm), dolomite (<,> 2mm bladed to sub rounded), pyrite cubes (<2mm) crystals. ● Highly fractured * 2530.9-2531.9: Large quartz crystals fill vugs. * 2534.5-2534.7: Pyrite cubes on top of dolomite. * 2534.7-2536.6: Highly fractured. * 2537-2538: Highly fractured, vertical fracture.	BOX 2 BOX 3 RUN 4	
-2084.39 -2089.39	2540' 2545'	Ce		2539-2549: Light gray, fine to medium grained, dolomite to slightly pitied to vuggy dolomite. ● Vugs and pities filled with dolomite and quartz druse. ● Slightly fractured.	BOX 3 BOX 4 RUN 5	
-2094.39	2550'	Ce		2540-2545: Light gray, fine to medium grained, dolomite to pitied, vuggy, cavity dolomite. Vugs filled with dolomite and quartz druse.	BOX 4 BOX 5 RUN 6	

Notes/Comments:

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Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
		Ce		● Highly fractured * 2549.5-2552.5: Vertical fracture with vugs and pyrite vein. * 2552-2555: Cavities and vugs filled with quartz druse (> 2mm crystals, euhedral).		
-2099.39	2555'	Ce		2555-2559.4: Light gray, fine grained to medium grained, dolomite to pitied, vuggy, cavity dolomite. ● Vugs filled with dolomite and quartz druse. ● Highly fractured. * 2555.3-2555.35: Fractured with chlorite staining and pyrite cube crystals.	BOX 5 RUN 7	
-2104.39 -2109.39	2560' 2565'	Ce		2559.4-2569: Light gray, fine grained to medium grained, dolomite to pitied, vuggy, cavity dolomite. ● Vugs filled with dolomite and quartz druse. Vugs filled with dolomite and quartz druse. Few vugs have pyrite cube crystals ● Highly fractured.	BOX 5 BOX 6 RUN 8	
-2114.39 -2119.39	2570' 2575'	Ce		2569-2579: Light gray, fine grained to medium grained, dolomite to pitied, vuggy, cavity dolomite. ● Vugs filled with dolomite and quartz druse. ● Moderately to highly fractured	BOX 6 BOX 7 RUN9	
-2124.39 -2129.39	2580' 2585'	Ce		2579-2589: Light gray, fine grained to medium grained, dolomite to pitied, vuggy, cavity dolomite. ● Vugs filled with dolomite and quartz druse. ● Vertical fractures filled with quartz druse (euhedral crystals), pyrite spotty throughout.	BOX 7 BOX 8 RUN 10	
-2134.39	2590'	Ce		2589-2599: Light gray, fine grained to medium grained, dolomite to pitied, vuggy, cavity dolomite. ● Vugs filled with dolomite and quartz druse. ● Moderately fractured	BOX 9 BOX 10 RUN 11	

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
		Ce		● Other minerals: calcite and pyrite * 2592.5-2592.55: Round vug filled with white mineral (barite?). * 2594.3-2594.5: Vug filled with weathered dolomite crystals.		
-2139.39	2595'	Cp		2595: **Potosi Dolomite?** * 2594.7-2594.9 Euhedral quartz crystals interlaced with bladed dolomite crystals. * 2598.6-2599: Beautiful dolomite core with bulls eye and flow patterns. Quartz druse.		
-2144.39	2600'	Cp		2595-2605.5: Light gray, fine to medium grained, dolomite to pitied, vuggy, cavity dolomite. ● Vugs filled with dolomite and quartz druse. ● Highly fractured. * 2599-2599.7:Beautiful cavity filled with euhedral quartz crystals.	BOX 10 RUN 12	
-2149.39 -2154.39	2605' 2610'	Cp		2605.5-2615.5: Light gray to fine to medium grained, dolomite to vuggy dolomite. * 2613.3-2614.5: Vertical Fracture. * 2617.6-2117.7: glauconite mineralization.	BOX 10 BOX 11 RUN 13	
-2159.39	2615'	Cp		2615.5-2616.5: Light gray to fine to medium crystalline, dolomite to vuggy dolomite ● Highly Fractured.	BOX 11 RUN 14	
-2164.39	2620'	Cp		2616.5-2626.5: Light brown to light gray, fine to medium grained, dolomite. ● Fractured, fractures from vertical to horizontal; abundant vugs ranging from 1mm to >5cm, vugs line with banded to quartz druse * 2616.5-2617.5: appears cross bedding. * 2617.5-2621.5: Bioturbated(stromatolitic?) * 2621.5-2623: Finely laminated bedding. * 2623-2626.5: boiturbated (stromatolitic?)	BOX 11 BOX 12 RUN 15	
-2169.39 -2174.39	2625' 2630'	Cp		2615-2632.6: Light brown to light gray, fine to medium grained, dolomite. ● Bioturbated ● Quartz banded and druse lined vugs ● Vugs common up to 5cm diameter. ● Fractures common vertical to horizontal. * 2628-2629.1: Rubble– extensively fractured; Quartz, calcite, pyrite mineralization.	BOX 12 BOX 13 RUN 16	

Notes/Comments:

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Elevation	Depth
-2179.39	2635'
-2184.39	2640'
-2189.39	2645'
-2194.39	2650'
-2199.39	2655'
-2204.39	2660'
-2209.39	2665'
-2214.39	2670'

Formation	Member	Lithologic Description	Samples Interval	Comments
Cp		* 2629.7-2632.6: fractures healed with calcite, pyrite and quartz.		
Cp		2632.6-2642.6: Light brown to light gray, fine to medium grained, pitted to vuggy dolomite. ● Vugs lined with quartz druse and pyrite, pyrite orbs at 2634.2 in fracture. ● Fracturing thought out ranging from vertical to horizontal, rubble zone. * 2636.7-2637.5: Calcite mineralization; bioturbated thought out * 2638.8: Hiatus??-distinct bdg change with lithic fragments (angular)	BOX 13 BOX 14 RUN 17	
Cp		2642.6-2645.6: Light brown to light gray, fine to medium grained, vuggy dolomite. ● Vugs healed with quartz. ● Extremely fractured-rubble zones. * 2644.1-2645.6: Chlorite and quartz mineralization in fractures.	BOX 14 BOX 15 RUN 18	
Cp		2645.6-2653.6: Light brown to light gray, fine to medium grained, bioturbated, pitted to vuggy dolomite. ● Vugs up to 9 cm long by 2 cm wide, lined with banded and druse quartz. ● Abundant fracturing (predominately horizontal). * 2647.2: glauconite veining. * 2653.0-2653.3: Void.	BOX 15 BOX 16 RUN 19	
Cp		2653.6-2663.6: Light brown to light gray, fine to medium grained, massive bedded, dolomite. ● Intermittent bioturbation; less vuggy, vugs lined with quartz, pyrite crystals, dolomite rhombs. ● Vugs 1mm up to >6 cm. ● Not as intensely fractured, fractures sub vertical to horizontal * 2663.2-2663.6: Vug >6cm with 4cm quartz crystal, (2cm) dolomite rhombs, (1cm) cubic pyrite .	BOX 16 BOX 17 RUN 20	
Cp		2663.6-2673.6: Light brown to light gray, fine grained, massive bedded, bioturbated to laminated, dolomite to vuggy dolomite. ● Vugs ranging 1mm to 6cm. ● Vugs lined with banded to quartz druse, euhedral calcite, crystalline dolomite, euhedral pyrite. ● Fracturing common with occasional rubble zone.	BOX 17 BOX 18 RUN 21	

Notes/Comments:

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Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
		Cp				
-2219.39 -2224.39	2675' 2680'	Cp		2673.6-2683.6: Light brown to light gray, fine grained, massive bedding, dolomite to vuggy dolomite. ● Occasional fractures, commonly sub vertical to horizontal ● Vugs spaced though out, raining up to >6cm, vugs contain agate and quartz druse, euhedral calcite and pyrite (<1mm) maybe present. * 2673.6: Rubble zone (~2”). * 2674.5: Slight fracture fill with chlorite.	BOX 18 BOX 19 RUN 22	
-2229.39 -2234.39	2685' 2690'	Cp		2683.6-2693.6: Light brown to light gray, fine grained, sacchroidal, massive bedding, dolomite to vuggy dolomite. ● Occasional fractures, commonly sub vertical to horizontal ● Vugs spaced though out, raining up to >6cm, vugs contain agate and quartz druse, euhedral calcite and pyrite (<1mm) maybe present. * Black gooey/clayey/ground sulfide. Substance in vug at 2692.6; contains sulfide particles <0.2mm. Not grease, feels gritty (driller says it's not their grease; none was used).	BOX 19 BOX 20 RUN 23	
-2239.39 -2244.39	2695' 2700'	Cp		2693.6-2703.6: Light brown to light gray, fine grained to medium grained, sacchroidal, massive bedded, dolomite to vuggy dolomite. ● Biotrubated or non descript laminations. ● Vugs contain agate, quartz druse and pyrite (<1mm) as euhedral crystals. ● Fractures are common, predominantly horizontal to sub horizontal, fractures maybe healed by quartz (SiO_2) or contain chlorite. * 2693.6-2699: Abundant vugs. * 2695.1 and 2702-2703: Possible lithics. * 2696.6– 2699: Very porous quartz fill.	BOX 20 BOX 21 RUN 24	
-2249.39 -2254.39	2705' 2710'	Cp		2703.6-2713.6: Light brown to light gray, fine to medium grained, sacchroidal, massive bedded, dolomite to vuggy dolomite. ● Predominately incipient laminations and bioturbation. ● Vugs up to >6cm with agate linings and druse quartz, euhedral massive pyrite common and calcite in vugs; vugs abundant. ● Fractures common, predominately horizontally but range to vertical. * 2705.6-2707.6: extremely mineralized with quartz (SiO_2), pyrite (FeS_2) and calcite ($CaCO_3$). * 2713.6: observed at break surface pyrite occurs as very fine grained circular to ovate blebs in the dolomite.	BOX 21 BOX 22 RUN 25	

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
		Cp				
-2259.39	2715'	Cp		2713.6-2719.1: Light brown to light gray, fine to medium grained, saccharoidal, massive bedded, dolomite to vuggy dolomite. ● Incipient laminations and bioturbation. ● Vugs up to 1 > 6cm, common with lamination and quartz druse, ehedral to anhedral calcite and pyrite crystals. ● Fractures horizontal to sub vertical healed with quartz, calcite and pyrite. * 2715 and 2719: Display heavy mineralization.	BOX 22 BOX 23 RUN 26	
-2264.39 -2269.39	2720' 2725'	Cp		2719.1-2729: Light brown to light gray, fine to medium grained, saccharoidal, massive bedded to dolomite to vuggy dolomite. ● Incipient laminations and bioturbation. ● Vugs up to 1 >6cm, common with quartz (agate and druse), euhedral to anhedral masses of calcite and pyrite. ● Extremely fractured, some healed with quartz, calcite and pyrite. * 2719.1-2720.7: Mineralized rubble zone.	BOX 23 BOX 24 RUN 27	
-2274.39 -2279.39	2730' 2735'	Cp		2729-2739: Light brown to light gray, fine grained, saccharoidal, massive bedded, dolomite to vuggy dolomite. ● Vugs up to 1> 6cm, containing banded, quartz druse, pyrite and calcite. ● Highly fractured ranging from horizontal to vertical, some healed with quartz, pyrite and calcite. * 2729.5-2729.6: Void. * 2731.3-2731.5: Void.	BOX 24 BOX 25 RUN 28	
-2284.39 -2289.39	2740' 2745'	Cp		2739-2749: Mottled, light brown to light gray, fine grained, massive bedded, dolomite to vuggy dolomite. ● Vugs range up to >6cm, containing quartz druse, pyrite and calcite. ● Predominately fractured, horizontal to vertical, some healed with quartz, pyrite and calcite. * 2739-2740.6: Dark color, appears more competent. * 2742-2749: Extremely fractured, some areas rubble.	BOX 25 BOX 26 RUN 29	
-2294.39	2750'			2749-2759:		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2299.39	2755'	Cp		Mottled, light gray to gray brown, fine grained, massive bedded, dolomite to vuggy dolomite. • Vugs range up to ≤ 4cm, containing quartz druse, pyrite and calcite; not all vugs mineralized. • Slightly fractured, horizontal to vertical; fractured surfaces voids of mineralization. * 2749-2752.7: Nondescript. * 2752-2759: Styolitic. * 2752.7-2759: Mottled, possible bioturbation; more intense with depth, irregular shape, tannish gray to medium gray.	BOX 26 BOX 27 RUN 30	
-2304.39 -2309.39	2760' 2765'	Cp		2759-2769: Mottled, light gray to gray brown, fine grained, massive bedded, dolomite to slightly vuggy dolomite. • Vugs range up to ≤ 2cm (vugs less common and not as mineralized as previous occurrences), containing quartz druse and calcite. • Slightly fractured, horizontal to vertical, some healed by quartz. • Styolitic throughout. * 2759-2765.3: Mottled, possible bioturbation; irregular to elongated shape, tannish gray to medium gray. * 2765.3-2769: Patches of dense pitting, grain size increasing with depth.	BOX 27 BOX 28 RUN 31	
-2314.39 -2319.39	2770' 2775'	Cp		2769-2779: Mottled, light brown to light gray, fine grained, massive bedded, dolomite to slightly vuggy dolomite. • Fewer vugs; spaced apart, less mineralized with quartz druse and calcite. • Slightly fractured; spaced apart, horizontal to vertical. * 2773.6-2775.4: Transition zone from Potosi to Derby-Doerun Dolomite; alternating laminae to thin beds of gray to brown gray. * 2775.4: contact irregular with Derby-Doerun fragments and Potosi.	BOX 28 BOX 29 RUN 32	
		Cdd		2775.4: **Derby-Doerun Dolomite** Light tan to light brown to light gray, fine grained to gritty, incipient thin to massive bedding, dolomite to slightly vuggy dolomite. • Fewer vugs decreasing with depth, lined with quartz, pyrite and calcite. White clay (dickiete) in some vugs. • Slightly fractured or partings.		
-2324.39 -2329.39	2780' 2785'	Cdd		2779-2789: Light gray to light tan gray, fine grained, massive bedding, dolomite to slightly vuggy dolomite. • Fewer vugs, vugs range up to 2-3cm ; spaced apart, less mineralized with quartz druse and calcite. • Slightly fractured, healed with dark green and black clay. * 2779-2782: Light brown to banded to cross bedding. * 2782-2783.4: Banded and mottled * 2783.4-2789: Mottled with clay draping * 2781: calcite and dickiete in break.	BOX 30 BOX 31 RUN 33	
-2334.39	2790'			2789-2799:		

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2339.39	2795'	Cdd		Light gray to light tan gray, fine grained, massive bedding, dolomite. ● Very few vugs, vugs range up to cm, quartz druse. ● Fracturing not apparent. ● Clay partings throughout. * 2797.3: 3cm vug contains sphalerite and sulfur crystals.	BOX 31 BOX 32 RUN 34	 2797.3’
-2344.39 -2349.39	2800' 2805'	Cdd		2799-2809: Light gray to tan gray, fine grained, massive bedded, dolomite. ● Vugs more common spaced, <3cm, quartz druse. ● Fracturing not apparent. ● Clay partings throughout. * 2800.1-2802.9: calcite crystal (1cm). * 2802.9-2806.3: mottling, chert. * 2806.3-2809: pyrite (oxidized to black, mostly elongated) filled spaces, dolomite distinctly tan.	BOX 32 BOX 33 RUN 35	
-2354.39 -2359.39	2810' 2815'	Cdd		2809-2819: Light gray to gray tan, fine grained, massive bedded, dolomite. ● Vugs more common spaced, <3cm, quart druse. ● Fracturing not apparent. ● Clay partings very common. ● Quartz open spaced fillings throughout. * 2809-2813: Pyrite open filled spaces (oxidized to black, mostly elongated). * 2811-2819: Light mottling, fading with depth.	BOX 33 BOX 34 RUN 36	
-2364.39 -2369.39	2820' 2825'	Cdd		2819-2829: Light gray to gray tan, fine grained, massive bedding, dolomite. ● Fracturing not apparent. ● Clay partings throughout. * 2819-2822.8: Mottling, gray tan; iron filled spaces; vugs less common <1cm, quartz and pyrite. * 2822.8-2826: Light mottling; quartz filled spaces <3cm; few but larger vugs, 2-3 cm quartz, more brown color. * 2826-2827: mottling more prominent like above. * 2827-2829: Dense mottling more tan-brown, Iron-filled spaces.	BOX 34 BOX 35 RUN 37	
-2374.39	2830'			2829-2839		

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project
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Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2379.39	2835'	Cdd		Gray to light tan gray, fine grained, massive bedding, dolomite. ● Less vugs, few and small <2cm, quartz and pyrite. ● No fracturing apparent. ● Clay partings thought out. ● Mottling, few quartz filled spaces, <2cm * 2836.3-2839: Fine to medium grained, significantly less mottling to none at all, gray to tan color	BOX 35 BOX 36 RUN 38	
-2384.39 -2389.39	2840' 2845'	Cdd		2839-2849: Dark gray to brown to gray to light tan, fine to medium grained, massive bedded, dolomite. ● Very few vugs, <2cm, quartz and pyrite. ● Fracturing not apparent. ● Pyrite filled spaces, mostly elongated. ● Clay partings throughout. * 2839-2841: Fine to medium grained, no mottling, dark gray to tan color. * 2841-2847: Fine grained, mottling, light gray to tan color. * 2847-2849: Fine to medium grained, less mottling, dark gray to tan color.	BOX 36 BOX 37 RUN 39	
-2394.39 -2399.39	2850' 2855'	Cdd		2849-2859: Dark gray to light brown color, fine to medium grained, massive bedded, dolomite. ● Very small and few vugs, <1cm, quartz and pyrite. ● Fracturing not apparent. ● Less pyrite filled spaces but larger, quartz filled spaces more frequent and elongated shapes. ● Clay partings throughout, some areas high density. * 2853.4-2854: Mottling. * 2857-2859: Mottling with high density of clay partings, more pyrite.	BOX 37 BOX 38 RUN 40	
-2404.39 -2409.39	2860' 2865'	Cdd		2859-2869: Gray to light gray, fine to medium grained, massive bedded, dolomite. ● Few small vugs, clustered, <1cm, quartz and pyrite. ● Some horizontal fractures. ● Pyrite and quartz filled spaces, mostly elongated. ● Clay partings prominent.	BOX 38 BOX 39 RUN 41	
-2414.39	2870'			2869-2879		

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2419.39	2875'	Cdd		Light brown to medium gray, fine to medium grained, thin to massive bedded, dolomite. ● Predominantly fine to medium crystalline granular gray, pitted with thin interbeds of tan to light brown argillaceous fine grained dolomite containing dark green to gray elongated py/chl psuedomorphs. ● Few fractures. ● Abundant dark gray partings-irregular.	BOX 39 BOX 40 RUN 42	
-2424.39 -2429.39	2880' 2885'	Cdd		2879-2889: Light brown to medium gray, fine to medium grained, thin to massive bedded, dolomite. ● Predominantly fine to medium crystalline granular gray, pitted with thin interbeds of tan to light brown argillaceous fine grained dolomite containing dark green to gray elongated py/chl psuedomorphs. ● Few fractures. ● Abundant dark gray partings-irregular. * 2884.5: 1cm calcite open space filling.	BOX 40 BOX 41 RUN 43	
-2434.39 -2439.39	2890' 2895'	Cdd		2889-2896.6: Same as Above. * 2889: Sandy, Oolitic. * 2889-2894.2: Sparse glauconite. * 2894.2-2895.7: Strongly glauconitic. 2896.6-2899: Light green gray to light gray, dolomite with dark gray clay. ● Abundant clay drapings or clay partings irregular and inclined.	BOX 42 BOX 43 RUN 44	
-2444.39 -2449.39	2900' 2905'	Cdd		2899-2809: Brown gray to light gray, very finely crystalline-flakey to finely crystalline grainy, dolomite ● Spaced lenticular pitting ≤ 1cm length by ≤ 3mm width. ● Dense clay draping/partings, irregular inclined . ● Pyrite and quartz filled spaces, mostly elongated. * 2902 and 2908: Stromatollitic structures up to 1.3’ length. ⇒Examples: pyrite with clay in partings and as open space filling	BOX 43 BOX 44 RUN 45	
-2454.39	2910'			2809-2819		

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2459.39	2915'	Cdd		Brown gray to gray, fine to medium grained, dolomite. ● Discontinues lenses to thin beds of micrite-argillaceous in thick to massive fine to medium grained dolomite. ● Numerous clay irregular and inclined dark gray clay and pyrite partings, drapes, laminations or thin interbeds ● Pitting increases with depth.	BOX 44 BOX 45 RUN 46	
-2464.39 -2469.39	2920' 2925'	Cdd		2919-2922: Light brown to brown gray, fine grained, dolomite. ●Argillaceous light and dark color bands (similar to Derby-Doerun). ●A few vugs with calcite and pyrite ≤ 2cm length by 0.5 cm width. 2922-2929: Light brown gray to light brown, fine grained, dolomite. ● Abundant dark gray clay and pyrite drapes, partings or laminae. ●Irregular and inclined patchy densely pitted areas with non pitted dolomite.	BOX 45 BOX 46 RUN 47	
-2474.39 -2479.39	2930' 2935'	Cdv Cdv		2929-2932.2: Light brown gray to light brown, fine grained, dolomite. ● Abundant dark gray clay and pyrite drapes, partings or laminae, irregular and inclined. ● Patchy pitting throughout. 2932.2-2939: **Davis Formation** (First definite recognition) Dark gray shale laminae to interbedded gray sandy (fine grained quartz) dolomite. ● 50% shale-50% dolomite. ● Edgewise conglomerate scattered throughout. ● Glauconitic dolomite.	BOX 46 BOX 47 RUN 48	
-2484.39 -2489.39	2940' 2945'	Cdv		2239-2349: Dark gray shale laminae to interbedded gray sandy (fine grained quartz) dolomite. ● 50% shale-50% dolomite. ● Edgewise conglomerate scattered throughout. ● Glauconitic dolomite. * 2937.1-2938.3: Dark green shale (continuous bed of shale).	BOX 47 BOX 48 RUN 49	
-2494.39	2950'			2849-2859		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2499.39	2955'	Cdv		**Interbedded to interlaminated dolomite to shale. Edge-wise conglomerate beds, medium to thin beds, spaced throughout.** Gray, fine grained, sandy glauconitic dolomite. ● Thin bedded-laminae ● Horizontal to crossbedded Dark green, fissile shale. ● Pyritic; bed ≤ 2” thick.	BOX 48 BOX 49 RUN 50	
-2504.39 -2509.39	2960' 2965'	Cdv		2959-2869: Same as above.	BOX 49 BOX 50 RUN 51	
-2514.39 -2519.39	2970' 2975'	Cdv		2969-2979: Same as above.	BOX 50 BOX 51 RUN 52	
-2524.39 -2529.39	2980' 2985'	Cdv		2979-2989: Same as above. ● Intervals of edgewise conglomerate ≤ 6” thick. ● Maximum continuous shale thickness ~2”	BOX 51 BOX 52 RUN 53	
-2534.39	2990'			2989-2899		

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2539.39	2995'	Cdv		Same as above.	BOX 52 BOX 53 RUN 54	
-2544.39 -2549.39	3000' 3005'	Cdv		2999-3009: Same as above. ● Thicker continuous shale * 3000.8 Limestone interbeds(in place of dolomite).	BOX 53 BOX 54 RUN 55	
-2554.39 -2559.39	3010' 3015'	Cdv		3009-3019: Same as above. ● Interbedded or interlaminated with shale and limestone. ● Edgewise conglomerate intervals continues, dark green shale ≤ 1 foot. * 3016-3019: Extremely sandy glauconitic, limestone	BOX 54 BOX 55 RUN 56	
-2564.39 -2569.39	3020' 3025'	Cdv		3019-3029: Extremely sandy dolomite to dolomite cemented sandstone. ● Extremely glauconitic. ● Fine grained, rounded to sub rounded, frosted quartz sand, becoming more sandy with depth. * 3019-3022.5: Abundant interbeds of dark green shale. * 3022.5-3029: few and spaced shale beds (2” thick) and partings.	BOX 55 BOX 56 RUN 57	
-2574.39	3030'			3029-3039		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2579.39	3035'	Cdv		3029-3037: Sandstone to siltstone to dolomite (sandy/silty). ● Dolomite cement in sandstone and siltstone. ● Very fine to fine grained, rounded to sub rounded, quartz sand. ● Abundant pyrite and glauconite. ● Dark green to green, interbed or interlaminations, fissile, shale; pyrite throughout. * 3037-3039: same as above only limestone replaces dolomite.	BOX 56 BOX 57 RUN 58	
-2584.39 -2589.39	3040' 3045'	Cdv		3039-3049 Dark green to green, fissile, pyritic shale ● Gray, fine grained, Interbedded or interlaminated limestone. ● >70% shale; thick continuous shale intervals.	BOX 58 BOX 59 RUN 59	
-2594.39 -2599.39	3050' 3055'	Cdv		3049-3059: Same as above.	BOX 59 BOX 60 RUN 60	
-2604.39	3060'	Cdv		3059--3061.6: Dark green to green, fissile, thin to medium bedded; up to 1.2'thick, shale. ● Limestone, interbedded ≤ 0.4' thick, conglomerate.	BOX 51 BOX 52 RUN 53	
-2609.39	3065'	Cb		3061.6-3069: **Bonneterre Formation** Brown to gray, fine to medium grained, mottled, oolitic limestone. ● Tan to gray, abundant clay drapes, ● laminae irregular and insipient beds in massive bedding; appears clastic, round to subangular clasts.		
-2614.39	3070'			3069-3079		

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2619.39	3075'	Cb		Brown to gray brown, very fine to fine grained, oolitic limestone. ● Thin-laminated incipient bedding in massive bedding. ● Incipient bedding is irregular and bounded by highly irregular dark gray clay laminae-styolitic like.	BOX 65 BOX 66 RUN 66	
-2624.39 -2629.39	3080' 3085'	Cb		3079-3089: Same as above. ● 3088-3089: Less limey, more dolomitic.	BOX 66 BOX 67 RUN 67	
-2634.39 -2639.39	3090' 3095'	Cb		3089-3099: Limey top 6" of interval; light gray to dark gray to brown, fine to medium grained, dolomite with brown chert scattered throughout as clast and thin beds. ● Mostly vuggy with zone of less vugs, vugs up to 1>6cm, calcite to dolomite lining vugs. ● Fractures common but spaced, horizontal to vertical. ● Dark gray, irregular parting, laminae or thin beds. * 3097.7: Rubbly zones.	BOX 67 BOX 68 RUN 68	
-2644.39 -2649.39	3100' 3105'	Cb		3099-3109: Brown gray to medium gray, very fine to fine grained, dolomite ● Interbedded to interlaminated incipient bedding to massive bedding. ● Soft sediment deformation and rip up clasts. ● Vugs ≤ 3cm length throughout, locally concentrated vugs. Dolomite crystals lining vugs. ● No apparent fractures. ● Dark gray shale irregular parting, laminae, thin beds with dolomite throughout. ● Oolitic "ghosts" scattered in dolomite throughout.cx	BOX 68 BOX 69 RUN 69	
-2654.39	3110'	Cb		3109-3119:		

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2659.39	3115'	Cb		Same as above. * 3109-3110.2: Dolomite and shale, vuggy. * 3110.2-3117: Limestone and shale, no vugs. * 3117-3119: Dolomite and shale, vuggy.	BOX 65 BOX 66 RUN 66	
-2664.39 -2669.39	3120' 3125'	Cb		3119-3129: Gray to brown gray, fine grained, limestone. ● Thinly interbedded and interlaminated with medium dark gray shale in massive bedding. ● Pyrite associated with shale. ● Soft sedimentary deformation. ● Occasional pitting. * 3126-3127: high angle fracture , $^{1}/_{2}$” wide healed with calcite.	BOX 66 BOX 67 RUN 67	
-2674.39 -2679.39	3130' 3135'	Cb		3129-3134.6 Same as above. ● No vugs. * 3133.3-3134.3: Calcite healed fracture (high angle). 3134.6-3139: Dolomite. ● Same bedding as above. ● Pits with occasional vugs, intervals of intense pitting.	BOX 67 BOX 68 RUN 68	
-2684.39 -2689.39	3140' 3145'	Cb		3139-3149: Light brown to light gray to gray, very fine to fine grained. ● Interbedded to interlaminated, irregular, incipient bedding with gray shale in overall massive bedding. ● Soft sediment deformation. ● Possible rip up clasts. ● Pitting and vugs localized, vugs ≤ 5 cm by 1 cm lenticular, lined with dolomite crystals. ● Fractures hairline to thin, horizontal to vertical, healed with dolomite localized	BOX 68 BOX 69 RUN 69	
-2694.39	3150'	Cb		3149-3159:		

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2699.39	3155'	Cb		Same as above. * 3149-3151: Extremely vuggy and fractured, vugs up to > 6cm.	BOX 69 BOX 70 RUN 70	
-2704.39 -2709.39	3160' 3165'	Cb		3159-3169: Same as above. ● Prominent vugs spaced throughout dolomite and calcite and pyrite crystals. * 3168: Brachs?	BOX 70 BOX 71 RUN 71	
-2714.39 -2719.39	3170' 3175'	Cb		3169-3179 Same as above (lithology and bedding). ● Pyrite scattered widely throughout as crystals in vugs and open space filling (≤2mm). * 3170: large vug >6cm lined with quartz, dolomite and pyrite. * 3169-3173: Dolomite. * 3173-3174.5: Limey dolomite or interlaminated limestone. * 3174.5-3179 Limestone.	BOX 71 BOX 72 BOX 73 RUN 72	
-2724.39 -2729.39	3180' 3185'	Cb		3139-3149: Brown to gray, very fine to fine grained, thin bedded to laminated, limestone with gray to dark gray, thinly bedded to laminated to parting shale. ● Irregular laminated to thinly bedded with massive bedding. ● Soft sediment deformation, rip-up clast.	BOX 73 BOX 74 RUN 73	
-2734.39	3190'	Cb		3149-3159:		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2739.39	3195'	Cb		Brown gray to gray, very fine to fine grained, limestone with dark green to gray to gray, shale. ● Irregular partings laminations to thin beds (<2” thick) comprising a massive bed. ● Soft sediment deformation. ● Rip-up clasts scattered throughout. ● No pitting, vugs, fractures observed. (same as previous run)	BOX 74 BOX 75 RUN 74	
-2744.39 -2749.39	3200' 3205'	Cb		3199-3209: Same as above.	BOX 75 BOX 76 RUN 75	
-2754.39 -2759.39	3210' 3215'	Cb		3209-3210.5: Same as above. 3210.5-3219: Clay present only as partings.	BOX 76 BOX 77 RUN 76	
-2764.39 -2769.39	3220' 3225'	Cb		3219-3222.4 Same as above. 3222.4-3229: Brown to gray to gray, very fine to fine grained, limestone. ● Glauconitic or chloritic spheroids <1mm diameter quartz sand. ● <1mm diameter possible fossil (coral?) with replacement of openings. ● Irregular laminae or thin bedding <6 “thick Dark gray to gray shale. ● Irregular partings laminae or thin bedded <0.2”thick. ● Incipient bedding in massive bedding. ● No apparent pitting, vugs, fractures * Green mineral appears to be to hard for glauconite. Probably not quartz sand. Appears to scratch with knife blade, probably calcite.	BOX 77 BOX 78 RUN 77	
-2774.39	3230'	Cb		3229-3239:		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2779.39	3235'	Cb Cdv Cbv		Brown gray to gray, very fine to fine, pelletal at times, limestone. Green to gray to dark gray, shale as drapes, partings, laminae and beds ≤ 4” thick, irregular. ● Limestone and shale interbedded, interlaminated clay drapes, partings. ● Thin incipient bedding comprising massive bedding. ● Fossils? (coral?, brachiopods?, ostracods?) scattered throughout. * 3229-3231: Thin shale beddings to laminae in limestone. * 3231-3234: and 3238-3239: Limestone with clay drapes. * 3234-3238: Green shale beds ≤ 4” in limestone (similar to Davis).	BOX 78 BOX 79 RUN 78	
-2784.39 -2789.39	3240' 3245'	Cdv		3239-3249: Light brown to brown gray, very fine to fine, limestone with pellets and rip up clasts. Green to dark green, fissile, laminated to thin bedded; ≤ 3” thick , shale ● Limestone and shale interlaminated to thin or medium interbedding. ● This looks like Davis. Are the Davis and Bonneterre interfingered. * 3239-3239.6: Edgewise conglomerate.	BOX 79 BOX 80 RUN 79	
-2794.39 -2799.39	3250' 3255'	Cdv		3249-3259: Light brown to brown gray to gray, very fine to fine grained limestone with zones of pellets. Green gray to dark gray, fissile, <5” thick beds to laminae, shale. ● Interlaminated to interbedded (thinly) limestone to shale in variable beddings. * 3251-3251.6: fossils (brachiopods, spines, and others). * 3257.1-3257.4: Edgewise conglomerate.	BOX 80 BOX 81 RUN 80	
-2804.39 -2809.39	3260' 3265'	Cdv		3259-3269: Pinkish brown to light brown to brown gray, very fine to fine grained, limestone. Pale green to green to dark green to dark gray, fissile, beds up to 1.4’ thick, shale. ● Interlaminated up to thickly interbedded limestone to shale; intervals of soft sediment deformation. ● Intervals of edgewise conglomerate. ● Angular fractured clast healed with clay.	BOX 81 BOX 82 RUN 81	
-2814.39	3270'			3269-3279:		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2819.39	3275'	Cb-Cdv transition zone		Light brown to brown gray to gray, very fine to fine grained, limestone. Green to dark green to green gray, fissile, irregular bedding to laminae, bedding thickness up to 1.2'. • Limestone and shale interlaminated and interbedded. • Pelletal fossil fragments in some intervals, clastic, rip-up clasts. • Edgewise conglomerate intervals. • Soft sediment deformation • No apparent pitting, voids or fractures.	BOX 82 BOX 83 RUN 82	
-2824.39 -2829.39	3280' 3285'	Cb-Cdv transition zone		3279-3289: Gray to brown gray, fine to medium grained, limestone to oolitic limestone, includes gray clay partings; some fossil fragments Brown to gray, very fine to fine grained, laminae to thick beds, limestone. Green to dark gray to gray, fissile, shale. • Interlaminated to interbedded limestone and shale. • No apparent pitting, vugs, fractures.	BOX 83 BOX 84 RUN 83	
-2834.39 -2839.39	3290' 3295'	Cb-Cdv transition zone		3289-3299: Same as above (however interbedded with dolomite; no limestone). * 3299.1 Cdv-Cb transition to Cb	BOX 84 BOX 85 RUN 84	
-2844.39 -2849.39	3300' 3305'	Cb		3299-3309: Light brown to brown gray to gray, very fine to medium grained, oolitic and glauconitic, dolomite to pitted dolomite. Pale green laminae to <2" bedding, gray partings, shale. • Thinly to medium interbedded and interlaminated limestone, dolomite and shale. * 3299-3302.3: Limestone. * 3302.3-3302.3: Dolomite.	BOX 85 BOX 86 RUN 85	
-2854.39	3310'			3309-3219:		

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Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2859.39	3315'	Cb		Brown gray to gray, fine to medium grained, oolitic and glauconite, dolomite to pitted dolomite with gray clay irregular partings. ● Incipient thin bedding in massive bedding.	BOX 87 BOX 88 RUN 86	
-2864.39 -2869.39	3320' 3325'	Cb		3319-3325.4: Same as above. 3325.4-3327.3: Same as above with cross bedding 3327.5-3329: Extremely glauconitic, dark green peppering.	BOX 88 BOX 89 RUN 87	
-2874.39 -2879.39	3330' 3335'	Cec		3229-3339: **Eau Claire Formation** Interbedded glauconitic to oolitic dolomite in predominantly sandy silty to glauconitic. ● Clayey cross bedding.	BOX 89 BOX 90 RUN 88	
-2884.39 -2889.39	3340' 3345'	Cec		3339-3349: Light gray to dark gray to medium brown, fine to medium grained, dolomite to sandy dolomite to sandstone. Interbedded with thin beds of dolomite, sandstone and shale. ● Areas appear very silty, oolitic, very much like sandstone and are light gray in color. ● Clay partings throughout. * 3346.7: Flat pebble conglomerate.	BOX 90 BOX 91 RUN 89	
-2894.39	3350'			3349-3359:		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2904.39	3355'	Cec		Gray to dark gray to pink brown, fine to medium grained, dolomite to sandy dolomite to sandstone. Thin layers and clay partings, shale. ● Interbedded dolomite and sandstone is light gray with black spaces. ● Few areas of conglomerate. * 3357: Cross bedding and starts to look green.	BOX 91 BOX 92 RUN 90	
-2909.39 -2914.39	3360' 3365'	Cec		3359-3369: Light gray, orange, brown to tan, fine to medium grained, sandstone interbedded with shale and maybe dolomite. Dark gray shale, thin beds and clay partings. ● Some conglomerate and crossbedding. * 3365: pyrite in the sandstone.	BOX 92 BOX 93 RUN 91	
-2919.39 -2924.39	3370' 3375'	Cec		3369-3379: Same as above. ● Sandstone is getting coarser; light gray color with black spaces, some is brown, pink, tan. ● Interbedded shale and dolomite. ● Clay partings and some conglomerate. ● Overall dark gray color; cross bedding; fine to medium grained.	BOX 93 BOX 94 RUN 92	
-2929.39 -2934.39	3380' 3385'	Cec		3379-3389: Gray to brown to pink, fine grained with small areas of medium grained (<2 thick), some conglomerate, sandstone. ● Interbedded shale and clay partings, fossils and mud cracks. ● Little crossbedding, glauconite around the clay partings.	BOX 94 BOX 95 RUN 93	
-2939.39	3390'			3389-3399:		

Notes/Comments:

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Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2944.39	3395'	Cec		Same as above. ● Interbedded with some shale much less than above. ● Clay partings prominent. ● Color varies from light gray to brown to pink. ● Mostly fine grained; small areas of medium grained sandstone, light gray color. ● A lot more glauconite than before, beautiful emerald color. ● Little to no crossbedding.	BOX 95 BOX 96 RUN 94	
-2949.39 -2954.39	3400' 3405'	Cec		3199-3209: Light gray to brown to pink color, fine to medium grained, sandstone with less shale and much thinner clay partings. ● Some interbedded sandstone with glauconite. ● Same as above.	BOX 96 BOX 97 RUN 95	
-2959.39 -2964.39	3410' 3415'	Cec		3409-3419: Light gray to gray to significantly less brown and pink, mostly medium grained, massive bedding, sandstone with less shale and clay partings. ● Interbedding; no cross bedding apparent. * 3414-3415 and 3418.3-3418.7: weathered brown to red, medium grained sandstone with clay (scratches easily, smears when wet.)	BOX 97 BOX 98 RUN 96	
-2969.39 -2974.39	3420' 3425'	Cec		3419-3429: Gray to dark gray. fine grained, massive bedded, sandstone with gray to dark gray clay partings throughout. ● Few areas of light gray to brown sandstone. ● Lots of glauconitic throughout. * 3427.3: Very dark gray, medium to coarse grained, sandstone. * 3426: Small brown mineral found.	BOX 99 BOX 100 RUN 97	
-2979.39	3430'			3429-3439:		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-2984.39	3435'	Cec		Salt and pepper appearance, fine to coarse grained, sub rounded to rounded, dolomite cement, sandstone to glauconitic sandstone. Dark green to gray to medium brown, fissile to compact, shale that displays soft sediment deformation; predominant lithology. Gray, lamanea to thin bedded, glauconitic dolomite. ● Interlaminated and thinly interbedded (typically <1”, 3437.3-3437.9: glue sandstone with dolomite cement) with shale, sandstone, dolomite and siltstone. ⇒ Sandstone contains a subrounded to rounded black grain (Iron oxide? Or phosphate nodule?)	BOX 100 BOX 101 RUN 98	
-2989.39 -2994.39	3440' 3445'	Cec		3439-3449: Same as above. ● Sandstone appears to be fossiliferous. * 34439.7 and 3445: observed brachiopods.	BOX 101 BOX 102 RUN 99	
-2999.39 -3004.39	3450' 3455'	Cec		3449-3459: Same as above. ● Siltstone is predominant lithology in this run. Still interlaminated to interbedded siltstone, shale, sandstone and dolomite.	BOX 102 BOX 103 RUN 100	
-3009.39 -3014.39	3460' 3465'	Cec		3459-3469: Brown to light brown, silty, argillaceous, fossil (brachiopods), dolomite. Dark gray, irregular beds and partings, shale. Fine to medium grained, round to subangular, sandstone with some pyrite and black elongated fossils (brachiopod fragments). ● Shale, dolomite and sandstone interlaminated to thinly (<2”) bedded, irregularly bedded, soft sediment deformation; thicken sandstone beds at 3461-3462.5; 3464.1-3464.6; 3467.5-3469.	BOX 103 BOX 104 RUN 101	
-3019.39	3470'			3469-3479:		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-3024.39	3475'	Cec		Predominantly brown, fine grained, dolomite with fossils (brachiopods). • Glauconite soft sediment deformation. • Clayey to silty to sandy, dark gray shale partings to laminae to thin beds throughout. • Fine to medium grained, rounded to subangular, quartz sandstone with black mineral (FeO?) pyrite, thin beds to lenses scattered throughout dolomite.	BOX 104 BOX 105 RUN 102	
-3029.39	3480'	Cec		3479-3480.9: Transition Zone: Interlaminated to interbedded dolomite, to shale to sandstone; same as above sandstone beds (thicken 3480.4-3480.9)	BOX 105 BOX 106 RUN 103	
-3034.39	3485'	Cl		3480.9-3489: **Lamotte Sandstone** White to pink brown (where dolomite cement) to green (where iron oxide), fine to medium grained, well rounded to subrounded, mostly well cemented (cemented with $Si0_2$ and $MgCaCO_3$), quartz sand. • Massive bedding • Occasional shale streak associated with dolomite cement. * 3486.6-3488: cross bedding		
-3039.39 -3044.39	3490' 3495'	Cl		3489-3499: White to pink to gray (diffused color banding due to Iron oxide), fine to medium grain, well rounded to sub rounded, well cemented, massive bedding, quartz sandstone. • SiO_2 cement. • Massive bedding with occasional cross bedding.	BOX 106 BOX 107 RUN 104	
-3049.39 -3054.39	3500' 3505'	Cl		3499-3509: Same as above. • Associated hairline fractures.	BOX 107 BOX 108 RUN 105	
-3059.39	3510'			3229-3239:		

Notes/Comments:

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-3064.39	3515'	Cl		Same as above. • Much more abundance and intensity of Iron oxide intervals. • Much more occurrences of closed fractures.	BOX 108 BOX 109 RUN 106	
-3069.39 -3074.39	3520' 3525'	Cl		3519-3529: White with gray and maroon streaks or patches, very fine to medium grain, weakly friable, well rounded to subrounded quartz sandstone cemented with SiO_2. • Color streaks or patches result of Iron oxidation. • Fractures occasional, spaced closed, predominantly hair line. • Massive bedding with localized cross bedding. • No clast observed • Possible coarsening upwards sequence of sand grains	BOX 109 BOX 110 RUN 107	
-3079.39 -3084.39	3530' 3535'	Cl		3529-3539: Same as above.	BOX 110 BOX 111 RUN 108	
-3089.39 -3094.39	3540' 3545'	Cl		3539-3543.4: Same as above 3543.4-3549: Same as above. • Medium grained quartz sand becomes dominant grain size and is conspicuous • Iron oxide (maroon) becomes more dominant throughout.	BOX 111 BOX 112 RUN 109	
-3099.39	3550'			3549-3559:		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	Depth	Formation	Member	Lithologic Description	Samples Interval	Comments
-3104.39	3555'	Cl		Same as above. * 3549-3558: Medium grained prominent size * 3558-3559: Very fine to fine grained prominent size; less maroon coloration mostly white	BOX 112 BOX 113 RUN 110	
-3109.39 -3114.39	3560' 3565'	Cl		3559-3569: White with streaks and bands of maroon and gray (Iron oxidation), very fine to medium grained, well rounded to sub rounded, weakly friable, quartz sandstone cemented with SiO_2. ● Massive bedding with localized cross bedding. ● Tight hairline fractures throughout. ● No clast (pre Cambrian) observed.	BOX 113 BOX 114 RUN 111	
-3119.39 -3124.39	3570' 3575'	Cl		3569-3579: Same as above	BOX 114 BOX 115 RUN 112	
-3129.39 -3134.39	3580' 3585'	Cl		3579-3359: Same as above. * 3581.9-3582.	BOX 115 BOX 116 RUN 113	
-3139.39	3590'			3589-3599:		

Notes/Comments:

Project: Shallow Carbon Sequestration Demonstration Project
Site: Luecke Site
Hole Exploratory Borehole #4

Elevation	**Depth**	Formation	Member	**Lithologic Description**	**Samples** **Interval**	**Comments**
-3144.39	3595'	Cl		White to maroon to gray to brick red, very fine, fine to medium grained, sub rounded to sub angular, sandstone. * 3589-2597: Very fine to medium grained dominate becoming coarser with depth. * 3597-3598: Fine to coarse grained, quartz pebbles. * 3598-3599: Very fine to coarse grained. * 3589-3595.6: Cement SiO_2 and Fe oxide. * 3595.6-3599: Fe oxide. * 3589-3594: Highly fractures and rubble zones. Massive bedding with intervals of cross bedding (especially at 3598-3599).	BOX 117 BOX 118 RUN 114	
-3149.39 -3154.39	3600' 3605'	Cl		3599-3609: Pink to red, very fine to coarse grained, rounded to angular, sandstone to pebbly sandstone. ● Some minimal fragments appear euhedral (igneous clast?). ● Cement predominantly Iron oxide and SiO_2 . ● Variety of intervals with dominant grain size conspicuous (very fine to fine grained; fine to medium grained; fine to coarse grained, pebble conglomerate). ● Massive bedding with intervals of cross bedding. ● Fractures not apparent.	BOX 118 BOX 119 RUN 115	
-3159.39 -3164.39	3610' 3615'	Cl		3609-3619: Red to pink (Fe oxide), very fine to coarse grained, weakly friable, sandstone to pebbly sandstone. ● Cement SiO_2 and Fe oxide. ● Massive bedding with cross bedding intervals. * 3613.8-3619: Highly fractured, predominantly horizontal fractures; overall; appears to be coarsening, fewer predominantly fine to medium grained intervals.	BOX 119 BOX 120 RUN 116	
-3169.39	3620'	Cl		3619-3625: Same as above. ● Weakly disseminated in pyrite in sandstone.	BOX 120 BOX 121 RUN 117	
-3174.39	3625'			Bottom of EXP #4		
-3179.39	3630'					

Notes/Comments:

Shallow Carbon Sequestration Demonstration Project

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Final Project Report

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CHAPTER IV - MISSOURI STATE UNIVERSITY

EXECUTIVE SUMMARY

This report presents the experimental methods and research results of tasks undertaken by Missouri State University (MSU) researchers as part of the larger Shallow Carbon Sequestration Demonstration Project (SCSDP), a shallow carbon sequestration feasibility investigation. The SCSDP is a project funded by the U.S. Department of Energy through a Cooperative Agreement with City Utilities. City Utilities gathered a team of research partners which includes two universities, a state geologic research agency, and drilling and testing contractors. The work reported here includes activities related to three of the sites investigated for potential carbon sequestration consideration: the John Twitty Energy Center (JTEC) site near Springfield, the Thomas Hill Energy Center (THEC) site near Moberly, and the Sioux Power Plant (SPP) site near Florissant. Tasks reported here include various aspects of hydrologic testing and mineralogic and geochemical evaluation of the available site samples and data. Based only on the information in our evaluation, the THEC site appears to offer the most promising potential for carbon sequestration. This conclusion is based primarily upon two key findings: one which suggests the target formation zone beneath the THEC site is more permeable than at the SPP site, and a second which indicates the mineral assemblage and reported water chemistry beneath the THEC site is likely to lead to a greater mass of solid-phase carbon species precipitating out of solution after hypothetical injection of carbon dioxide than would be the case for the SPP site. Additional study would be needed for any of the sites to be more fully considered for actual carbon sequestration activities.

I. EXPERIMENTAL METHODS

Task 2.c. Determine the Hydrogeology of the Ozark Aquifer at the John Twitty Energy Center (JTEC) Site

Hydrologic data from the cooling water wells at the JTEC site, and other wells in the local vicinity, were used for this task.

Hydraulic Evaluation of Field Collected Hydrologic Data

Hydraulic tests were completed by measuring changes in water level in response to pumpage from and injection into various stratigraphic intervals within boreholes at the JTEC site. These values were used with the program AQTESOLV to determine transmissivity, hydraulic conductivity and permeability of potential injection zones and overlying confining units. AQTESOLV is a graphical curve-matching program used to determine the optimal fit between changes in water levels measured during such tests and those predicted by various analytical solutions/equations.

Task 3.b. Determine the Petrologic and Mineralogic Characteristics of the Confining Layer and Target Formation

Thin-Section Analysis of Rock Core Samples

The general method used to analyze rock core samples was to collect approximately one piece of a rock core nominally three inches long and one-half the diameter of the core out of every 10 feet of core collected during drilling activities.

The general thin-section method was to collect a small section of quartered core, approximately 3 inches in length. Then the small slab of core was impregnated with a blue epoxy, glued to slides using Hillquist Thin Section Epoxy, then trimmed and ground down to approximately 30 microns thickness as determined by the optical properties of quartz using a petrographic microscope. Finally, a cover slip was applied to protect the integrity of the sample. This method follows a procedure outlined by Chayes (1965). A Leitz Wetzlar petrographic microscope was used with a mechanical counting stage by James Swift and a Swift Model F counter with 12 channels. Over 1,000 points were counted for each thin section.

Before point counting, each sample was viewed using the microscope to determine the constituents present to assign to a channel on the counter. In the instance that more constituents were present than the 12 channels, a written tally was kept and the stage advanced without a count, and the tallied counts were added in after the count was completed.

Overall, 21 unique constituents were identified in the cores, with blue epoxy representing pore space. It is important to note that a second type of porosity was identified. This porosity is an artifact of the sample preparation, a result of the plucking of grains during the thin section procedure, and is referred to as artifact porosity. When this artifact porosity was encountered during point counting, the stage was advanced and no count was taken to prevent artificially inflating the true depositional porosity of the sample.

Example Thin Section Identifications

The following five pairs of photomicrographs (Figures 4.1 through 4.5) show how various types of detrital framework grains were identified in the Lamotte Sandstone for this project (samples from the THEC site). In all five figures, the photo on the left side is the microscope view under plane-polarized light and the photo on the right side is the microscope view under cross-polarized light.

FIGURE 4.1: CORE SAMPLE FROM THE THEC SITE AT A DEPTH 2,337.4 FEET. CONSTITUENTS: A) DETRITAL QUARTZ; B) DARK CLAY; C) POROSITY

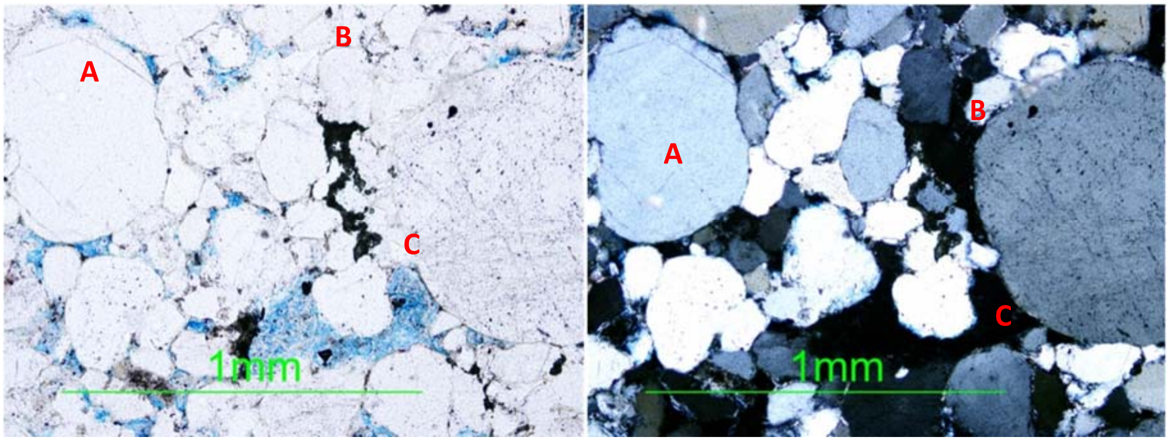


FIGURE 4.2: CORE SAMPLE FROM THE THEC SITE AT A DEPTH 2,403.5 FEET. .CONSTITUENTS: A) DETRITAL QUARTZ; B) POROSITY; C) ZIRCON; D) PORE-FILLING EPIDOTE; E) HEMATITE STAIN.

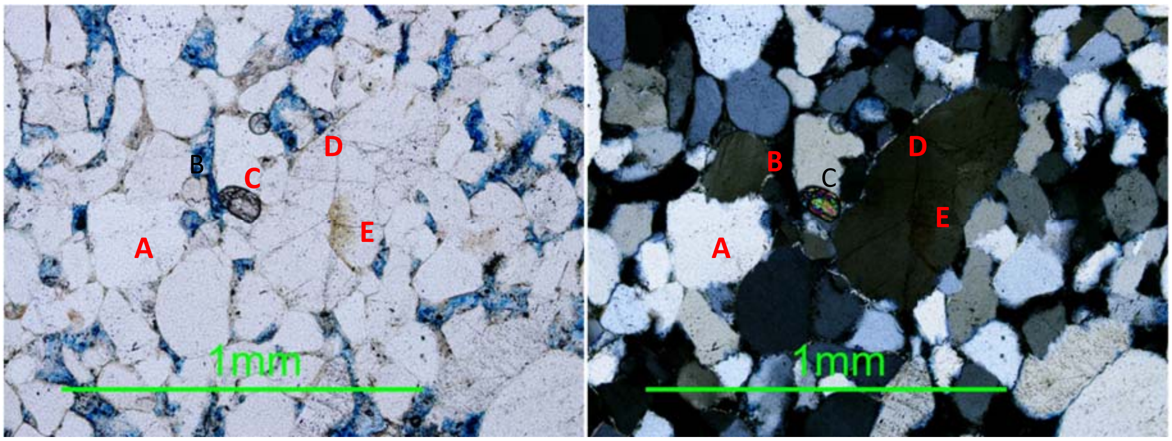


FIGURE 4.3: CORE SAMPLE FROM THE THEC SITE AT A DEPTH 2,411 FEET. CONSTITUENTS: A) DETRITAL QUARTZ; B) POROSITY; C) PORE-FILLING EPIDOTE.

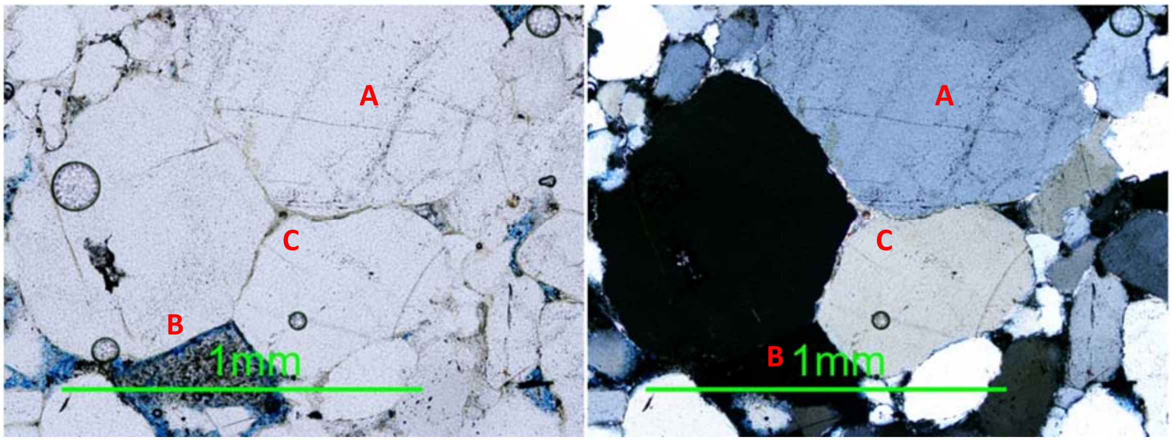


FIGURE 4.4: CORE SAMPLE FROM THE THEC SITE AT A DEPTH 2,479.5 FEET. CONSTITUENTS: A) DETRITAL QUARTZ; B) POROSITY; C) IGNEOUS ROCK FRAGMENT (RHYOLITE PORPHYRY).

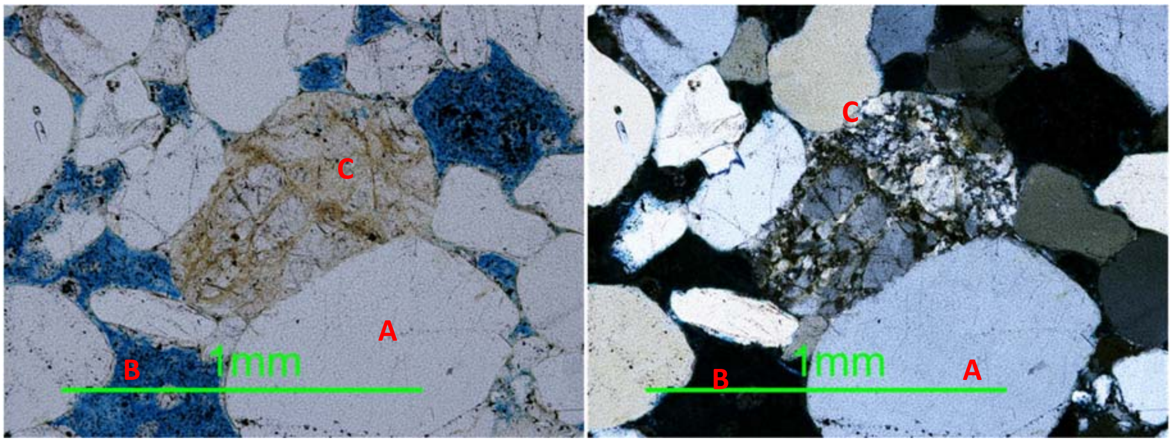
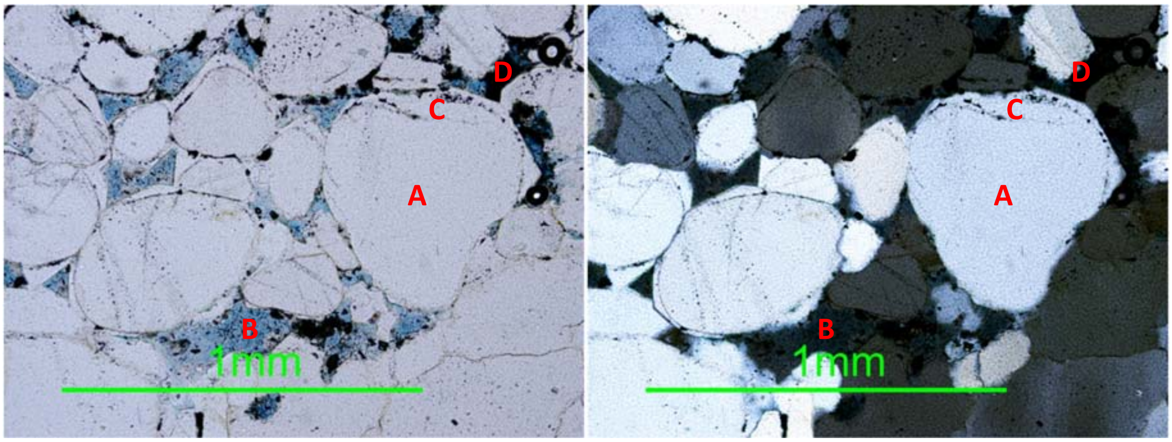


FIGURE 4.5: CORE SAMPLE FROM THE THEC SITE AT A DEPTH 2,533.8 FEET. CONSTITUENTS: A) DETRITAL QUARTZ; B) POROSITY; C) QUARTZ OVERGROWTH CEMENT; D) IRON OXIDE CEMENT.



X-Ray Fluorescence Methods

Also of note, during activities at JTEC, the utility of non-destructive testing using X-Ray Fluorescence (XRF) method was tested with a resulting determination that thin-section analysis was more useful for the project. The general details of the XRF method and resulting data for the JTEC site are reported in Appendix A. Based on these results, it was determined that thin-section analysis was the most time- efficient method of proceeding, therefore, no XRF analyses were conducted for either the THEC or SPP sites.

After determining the mineralogy of the target formation at a site based on thin-section analysis, an effort was made to combine site-specific water chemistry data (provided by SCSDP Research Partner Missouri University of Science & Technology (Missouri S&T) with the mineralogy data to provide a more thorough evaluation of each site with respect to how the site might respond to carbon dioxide injection. The method chosen for this evaluation was to perform a Geochemical Evaluation of Site-Specific Data.

Geochemical Evaluation of Site-Specific Data

Aqueous geochemistry consists of applying chemical principles to natural waters. Using published chemical thermodynamics data, and with sufficient chemical constituent detail about the water under consideration, one can calculate which ions in a solution will begin to react with which other ions in that same solution. Because most natural waters contain many ions, the number of calculations can be rather large. Therefore several automated computer programs have been developed to perform these calculations and display the end results. One widely used program for this process is the Geochemists Workbench software (Aqueous Solutions, LLC).

Geochemists Workbench software was used to calculate geochemical reactions of hypothetical carbon dioxide injections into site specific water chemistry data provided to MSU by Missouri S&T. These calculations were performed for both prograde (injection) and retrograde (injection ceases) phases of potential injection activities. These evaluations all were run with a hypothetical 10-year carbon dioxide injection phase and a 500-year post-injection phase.

When using any chemical calculation with mineralogic data, it is necessary to translate identified mineral constituents into the existing database of chemical properties of minerals i.e., known chemical properties only exist for certain minerals which have been widely tested and reported in the literature).

Table 4.1 below lists the method of translation used in this project. The middle column of the table lists the way in which minerals were identified in the thin-section point-counts and the right hand column indicates which mineral (or mineral combination) was used in geochemical calculations to approximate that mineral identified in thin-section.

TABLE 4.1. GEOCHEMICAL MODELING OF CONSTITUENTS (MODIFIED FROM BERGER, 2011).

Petrography	Counted as…	Simulated as…
Framework Grains	Quartz	Quartz
	Feldspar	4/10 K-feldspar, 1/10 Albite, 1/4 Kaolinite, 1/4 Illite
	Fossil Fragments (Carbonate)	Calcite
	Fossil Fragments (Phosphate)	Apatite
	Glauconite Pellets	Glauconite
	Detrital Mica	Muscovite
	Detrital Ferromag. Silicate (Epidotized Hornblende, etc.)	Epidote
	Opaque Grain	3/4 Pyrite, 1/4 Hematite
	Volcanic Rock Fragments	7/10 Quartz, 2/10 K-feldspar, 1/10 Albite
	Zircon	Zircon
	Chert	Quartz
Pore Space	Pore Space	Pore Space
Matrix/Cement	Quartz (Overgrowth)	Quartz
	Clay (Dark)	1/4 Glauconite Smectite, 1/4 Chlorite, 1/4 Hematite, 1/4 Goethite
	Clay (Light)	1/2 Illite, 1/2 Montmorillonite Smectite
	Glauconite	1/2 Glauconite Smectite, 1/2 Chlorite
	Calcite (Pore Filling)	Calcite
	Dolomite (Rhombs)	Dolomite
	Opaque (Pore Filling)	3/4 Pyrite, 1/4 Hematite
	Epidote (Pore Filling)	Epidote
	Phosphate (Pore Filling)	Apatite
	Feldspar (Overgrowth)	4/10 K-feldspar, 1/10 Albite, 1/4 Kaolinite, 1/4 Illite

Task 3.c. Determine the Permeability of the Confining Layer and Target Formation

The MSU team used hydrologic testing data at the JTEC site to determine the hydraulic conductivity and permeability of the confining layer above the proposed "target formation" for CO2 injection. Standard and shut-in pressure tests were completed over approximate 21-foot vertical intervals within the borehole, beginning above the confining layer and continuing to the base with nearly continuous coverage. These data were evaluated using standard techniques for pressure-injection testing to calculate hydraulic conductivity for each test interval.

At the other two sites, THEC and SPP, drilling conditions precluded the use of pressure tests in the wells; therefore, no pressure tests were conducted. In an effort to collect information at each of these sites, water levels and pumping during well development and collection of a site-specific water sample were monitored to collect some water level and drawdown information. These data were then used to determine an estimate of site-specific permeability for the target formation.

Task 3.d. Determine the Injection Rate Profile for the Target Formation

Three conventional single-well pumping tests were completed within the target formation at the JTEC site and pressure-test results also were analyzed within the same interval to determine hydraulic conductivity and permeability.

At the other two sites, THEC and SPP, drilling conditions precluded the use of pressure tests in the wells. As a result, no evaluation of the injection rate profile for the target formation was possible (the only data available represent the entire target formation as a whole).

II. RESULTS

1. JOHN TWITTY ENERGY CENTER

Task 2.c. Determine Hydrogeology of the Ozark Aquifer at the John Twitty Energy Center (JTEC) Site in Springfield.

AQTESOLV analysis of City Utilities' pumping records and analysis of both steady and transient water levels onsite at the JTEC site and from sixteen nearby property owners willing to allow measurements of their wells during the third quarter of 2009 provided the following results for the Ozark Aquifer system.

For quasi-steady conditions in December of 2008, the Thiem solution gave limiting transmissivity values of 0.015 and 0.042 square feet per second (ft^2/sec). For transient conditions following restart of two of the onsite wells, the response in the third well gave transmissivities ranging between 0.017 and 0.025 ft^2/sec. with storativity centered around 6×10^{-4}. Analytical models were not particularly sensitive to leakance values of the confining layer (the Northview Formation), but indicate a vertical hydraulic conductivity $< 10^{-9}$ ft/sec. When steady-state conditions were reached again for all three wells, flow-net analysis gave a transmissivity of 0.011 ft/sec. Thus, direct field measurements provide a median transmissivity of 0.027 ft^2/sec.

Digital model simulations of the steady potentiometric surface closely match measured levels with a calibrated transmissivity of 0.027 ft^2/sec and a vertical hydraulic conductivity within the confining unit of 9×10^{-11} ft/sec. Thus, these calibrated values are very consistent with measured values and the calibrated model should provide reasonable estimates of a future capture zone under various pumping scenarios.

A MODFLOW digital model of the Ozark Aquifer in the vicinity of the JTEC site was validated and used to simulate various scenarios where pumping of nearby municipal water wells was increased. The initial results are consistent and show median parameter values of 0.028 ft^2/sec. for transmissivity, 4.3×10^{-4} for the storage coefficient, and 2.7×10^{-11} ft/sec. for the vertical hydraulic conductivity of the Ozark Aquifer Confining Layer.

Task 3.b. Determine the Petrologic and Mineralogic Characteristics of the Confining Layer and Target Formation

Thin-Section Analysis of Rock Core Samples

As described in the experimental methods section, thin-sections of rock core were prepared at regular intervals throughout the target formation (Lamotte Sandstone). Results of the JTEC core analysis for the Lamotte Sandstone are summarized below in Table 4.2.

TABLE 4.2. DISTRIBUTION OF CONSTITUENTS FOR THE LAMOTTE SANDSTONE OF THE JTEC CORE.

Petrography	Constituent	Average (%)	Minimum (%)	Maximum (%)
Framework				
	Quartz	71.46	52.89	82.36
Grains				
	Feldspar	0.62	0.00	4.62
	Fossil Fragments (Carbonate)	0.00	0.00	0.00
	Fossil Fragments (Phosphate)	0.22	0.00	3.04
	Glauconite Pellets	0.56	0.00	14.22
	Detrital Mica	0.07	0.00	1.79
	Epidotized Hornblende	0.00	0.00	0.00
	Iron Oxide	0.12	0.00	2.54
	Volcanic Rock Fragments	0.06	0.00	1.07
	Zircon	0.02	0.00	0.10
Pore Space				
	Pore Space	9.79	0.19	16.36
Matrix/Cement				
	Quartz Overgrowth	10.22	0.00	21.45
	Clay (dark)	2.90	0.00	30.46
	Clay (light)	2.42	0.00	35.72
	Glauconite	0.00	0.00	0.00
	Calcite (Pore filling)	0.08	0.00	2.37
	Dolomite (Rhombs)	0.00	0.00	0.00
	Iron Oxide (Pore filling)	1.47	0.00	12.05
	Epidote (Pore filling)	0.00	0.00	0.00
	Phosphate (Pore filling)	0.00	0.00	0.00
	Feldspar (Overgrowth)	0.00	0.00	0.00
Total	Total	100.00		

Input geochemical data (as provided by Missouri S&T) used in the geochemical evaluation are shown in Table 4.3. Simulation results for the end of 10 years of hypothetical carbon dioxide injection and a 500- year post-injection phase at the JTEC Site are shown below in Table 4.4.

TABLE 4.3. IONIC SPECIES CONCENTRATIONS REPORTED BY MISSOURI S&T, IN MILLIGRAMS PER LITER (MG/L) FOR THE JTEC SITE.

	Ionic Species	Springfield (JTEC) Site Data
Cations (mg/l)	Fe^{2+}	0.56
	Ca^{2+}	22.4
	Mg^{2+}	8.32
	K^{+}	3.31
	Na^{+}	48
	Mn^{2+}	0.05
	Al^{3+}	0.01
	H^{+}	1.2E-05
Anions (mg/l)	Cl^{-}	56.7
	HCO_3^{-}	131
	SO_4^{2-}	10.6
	NO_3^{-}	0.1
	F^{-}	0.5
	HPO_4^{2-}	0.1

TABLE 4.4. CARBONATE MINERALS PRECIPITATED ACCOUNTING FOR MASS OF CARBON BEARING SPECIES AT THE SPRINGFIELD SITE, 500 YEARS AFTER INJECTION.

Carbonate Minerals Precipitated	Mass of CO_2 -bearing mineral species (g/kg)	Mass of CO_2 stored (g/kg)
Dawsonite	8.8	2.7
Dolomite	1.9	0.4
Siderite	8.3	3.2
Total	19.0	6.3

Task 3.c. Determine the Permeability of the Confining Layer and Target Formation Permeability of the Confining Layer at the John Twitty Energy Center Site in Springfield.

Results of the pressure-injection analyses are listed in Table 4.5. Twelve tests were completed within the confining unit (Derby-Doerun and Davis Formations). Two of these tests provided only a maximum possible value due to equipment malfunctions. These are listed as "less than" values in Table 4.5. The remaining tests gave hydraulic conductivities ranging from 2.1E-7 to 2.2E-14 m/sec. The highest value was within a relatively pure dolomite layer within the Davis Formation. With this exception, the conductivity values generally decreased to near the base of the confining layer, in proportion to shale content as determined qualitatively from the core samples and geophysical logs.

The equivalent vertical conductivity of the entire confining unit (a weighted harmonic mean) is 1.0E-13 meters per second (m/sec), using an interpolated value for the "less-than" intervals. The latter value is approximately equivalent to a permeability of 1E-5 Millidarcys, an extraordinarily low value, meaning that these formations form a highly effective seal between the proposed injection zone and overlying strata.

TABLE 4.5. RESULTS OF PRESSURE-INJECTION TESTS WITHIN THE CONFINING LAYER.

Test #	Depth (ft.)	Hydraulic Conductivity(m/sec)	Stratigraphic Interval
10	1511.3-1532.6	1.5E-6	Potosi Fm. (not part of confining unit)
9	1536.5-1557.8	2.8E-8	Derby-Doerun
8	1556.5-1577.8	3.8E-13	Derby-Doerun
7	1597.5-1618.8	<1E-9	Derby-Doerun
6	1597.5-1618.8	<1E-9	Derby-Doerun- Davis
5	1616.5-1637.8	1.8E-13	Davis
4	1636.5-1657.8	8.2E-14	Davis
3	1656.5-1677.8	2.2E-14	Davis
2	1676.5-1697.8	1.6E-12	Davis
1	1699.3-1720.6	2.1E-7	Davis (dolomite interval)
13	1713.1-1733.7	9.4E-11	Davis (dolomite & shale)
12	1733.7-1754.3	3.0E-14	Davis
11	1754.3-1774.9	3.0E-12	Davis

Task 3.d. Determine the Injection Rate Profile for the Target Formation

The target formation includes four different stratigraphic units with varying permeability. Two sandstones (an upper sand unit and a lower sand unit, both within the Lamotte Sandstone) are separated by dolomitic silts and shales. The upper sand unit is approximately 100 feet thick, while the lower sand unit is approximately 160 feet thick, and the intervening silts and shales are approximately 110 feet thick. The well bore was completed to a depth of approximately 40 feet beneath the Lamotte Sandstone within a jointed granite.

The first pumping test was completed after casing off the strata above the target formation and then drilling to the base of the (upper) sand unit. This test, which isolated the response of the upper sand unit, gave a hydraulic conductivity of 1.2E-6 m/sec based on a thickness of 100 ft (Table 4.6). The bulk hydraulic conductivity of the upper sand unit is approximately equivalent to a permeability of 125 Millidarcys. However, the core and geophysical logs indicate that the uppermost 10-20 feet of the unit is much more porous than the lower part, so most of the permeability within this tested interval is likely within the uppermost portion.

The second pumping test was completed upon drilling into the granite and tested the full target formation. This test gave a hydraulic conductivity of 3E-7 m/sec, based on a thickness of 410 feet (Table 4.6). The lower value of the second test indicates that the lower sand unit has much lower permeability than the upper sand unit, so this test, averaged over the larger thickness, gave a proportionately lower average value of conductivity than the upper sand unit test.

The third pumping test was isolated to the (lower) Lamotte Sandstone and granite by inflating a packer within the borehole immediately above the top of the lower sand unit. This test gave a hydraulic conductivity of 1E-7 m/sec (Table 4.6), approximately one tenth that of the upper sand unit. Therefore, most of the permeability is concentrated within the upper sand unit.

TABLE 4.6. PUMPING TEST RESULTS.

Test #	Unit(s) tested	Thickness (ft.)	Bulk Hydraulic Conductivity (m/sec)
1	Upper sand unit	100	1.2E-6
2	Upper and lower sand units, Granite	410	3E-7
3	Lower sand unit, Granite	200	1E-7

Seven pressure tests were completed within the target formation. The upper six tests were completed over approximate 42-foot intervals, while the lowest test was over a 92-foot section. Due to cost constraints, the entire stratigraphic interval could not be tested. Nevertheless, the results as shown in Table 4.7 confirm that the Bonneterre Formation and upper Lamotte Sandstone have the lowest hydraulic conductivity within the target zone with values ranging from 1E-12 to 4E-13 m/sec. These values are very low and indicate that the Bonneterre and upper Lamotte Sandstone also are a confining unit that forms an effective seal restricting cross flow between the upper and lower sand units and underlying granite.

The uppermost sand unit could not be pressure tested, because irregularities along the borehole wall prevented the packer from sealing this interval. Nevertheless, the results for this formation still confirm that hydraulic conductivity increases upward within the upper sand unit (Table 4.7).

The lowest pressure test, within both the Lamotte Sandstone and the granite gave the same hydraulic conductivity (1E-7 m/sec) as the pumping test within this interval. As the pressure-test value is averaged over a smaller thickness, the bulk conductivity from this method would actually be somewhat lower than the pumping-test value. This difference, however, is very common and consistent when comparing pumping and pressure-test values, due to different responses to heterogeneity within the test medium.

TABLE 4.7. RESULTS OF PRESSURE TESTS WITHIN THE TARGET FORMATION

Test #	Unit Tested	Interval (Depth in feet)	Hydraulic Conductivity (m/sec)
7	Upper sand unit	1,795.3-1,837.5	9E-8
6	Upper sand unit	1,835.3-1,877.5	2E-8
5	Lamotte	1,869.3-1,911.5	1E-11
4	Lamotte	1,909.3-1,951.5	4E-13
3	Lamotte	2,005.3-2,047.5	1E-12
2	Lamotte	2,089-2,110.1	1E-12
1	Lamotte/Granite	2,095-2,187	1E-7

2. THOMAS HILL ENERGY CENTER CENTER

Task 3.b. Determine the Petrologic and Mineralogic Characteristics of the Confining Layer and Target Formation

Thin-Section Analysis of Rock Core Samples

Results of the thin-section point counting for the Lamotte Sandstone samples from the THEC site are presented below in Table 4.8.

TABLE 4.8. ABUNDANCE OF CONSTITUENTS FOR THE LAMOTTE SANDSTONE OF THE THEC CORE.

Petrography	Constituents	Average (%)	Minimum (%)	Maximum (%)
Framework Grains	Quartz	67.0	60.6	76.1
	Feldspar	0.3	0.0	1.7
	Fossil Fragment (Carbonate)	0.0	0.0	0.0
	Fossil Fragment (Phosphate)	0.0	0.0	0.0
	Glauconite Pellet	0.5	0.0	1.5
	Detrital Mica	0.0	0.0	0.2
	Epidotized Hornblende	0.0	0.0	0.2
	Opaque Grain	0.3	0.0	1.4
	Volcanic Rock Fragment	0.2	0.0	1.5
	Zircon	0.1	0.0	0.3
	Chert	0.1	0.0	0.5
Pore Space	Porosity	19.5	7.7	29.3
Cement	Quartz (Overgrowth)	1.8	0.4	7.0
	Hematite	0.6	0.0	3.7
	Iron Oxide (Not Hematite)	1.8	0.0	16.0
Matrix	Clay (Dark)	3.8	0.2	16.9
	Clay (Light)	1.8	0.2	4.8
	Opaque (Pore Filling)	0.2	0.0	0.9
	Glauconite	0.0	0.0	0.2
	Calcite (Pore Filling)	0.0	0.0	0.0
	Dolomite (Rhombs)	0.0	0.0	0.0
Diagenetic	Epidote	2.1	0.1	5.3
	Total	100.0		

Geochemical Evaluation of Site-Specific Data

Input geochemical data (as provided by Missouri S&T) used in the geochemical evaluation are shown in Table 4.9. Simulation results for the end of 10 years of hypothetical carbon dioxide injection and a 500- year post-injection phase at THEC are shown in Table 4.10.

TABLE 4.9. IONIC SPECIES CONCENTRATIONS REPORTED BY MISSOURI S& T (IN MG/L) FOR THE THEC SITE.

	Ionic Species	THEC Site Data
Cations (mg/l)	Fe^{2+}	10.3
	Ca^{2+}	2491
	Mg^{2+}	860
	K^{+}	206
	Na^{+}	14662
	Mn^{2+}	0.4
	Al^{3+}	0.01
	H^{+}	0.00024
Anions (mg/l)	Cl^{-}	17061.23
	HCO_3^{-}	200
	SO_4^{2-}	17000
	NO_3^{-}	0
	F^{-}	0
	HPO_4^{2-}	0

TABLE 4.10. CARBONATE MINERALS PRECIPITATED ACCOUNTING FOR THE MASS OF CARBON BEARING SPECIES AT THEC, 500 YEARS AFTER INJECTION.

Carbonate Minerals Precipitated	Mass of CO_2- bearing mineral species (g/kg)	Mass of CO_2 stored (g/kg)
Dawsonite	27.7	8.5
Dolomite	10.0	2.4
Siderite	14.4	5.5
Total	52.1	16.4

Task 3.c. Determine the Permeability of the Confining Layer and Target Formation

MSU personnel conducted a 24-hour single-well pumping test at the THEC site. Pumpage was isolated to the Lamotte Sandstone by a packer directly above the formation top. Drawdowns were monitored with a downhole pressure transducer at one-minute intervals, and the pumpage rate was monitored periodically from the discharge line. The drawdown measurements were analyzed with AQTESOLV using three different analytical solutions (Table 4.11). Average values at the THEC site are transmissivity of 1.8E- 5 m^2/sec. and hydraulic conductivity of 3.0E-7 m/sec.

TABLE 4.11. THEC SITE SINGLE-WELL PUMPING TEST RESULTS.

Cooper-Jacob T: 2.05E-5 m^2/sec
Cooper-Jacob K: 3.4E-7 m/sec

Theis T: 1.7E-5 m^2/sec
Theis K: 2.8E-7 m/sec

Hantush-Jacob T: 1.7E-5 m^2/sec Hantush-
Jacob K: 2.8E-7 m/sec

Task 3.d. Determine the Injection Rate Profile for the Target Formation

Because no individual pressure testing was conducted at the THEC site, only a bulk analysis of permeability of the entire target formation can be developed. Therefore, no injection rate profile is available for this site based on our research activities.

3. IATAN GENERATING STATION SITE

No tasks assigned to MSU were conducted at this site because activities were halted without completing drilling.

4. SIOUX POWER PLANT SITE

Task 3.b. Determine the Petrologic and Mineralogic Characteristics of the Confining Layer and Target Formation

Thin-Section Analysis of Rock Core Samples

Table 4.12 summarizes the constituents of the Lamotte Sandstone based on the core samples collected at the SPP site.

TABLE 4.12. ABUNDANCE OF CONSTITUENTS FOR THE LAMOTTE SANDSTONE FOR CORE FROM THE SPP SITE.

Petrography	**Constituents**	**Average (%)**	**Minimum (%)**	**Maximum (%)**
Framework Grains	Quartz	70.7	48.5	82.9
	Feldspar	0.0	0.0	0.0
	Fossil Fragment (Carbonate)	0.0	0.0	0.0
	Fossil Fragment (Phosphate)	0.0	0.0	0.0
	Glauconite Pellet	0.0	0.0	0.2
	Detrital Mica	0.0	0.0	0.1
	Epidotized Hornblende	0.0	0.0	0.0
	Opaque Grain	0.1	0.0	0.7
	Volcanic Rock Fragment	0.6	0.0	7.5
	Zircon	0.0	0.0	0.2
	Chert	0.0	0.0	0.3
Pore Space	Porosity	16.9	10.6	31.0
Cement	Quartz (Overgrowth)	4.0	0.5	9.7
	Hematite	2.1	0.3	4.4
	Iron Oxide (Not Hematite)	2.2	0.0	7.3
Matrix	Clay (Dark)	2.2	0.0	7.2
	Clay (Light)	0.0	0.0	0.2
	Opaque (Pore Filling)	0.0	0.0	0.2
	Glauconite	0.0	0.0	0.0
	Calcite (Pore Filling)	0.0	0.0	0.0
	Dolomite (Rhombs)	0.0	0.0	0.0
Diagenetic	Epidote	1.1	0.0	3.4
	Total	100.0		

Geochemical Evaluation of Site-Specific Data

Input geochemical data (as provided by Missouri S&T) used in the geochemical evaluation are shown in Table 4.13. Simulation results for the end of 10 years of hypothetical carbon dioxide injection and a 500-year post-injection phase at the SPP Site are shown below in Table 4.14.

TABLE 4.13. IONIC SPECIES CONCENTRATIONS REPORTED BY MISSOURI S&T (IN MG/L) FOR THE SPP SITE.

	Ionic Species	**SPP Site Data**
Cations (mg/l)	Fe^{2+}	16
	Ca^{2+}	2695
	Mg^{2+}	504
	K^{+}	240
	Na^{+}	12453
	Mn^{2+}	1
	Al^{3+}	0.01
	H^{+}	1.2E-05
Anions (mg/l)	Cl^{-}	25078.9
	HCO^{-}_{3}	169
	SO_{4}^{2-}	680
	NO^{-}_{3}	0
	F^{-}	0.05
	HPO^{2-}_{4}	0

TABLE 4.14. CARBONATE MINERALS PRECIPITATED ACCOUNTING FOR MASS OF CARBON BEARING SPECIES AT THE SPP SITE, 500 YEARS AFTER INJECTION.

Carbonate Minerals Precipitated	**Mass of CO_2-bearing mineral species (g/kg)**	**Mass of CO_2 stored (g/kg)**
Dawsonite	9.4	2.9
Dolomite	12.8	3.1
Siderite	9.5	3.6
Total	31.7	9.6

Task 3.c. Determine the Permeability of the Confining Layer and Target Formation

MSU personnel conducted a 24-hour single-well pumping test at the SPP site. The top of the target formation (Lamotte Sandstone) at this site is approximately 3,480 feet below ground surface.

Unfortunately, the borehole packer installed for the pumping test could not be set below approximately 1,950 feet depth, which was insufficient to isolate the Lamotte Sandstone from all of the overlying permeable strata. Several carbonate beds with discrete fractures and solution-widened bedding planes are present within the interval between the packer and Lamotte Sandstone (e.g., gaps shown at arrows on Figure 4.6), and these overlying zones inevitably contributed water during the pumping test.

FIGURE 4.6 INTERBEDDED SHALE AND CARBONATE WITH THE BASAL PORTION OF THE DAVIS FORMATION. ARROWS POINT TO TWO SOLUTION-WIDENED BEDDING PLANES.

The Lamotte Sandstone at this site is a porous medium, based on visual examination of the core, but it is tightly cemented, which reduces the hydraulic conductivity. Therefore, it was anticipated that a significant portion of the water produced during the test originated from the overlying fractured and solutioned carbonate beds within the Davis Formation.

At the beginning of the pumping test, discharge was restricted by partially closing a valve on the discharge line. Discharge was held approximately constant at 15 gallons per minute (gpm) for much of the test by progressively opening this valve to counteract the normal decline in discharge rate as the water level dropped and the pumping lift increased. After about 500 minutes the valve was completely opened, and thereafter the discharge rate gradually decreased to approximately 13 gpm by the end of the test. This decrease amounted to approximately 13% of the original pumping rate, which is nearly insignificant for the analysis of most pumping tests.

Water levels during the test were measured at one-minute intervals with a downhole pressure transducer. The measured drawdowns (drop in water level) during the test are shown in Figures 4.7 and on semilog and log-log plots, respectively, using the original units as measured in the field (feet and minutes).

FIGURE 4.7. DRAWDOWN VERSUS TIME DURING THE SPP SITE PUMPING TEST –SEMILOG PLOT

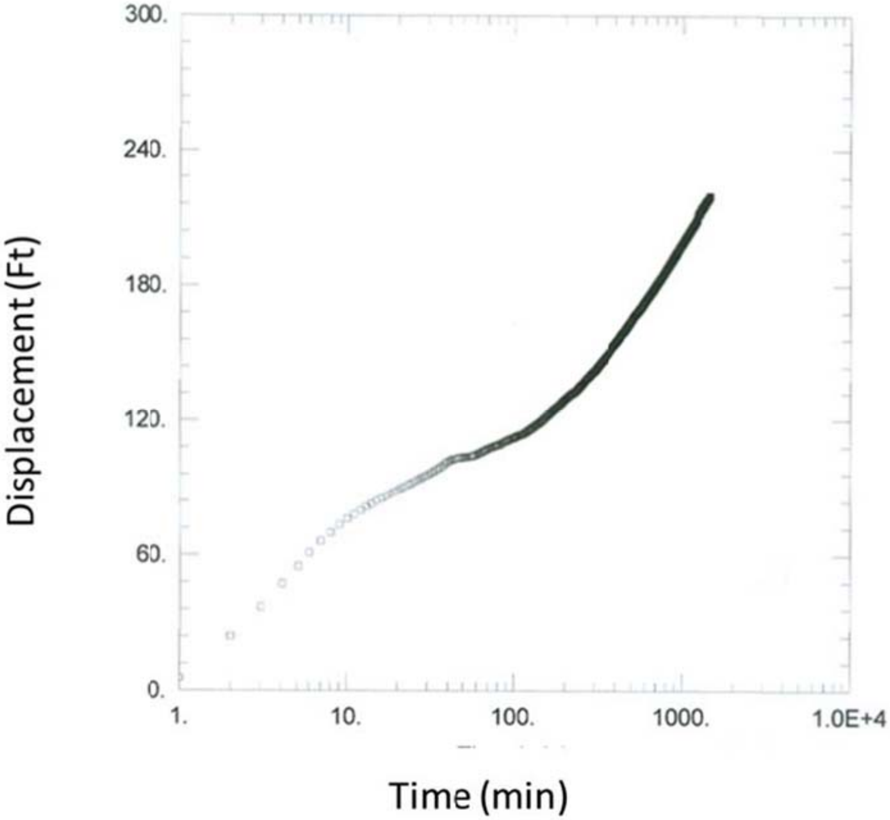
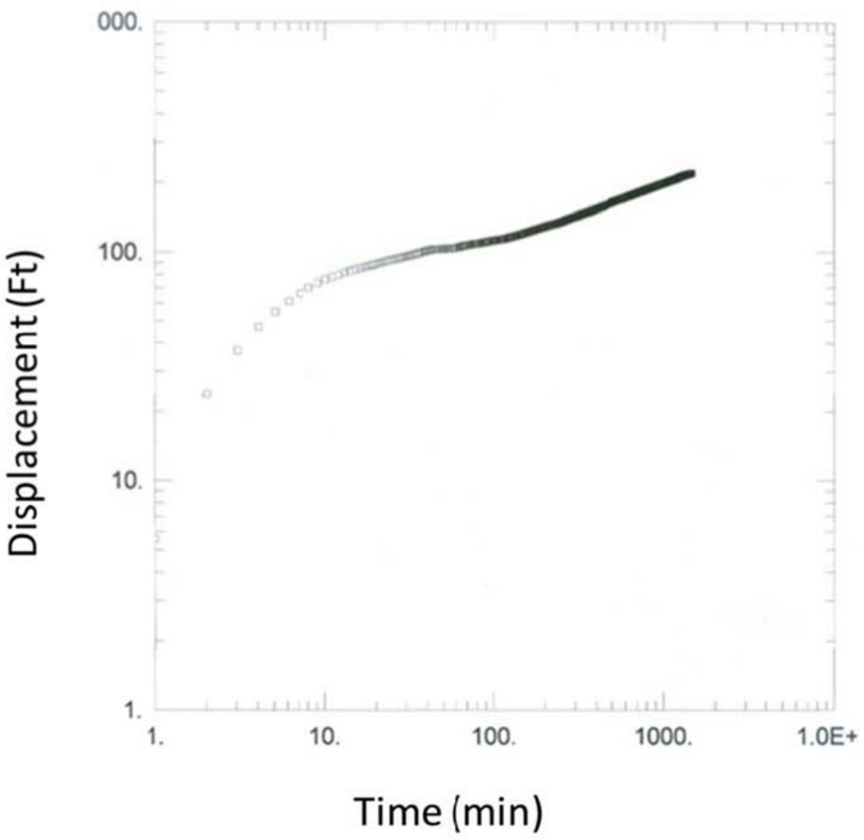


FIGURE 4.8. DRAWDOWN VERSUS TIME DURING THE SPP SITE PUMPING TEST – LOG-LOG PLOt



Because drawdown measurements were made within the pumped well (a single-well test), the earliest pumpage removed water that was already within the borehole prior to the start of the test.

Consequently, the earliest drawdowns (approximately the first 20 minutes) do not follow the (conventional) theoretical response; this deviation is termed “borehole storage effects.” After 20 minutes all of the pumpage was coming from water flowing into the borehole, meaning that the borehole storage effects had dissipated and were now insignificant. This transition is marked by the beginning of a straight-line segment between 20 and 60 minutes on the semilog plot (Figure 4.7). If a normal or theoretical response of an “infinite acting” aquifer had continued, this linear trend would have continued for the remainder of the test, while the slope of the log-log plot (Figure 4.8) would have gradually decreased, asymptotically approaching a horizontal line. This did not occur.

Instead, after approximately 60 minutes the (logarithmic) rate of drawdown increased dramatically as shown by the increased slopes on both the semilog and log-log plots. Given the nearly constant pumping rate, this increase could only have been caused by “boundary effects”, meaning that the test’s radius of influence reached a distance beyond the borehole where the hydraulic conductivity of the bed(s) supplying most of the water decreased substantially.

Such changes are characteristic of isolated beds with secondary porosity (fractures and solutioned bedding planes) within carbonates (i.e. lower Davis Formation), but not within sandstones (i.e. Lamotte Sandstone) with primary inter-granular porosity.

After 130 minutes the drawdown curve on the log-log plot (Figure 4.8) reaches a straight line segment that prevailed through the remainder of the test, albeit with a minor deviation (slightly lower slope) over the last few hours, corresponding to the nominal decrease in pumpage at that time. Late-time linear segments on a log-log plot indicate “single fracture” or “isolated fracture” flow. This means that most of the water reaching the borehole flowed through a single discontinuity (fracture or bedding plane) or perhaps multiple discontinuities that are effectively isolated from each other. If the aquifer supplying the water had acted as a porous medium (i.e. Lamotte Sandstone) the slope of the log-log plot would have decreased systematically through the end of the test.

The hydraulic conductivity of the Lamotte Sandstone at this site is low enough that it did not contribute a significant amount of water during the pumping test. Nevertheless, a limiting value of hydraulic conductivity can be obtained by analyzing the late-time response shown on Figures 4.7 and 4.8.

Analytical solutions for single-fracture flow are difficult to apply and results can be non-unique due to the multiple hydraulic parameters that influence the rate of drawdown. The best option is to calculate an apparent hydraulic conductivity from the semilog plot based on the slope of the late-time data and using conventional (Cooper-Jacob) methods. Carrying through this calculation, an apparent transmissivity was obtained of 4.4E-6 m2/sec and an apparent hydraulic conductivity of 1E-7 m/sec.

Therefore, the true transmissivity and hydraulic conductivity of the Lamotte Sandstone must be significantly less than these limiting values.

Task 3.d. Determine the Injection Rate Profile for the Target Formation

Because no individual pressure testing was conducted at the SPP site, only a bulk analysis of permeability of the entire target formation can be developed. Therefore, no injection rate profile is available for this site based on our research.

III. DISCUSSION AND CONCLUSIONS

Although the JTEC site contains porous rock with suitable mineralogic constituents for carbon sequestration, the reported low-salinity of groundwater beneath the JTEC site makes it unsuitable for carbon dioxide injection.

Both the THEC and SPP sites had groundwater of sufficient salinity to merit further investigation for potential usage as carbon sequestration sites. Of these two sites, the average values at the THEC site are transmissivity of 1.8E- 5 m^2/sec. and hydraulic conductivity of 3.0E-7 m/sec, while the SPP site has an apparent transmissivity of 4.4E-6 m^2/sec and an apparent hydraulic conductivity of 1E-7 m/sec.

Apparent values are used because of the limited test conditions at the SPP site. Based on these limitations, the true values of these parameters must be significantly less than these limiting values for this site. This means that the THEC site has a target formation transmissivity which is at least an order of magnitude, e.g., a factor of 10 times, more transmissive than the same formation appears to be at the SPP site.

In addition to the hydrologic analysis, the geochemical analysis (which includes the site specific mineralogic data for each test location) indicates the THEC site is able to solidify significantly more stored carbon dioxide than the SPP site. Table 4.15 shows the comparison between all three sites for solid-phase storage capacity at the end of 500 years (using the same theoretical 10-year carbon dioxide injection phase), where the THEC site stores almost twice as much carbon dioxide as the SPP site.

TABLE 4.15. CARBON DIOXIDE IN SOLID PHASE MINERAL FORM. MASS IS CALCULATED AS STORED AT EACH SITE 500 YEARS AFTER INJECTION (THEORETICAL 10-YEAR INJECTION PHASE FOR EACH SITE).

	JTEC Site	THEC Site	SPP Site
Mass of solid phase	CO_2 stored (g/kg)	CO_2 stored (g/kg)	CO_2 stored (g/kg)
Total	6.3	16.3	9.6

Conclusions

Based on these findings – that the target formation beneath the THEC site can store significantly more carbon dioxide and is more transmissive than the SPP site – it appears the THEC site would be the highest priority site for further investigation and that the SPP site might be worth further investigation to more accurately determine the hydrologic parameters of the target formation in order to more accurately estimate storage potential at that site.

IV. REFERENCES CITED

Berger, M.L. “Petrographic analysis to determine spatial variation of porosity and mineralogy in the Lamotte Sandstone in Southwest Missouri, Missouri,” [Master’s Thesis]: Springfield, Missouri State University, (2011).

Chayes, F.: “Discussions: Reliability of Point Counting Results,” *American Journal of Science*, (1965) 719- 721.

APPENDIX 4 A: MISSOURI STATE UNIVERSITY REPORT FOR X-RAY FLUORESCENCE METHODOLOGY DURING ACTIVITIES AT THE JOHN TWITTY ENERGY CENTER (JTEC) SITE.

Introduction

During Phase 1 activities, preliminary concern had been expressed about a need to retain as much site-specific core as possible in the event future questions arose which could be addressed by re-testing the site-specific materials. In an effort to optimize the amount of data collected with only a limited amount of analytical consumption of core, Missouri State University proposed using a methodology to determine site-specific mineralogy using X-Ray Fluorescence and then using the resulting geochemical results of the rock in geochemical evaluations of the site's suitability for carbon sequestration. The method and results from this preliminary effort are presented below.

Task 3.b. – Petrologic and Mineralogic Characterization of the Confining Layer and Target Formation

Due to delays in scheduling drilling activities at the JTEC site (and obtaining site-specific core samples), the MSU team adjusted its original approach to this task by adding an interim work effort to review and sample available cores in the McCracken Core Library (maintained by the Missouri Geological Survey). Four existing wells were located which were in the regional vicinity of the JTEC project site and which had core available in the Library for the Lamotte Formation (the target formation of interest for this project). Sample intervals were selected from the Lamotte Formation portion of those four cores in the Library and X-Ray Fluorescence (XRF) bulk elemental analyses were performed on those intervals.

Following this, a subset of the core segments used in the XRF analysis were made into thin-sections and designated for point-counting of the mineral grains visible in the thin-section. This adjustment to the original approach was made for two reasons:

a) Analyses of other historical cores in the region would provide improved context for interpretation and understanding of results from site-specific core

b) Analyses of historical cores from the McCracken Core Library would allow opportunity to test the methods and make appropriate adaptations to the analytical methods so that the processing of site-specific core would be streamlined when it became available.

Experimental Methods

Core samples of Lamotte Formation were obtained from four existing wells in the vicinity of Springfield stored in the McCracken Core Library. In addition to samples from core NS-4C, three-inch lengths of core were collected approximately every three feet of vertical length from the wells: M1J1 in north- central Webster County and MHR1 in northern Polk County, and NS3D in Dade County. These well codes are used in the McCracken Library to serve as a unique identifier for the well. In addition, selected areas of visually interesting rock (e.g., differently colored laminations) were collected. All selected samples were brought to the MSU campus for lab analysis using a Bruker handheld XRF unit operated in benchtop mode. Each piece of core was analyzed at five random locations.

Thin sections were then made from samples which had been analyzed using the XRF method. Due to the more time-intensive nature of thin section preparation and point-counting analysis, these thin sections represent approximately every 10 feet of core (every third " systematic" sample used for the

XRF analysis), plus a modest number of additional samples chosen within these intervals through visual inspection and interesting geochemical anomalies detected from the XRF analysis.

Point counting is the established method for estimating total porosity and bulk mineral composition of sandstones using thin sections. This method uses a randomly placed grid and involves the identification of mineral grains (or void spaces) at each grid intersection point. The resulting tabulation is a statistical estimate of the volume percent of constituent minerals and void spaces, which can then be extrapolated to represent a larger section of rock.

XRF Results

XRF analysis of all cores, including the onsite exploratory core at the JTEC site has been completed. A summary of the average elemental composition is listed below in Table A-1. The onsite exploratory core has been labeled as "JTEC" for reference throughout this report.

The mass analyzed does not always add up to 100% due to various reasons. The first is that the handheld XRF technique is unable to detect any fluorescence from either sodium or magnesium. Another explanation for the missing mass is the loss of water that would have been bound to hydrous phyllosilicates. Additionally, there is some mathematical uncertainty due to rounding, and some of the samples were beyond the calibrated range of the software (sandstone standards which had little or no carbonate content were used for calibration).

TABLE A-1. SUMMARY OF ELEMENTAL ANALYSIS FOR EACH OF THE STUDIED CORES. ALL ELEMENTAL ANALYSIS FOR EACH OF THE STUDIED CORES.

	JTEC	M1J1	NS3D	NS4C	MHR1
SiO_2	90.83	94.34	94.99	94.48	89.73
TiO_2	0.05	0.05	0.06	0.07	0.14
Al_2O_3	1.11	1.51	1.19	2.02	2.90
Fe_2O_3	0.52	0.31	0.50	0.42	0.72
MnO	0.04	0.03	0.03	0.03	0.04
CaO	0.60	0.22	0.24	0.29	0.36
K_2O	0.60	0.22	0.24	0.29	0.36
P_2O_5	0.05	0.01	0.01	0.01	0.02
Remainder	5.71	3.01	2.11	2.05	4.11

Conclusions about XRF Methodology

As noted above, the X-Ray Fluorescence unit is not designed to detect certain things – specifically the elements sodium and magnesium, and water bound to hydrous phyllosilicates. Therefore, thin-sections are needed for a complete mineralogic and petrologic analysis of site-specific rock core. Also during XRF testing, it was determined that sample preparation involved making a small slab of site core (approximately 3 inches in length), which is actually the first step in thin-section making and involves destruction of the same amount of core as a thin-section. Thus, it was concluded that making thin-sections of site rock and conducting point-counts on those thin-sections would be necessary, and the most expedient and efficient means to accomplish the task of characterizing mineralogic and petrologic character of the target formation. The XRF method added insignificant amount of information relevant to site evaluation, yet added additional time and labor to the project. Therefore, the XRF method was discontinued after the JTEC site activities were completed.

Shallow Carbon Sequestration Demonstration Project

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Final Project Report

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CHAPTER V - MISSOURI UNIVERSITY OF SCIENCE & TECHNOLOGY

EXECUTIVE SUMMARY

City Utilities of Springfield (CU), along with other coal-burning utility companies, is faced with the growing national concern for global warming, the prospect of federal and state regulation of carbon dioxide (CO_2) emissions, and the need to develop an effective, economical means to capture and sequester CO_2. CU expressed an interest in, and began to investigate the feasibility of, sequestering CO_2 in the Lamotte Sandstone, a geologic formation that is located beneath the surface throughout most of Missouri.

A project to investigate the possibility of sequestering carbon dioxide (CO_2) from coal-burning power plants in Missouri was undertaken by City Utilities (CU) of Springfield, Missouri, in conjunction with its funding partners, Ameren UE, Aquila, Inc., Associated Electric Cooperative, Inc. (AECI , Empire District Electric Company (EDE) and Kansas City Power and Light (KCP&L). In addition, the project involved research partners at Missouri State University (MSU), the Missouri Geological Survey (MGS) (formerly the Division of Geology and Land Survey) of the Missouri Department of Natural Resources (MDNR), and Missouri University of Science and Technology (Missouri S&T). This project was focused on drilling an experimental borehole at the John Twitty Energy Center (JTEC), located at CU's Southwest Power Station, and evaluating it for potential CO_2 sequestration. Key questions to be addressed included, "Is the Lamotte Sandstone a suitable formation for carbon sequestration?", "Is the Davis Formation an adequate seal?" and "How much CO_2 could be sequestered in the Lamotte Sandstone?"

The JTEC borehole was drilled, and cored continuously through the formations of interest. The borehole included approximately 70 feet of Reagan Sandstone above a 120-foot section of the Lamotte Sandstone. The Reagan Sandstone had superior porosity and permeability compared to the Lamotte Sandstone section which had extremely low permeability (2.1 md). Drawdown tests conducted by MSU confirmed little flow contribution from the Lamotte Sandstone, although this test was measured with water flow and not representative of gas injection.

Numerous reservoir simulations were conducted for the JTEC site in an effort to identify the Lamotte's potential for carbon sequestration. Rock mechanics tests and pressure injection tests conducted by researchers at Missouri S&T provided key values of Young's Modulus, Poisson's ratio, breakdown pressure and minimum in-situ stress. Findings from these tests enabled an estimation of the carbon sequestration potential for this site. Based on an 800 meter (m) x 800 meter reservoir, and allowing for 5-spot water withdrawal, an injection rate of 60 cubic meters per day (m^3/day) is feasible, and a total CO_2 storage capacity of $2.55 \text{ X } 10^5$ metric tons over 15.8 years. This estimate includes displacement of water in the pore space, CO_2 solubility trapping, but does not include mineral trapping due to the long time characteristic of that process.

Permeability measurements made for the Davis Formation at the JTEC site indicated permeability less than 0.001 millidarcies (md) over the interval. No capillary pressure measurements were made for JTEC core samples. This was mainly due to the fact the site proved unsuitable for CO_2 sequestration as the water found in the target formation contained fewer than 10,000 milligrams per liter (mg/L) Total Dissolved Solids (TDS) and therefore would be defined as an underground source of drinking water, excluding any disposal or storage injection by federal law.

Three additional sites were selected to perform a more limited investigation of the potential for CO_2 sequestration in the Lamotte. These three sites included wells at the Thomas Hill Energy Center (THEC), Moberly, MO; the Iatan Generating Station (IGS), Weston, MO; and the Luecke Quarry near the Sioux Power Plant (SPP), near Florissant, MO. Difficulties were encountered while drilling the borehole at the IGS site; therefore, it was plugged and abandoned in accordance with Missouri Well Construction Rules. Boreholes were successfully drilled and cored at the THEC and SPP sites. In addition, the borehole at the THEC site was logged through the formations of interest.

Results indicated the THEC site has the best permeability in the Lamotte, and an average porosity value similar to the JTEC borehole. The Davis Formation is present at the THEC site and has permeability similar to the Davis Formation found at the other sites. Of the three sites, THEC appears most promising for carbon sequestration. The SPP site would be a secondary choice as the Lamotte Sandstone at this site was not as permeable as the section in the THEC borehole.

However, the Lamotte Sandstone at the SPP site is deeper (>2,500 feet) and CO_2 injected at this site will more likely be injected as a denser, supercritical fluid, resulting in an increased storage capacity.

A. OVERVIEW OF MISSOURI S&T ROLE

Missouri S&T provided a critical role to the project by completing specific tasks embodied within the project's direct labor plan as follows:

- Assessing the confining layer and target formation fundamental rock, petrophysical and geomechanical properties (tasks 3b, 3c, 3d, 4a and 4b).
- Modeling the CO_2 injection and storage capacity of the target formation (task 3d).
- Assessing the water quality of the target formation fluid (task 3e).
- Defining formation minimum in-situ stress within the confining layer and target formation, and identifying possible limits to injection pressure (task 3d).
- Identifying and quantifying the relative proportions of clay minerals present in the host rock formations (tasks 3b and 4b).
- Conducting accelerated corrosion tests simulating the potential conditions that would result from the subsurface injection of CO_2 in order to assess both alteration processes affecting minerals in the host rock formations and potential secondary alteration minerals that may form following reactions (task 3b).

Missouri S&T reviewed core from three boreholes and selected representative samples throughout the total length of each core retrieved from the JTEC, THEC and the SPP sites. Core analysis was performed to obtain formation thickness and porosity measurements, and then used in reservoir modeling to determine storage capacity. In addition, well log analysis provided calculated values of porosity, which were compared to porosity values obtained from core samples.

Core analysis also provided measurements of absolute permeability, which was used in modeling CO_2 injection with a compositional reservoir simulator (CMG). Capillary pressure measurements were used to determine the CO_2 entry pressure, in the THEC and SPP sites, focusing primarily on the confining layer. Capillary pressure also provided pore distribution curves. This provided a better understanding regarding the suitability of the confining later for sustained CO_2 sequestration.

X-Ray Diffraction (XRD) analysis was performed to determine approximate proportions of illite, montmorillonite, chlorite, mixed-layer clay minerals, and kaolinite. Understanding the clays present, combined with pore sizes and pore size distribution, provides useful information about possible impediments to sustained CO_2 injection.

Fluidized bed reactors tests were conducted, passing food grade CO_2 through crushed and prepared particles of the target formation, taken from core samples. At the conclusion of this work, the leachate fluid was analyzed along with the sample, using scanning Electron Microscopy (SEM) to look for alteration patterns and precipitated phases. This work provides an understanding of the precipitates which may form during CO_2 injection, and the overall contribution of this mechanism to storage capacity in the target formation.

Hydrofracture and hydrojacking tests were conducted on ten intervals of the JTEC borehole to determine the formation minimum in-situ stress. Open hole well logs, combined with Young's modulus and Poisson's ratio determined from core analysis, were used with commercial hydraulic fracturing software (STIMPLAN) to analyze the pressure tests and determine upper bounds for sustained injection pressure during CO_2 sequestration.

Missouri S&T researchers also took representative water samples from the target formation, and analyzed the water for total dissolved solids, chemistry, and conductivity. These results were used to verify the nature of aquifer waters in the respective borehole locations, and to determine if any of the sites investigated met regulatory requirements for CO_2 injection.

B. EXPERIMENTAL METHODS

Task 2.d. Determine the Baseline Water Chemistry of the Target Formation at Each of the Four Missouri Power Plant Sites

FIELD WATER COLLECTION PROCEDURES

Water samples were collected from exploratory boreholes that intersected the rock units comprising the St. Francois Aquifer at the following three locations in Missouri:

Exploratory Borehole #1; John Twitty Energy Center (JTEC), Springfield, MO

Exploratory Borehole #2; Thomas Hill Energy Center (THEC), near Moberly, MO

Exploratory Borehole #4 Sioux Power Plant (SPP) Site, near Florissant, MO

*Formation water samples were not collected from Exploratory Borehole Site #3

Water samples were collected from formation waters of the St. Francois Aquifer Unit. A plastic water bath was used to isolate the borehole water and limit the interaction of the water samples with the ambient atmosphere by covering the device with a plastic top and filling the device with formation water to eliminate as much gas space as possible. The water bath included an inflow port to receive water directly from the borehole, an outflow port where water sample aliquots were collected, and sampling ports on the top for the insertion of in situ-water measurement probes (Figure 5.1). Water sampling followed a modified version of the water collection procedure titled "Low Stress (low flow) Purging and Sampling Procedure for the Collection of Ground Water Samples from Monitoring Wells" U.S. Environmental Protection Agency, July 30, 1996, Revision 2. Parameters such as visual turbidity and pH were continuously checked to ensure that readings were stable before any measurement data or water samples were collected.

All chemical measurements and water sample collection procedures followed an in-house predetermined collection procedure document entitled "Procedure for Sequential Filtration of Water Samples – DRAFT 11/1/2010" (Appendix A). Measurements for pH (activity of hydrogen ions), Eh (activity of electrons), water temperature, conductivity, and dissolved oxygen (DO) were made by inserting respective probes into the water bath system for in-situ measurement (Figure 1.1). Measured values were recorded only after readings had stabilized as a constant value or readings that cycled back and forth between two end points. Alkalinity, total hardness, calcium (Ca) hardness, magnesium (Mg) hardness (equal to total hardness minus Ca hardness), and turbidity (measured in nephelometric units; NTU) were determined from water samples that were collected from the outflow port of the water bath device and trapped into pre-cleaned high-density polyethylene containers . All of these measurements were conducted at the field site as soon as possible after collection of the samples. Alkalinity measurements were given highest priority as the loss of CO_2 from the solutions following removal from the subsurface will induce changes in these values. Turbidity measurements were given second priority to avoid the potential influence of phase precipitation following CO_2 loss and/or absorption of atmospheric oxygen.

Additional water aliquots were collected in pre-cleaned polyethylene vials and taken back to the Missouri S&T Environmental Research Center Laboratory for further testing. These samples included cation and anion concentrations that were determined by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) for major element cations, Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) for trace element cations, and Ion Chromatography (IC) for anion analysis. Trace element cations could not be determined for the formation water samples draw from the THEC and SPP sites as the high salinities of these waters interfered with the detection of trace elements. All cation and anion samples for these analyses were processed in the field for various filtrate sizes using disposable syringes and filters. The filtration process was completed in the field shortly after water collection. More details on the filtration process are described in the paragraph below. Additional sample aliquots were filtered on site and processed for total carbon (TC), dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC): however, the organic carbon instrument failed to produce reliable analytical results. Total suspended solids (TSS) and total dissolved solids (TDS) analyses were performed on unfiltered water samples that were transported back to the Missouri S&T laboratories for processing. All sample aliquots were inserted and stored in an insulated cooler and thus kept near ambient well water temperature following collection and transport to the laboratory.

Water aliquots for further analytical testing at the laboratory were field processed into pre- cleaned polyethylene vials for ICP-OES and ICP-MS analyses using disposable plastic syringes and filters. Aliquots for cation analysis included: 1) an unfiltered water sample, 2) filtered water sample passed through a 5.0 micron nylon filter, 3) filtered water sample passed through a 0.45 micron surfactant-free cellulose acetate filter, and 4) filtered water sample passed through a 0.02 micron alumina filter. Samples for anion analyses were also processed through the same 0.45 micron surfactant free cellulose acetate filters, but were collected into separate polyethylene bottles. All filtration was performed in the field as soon as possible after the water samples were collected to minimize any potential fractionation of components that may have occurred due to mineral precipitation or adsorption reactions. Water samples destined for ICP-MS or ICP-OES analysis were acidified with ultra-pure nitric acid (HNO_3) to a pH of approximately 2.0 or lower upon return to the laboratory. Acidification prevents the precipitation of solid phases, or digests any solid phases that may have formed. Sample aliquots destined for anion and carbon analyses were not acidified. These solutions were filtered a second time with the appropriate filter medium if precipitates had formed in the solutions after the first filtration performed in the field (iron precipitation did occur for the THEC and SPP site samples). Field blanks and lab blanks were processed using high purity deionized water (>18.0 micro Ω resistance) collected from the laboratory on the day of the filtration. All blanks were processed in the identical manner as the regular field samples.

For the trace elements in the blanks, up to 0.2 parts per billion (ppb) molybdenum (Mo), 0.3 ppb barium (Ba), and 2.35 ppb zinc (Zn) were detected in the laboratory blank samples. This suggests that we may have some minor trace metals such as Zn leaching from the polyethylene bottles.

Analysis of the field blanks also picked up sporadic, but low concentrations of nickel (Ni), antimony (Sb), and lead (Pb), all present at concentrations <1.2 ppb. These field blanks may have picked up dust contaminant particles present at the sampling site. The deionized water supply was routinely checked for metal content and was found to have below detection values for these metals.

FIGURE 5.1. WATER BATH USED TO COLLECT WATER DIRECTLY FROM THE BOREHOLES. THE WHITE PVC PIPE REPRESENTS INFLOW FROM THE BOREHOLE AND THE BLACK EXIT TUBE IS SHOWN ON THE OPPOSITE SIDE. THE WHITE PVC CAPS ON THE TOP OF THE VESSEL HOLD IN-SITU MEASURING PROBES FOR PH, EH, TEMPERATURE, DISSOLVED OXYGEN AND CONDUCTIVITY. BLACK WIRES CONNECTING THE RESPECTIVE PROBES TO THE RECORDING INSTRUMENTS ARE VISIBLE LEADING FROM THE WHITE CAP POSITIONS.

FIELD INSTRUMENT CALIBRATION AND DATA COLLECTION

All sampling followed appropriate quality assurance/quality control (QA/QC) protocols. These included the analysis of replicate samples, field blanks, lab blanks, and calibration of analytical instruments using traceable commercial standards.

An Accumet model AP115 pH-Eh combination probe-meter was calibrated in the field by using commercial standards at pH values of 4.00, 7.00 and 10.00. Standards were kept close to room temperature by transporting into the field in an insulated cooler. The accuracy for pH also was routinely checked between sample analyses and was generally good to within +/- 0.04 pH units using the pH 7.00 standard as a reference. The pH meter was recalibrated if any significant analytical drift was detected and any pH measurements were noted when drift was apparent. The Eh probe is combined with the pH probe device and both use the same meter. The Eh values were internally calibrated using a silver-hydrochloric acid (HCl) junction.

The conductivity meter (model WTW Cond 330i) was calibrated in the field before use with commercial salinity standards that bracketed the expected salinity range of interest. For the JTEC site, the instrument calibration was performed using the standards at 100.8 and 998 micro-Siemens/centimeter (cm). Accuracy for the instrument was monitored using the 100.8 micro-Siemens/cm standard as this had the closest value to the water being obtained from the borehole (310 to 340 micro-Siemens/cm). Accuracy values remained within +/- 1.5 micro-Siemens/cm during all testing periods. For the higher salinity boreholes of the THEC and SPP sites, standards at 998, 9,990, 100,143 micro-Siemens/cm were used for calibration. The 100,143 micro-Siemens/cm standard was used as a cross-check standard during the analyses as it was closest to the approximately 64,000 to 71,000 micro-Siemens/cm readings obtained from these field sites.

The Accumet AP 64 dissolved oxygen probe was calibrated in the laboratory prior to field use using both air (oxygen in the atmosphere) and flowing CO_2 gas (oxygen free). Before field use, the calibration was rechecked using the atmospheric oxygen content once again. Routine checks for Dissolved Oxygen (DO) were performed in a moist atmosphere environment and generally read between 8.71 and 8.75 mg/L. The probe failed to record any acceptable atmospheric readings for the SPP site, thus an accurate DO reading could not be obtained here.

The temperature probe was manufactured by Control Company and was periodically cross- checked for accuracy in the laboratory using ice water. Temperature checks fell between 0.1 and 0.4^{o}C for tests with ice water performed both in the laboratory and at the field site.

Alkalinity, total hardness, and Ca hardness tests were performed using HACH colorimetric titration test kits. Alkalinity was measured after adding a premeasured bromocreosol packet to the solution and then titrating with sulfuric acid to produce a color change that corresponds to the inflection point where the bicarbonate ion (HCO^{-3}) buffer was consumed (HACH method 8203). A phenolphthalein test also was performed to test for the presence of the carbonate ion (CO_3^{2-}), but the concentration of this aqueous specie was always too low to be detected by the colorimetric method. The absence of detectable CO_3^{2-} was expected given the pH range for the borehole water (pH ~7.8). Total-hardness and Ca-hardness determinations were made using an EDTA titration kit (HACH methods 8213 and 8204). The Mg-hardness determination was calculated by subtracting the Ca-hardness value from the total hardness. Total hardness, Ca-hardness, and Mg-hardness were determined by the above techniques as equivalent weight of CaCO3 (i.e. cation and anion weights were calculated together).

Turbidity was measured using a HACH 2100P light-scattering turbidity meter, with field samples and standards contained in glass vials that were inserted into the instrument's light path to induce a scattering effect of light to the detector. Calibrations were checked using deionized water, plus and 60.2 nephelometric turbidity unit (NTU) gelex turbidity standards. The 6.11 NTU standard most closely approximated the turbidity of the water samples from the borehole and thus was used as the calibration QA/QC check during the analyses. Readings on this standard remained within +/- 0.07 NTU units of the expected value for all time periods. Each of the glass vessels was measured first with deionized water to determine a background value for the respective sample vial. The deionized water was then discarded; the vial rinsed with formation water, then the vial was filled with formation water for the analysis. The deionized water blank light reading value was subtracted from turbidity runs conducted with the borehole water samples. Several of the vessels developed gas bubbles on their sides during the turbidity measurements. These were believed to result from the volatilization of aqueous CO_2 following the pressure decrease occurring after removal of the borehole water samples from their respective sampling depths. Unfortunately, no method exists to counteract this problem. Waiting for the devolatilization process to be completed was considered as an option, however, the loss of CO_2 from the water will result in a pH rise and/or oxidation of the water and often may induce other mineral precipitation reactions, which in turn also will influence the turbidity values. We also tested for the potential formation of minerals in the water samples by measuring turbidity for Lamotte Sandstone borehole waters over an eight hour period, shaking the vials before each reading to suspend any potential solid phases that may have precipitated and settled to the bottoms of the vials. Minor increases in turbidity were noted for the JTEC site samples, indicating that minerals were forming in the test solution. Both the THEC and SPP site samples precipitated an abundance of red color iron oxide particles that were readily visible to the naked eye, due to absorption of oxygen into the water.

TSS and TDS determinations were completed with the water samples by filtering and evaporating, respectively water from each site upon return to the laboratory. A 45 millimeter (mm) diameter Millipore filter with 0.45 micron pore-size openings was used for the TSS filtration procedure. The filters were dehydrated in an oven at 105°C both prior to, and subsequent to the filtration process, then cooled in a desiccation chamber. The filters were weighed on an electronic balance with 0.0001 gram measuring capability before and after the filtration process. In performing the filtration procedure, pre-weighed filters were mounted to a vacuum flask system, rinsed and wetted with deionized water, with the deionized water then being discarded. A formation water sample volume of approximately 150 ml was poured from the polyethylene field container and passed through the filter paper under vacuum. The total weight of the water sample passed through the filter was determined by measuring the weight change between the full and empty beaker, whereas the weight of the particulate material was determined from the weight change in the filter following the passing of the formation water sample and drying the paper in the oven. Measurement of the TSS fraction was omitted for the higher salinity samples from the THEC and SPP sites because of the precipitation of iron phase(s) in the water samples following their removal from the borehole. This is not considered to be a significant sampling omission because the amount of particulate material in the water samples prior to formation of the iron phase(s) was negligible as indicated by the very low turbidity values.

The filtrate solution collected from the TSS procedure from the JTEC site was transferred into a pre-weighed 200 milliliter (ml) capacity glass beaker and then used for determination of the TDS values. These solutions were first evaporated to visible dryness at 95°C. A watch glass cover plate was used to minimize the inadvertent collection of dust particles during the drying process. The oven temperature was increased to 180°C after there was no more visible fluid in the beakers.

The increased temperature was used to remove any surface layers of water attached to the hydroscopic surfaces of the salt particles, fracture any brine fluid inclusions in the crystals, and destroy the structures and release water from any hydrous phases (e.g., gypsum $CaSO_4.2H_2O$). The weights of the vessel + accumulated salts were checked periodically and weighed while still retaining heat from the oven. A value for the dried solids component was obtained when the weights remained stable over a few days. The beakers were weighed to 0.01 gram capability both before and after water evaporation.

The THEC and SPP site samples both precipitated iron oxide particles following their collection from the borehole and interaction with oxygen from the atmosphere. The samples were acidified by adding 0.7 grams of HNO_3 per liter of fluid. The acidification process resulted in the iron being dissolved back into solution within an hour or two. Three replicate 150 ml aliquots were then collected in the pre-weighed 200 ml glass beakers for the TDS analysis of the THEC and three from the SPP site (i.e. one from each of the field samples collected from each site). These beakers were then covered with watch glasses and placed in an oven at 95 ° C for several days, then further dehydrated at 180°C in a similar manner as described above. Samples were then taken one by one directly from the oven to the scale for a final weighing, while still retaining residual heat from the oven to minimize adsorption of moisture from the atmosphere. This process was repeated over several days until the final weight had stabilized. The TDS determinations for the water thus include the soluble fraction, the precipitated iron oxides (these were originally present as a dissolved specie when the borehole water was collected), and any trace amount of solid phases that would have been present in the water as it was drawn from the well.

A brine density measurement was made for water samples obtained from the THEC and SPP sites, relative to an equivalent volume standard of deionized water. The samples were allowed to sit overnight to equilibrate to room temperature before measuring. A 25 ml volume sample of the formation water samples were transferred into a beaker by pipette and then weighed on a balance to 0.0001 gram accuracy. An equivalent volume of deionized water was used as the standard. A temperature correction factor for density was not applied, but was not necessary as the pipettes were calibrated using deionized water that was weighed at the same temperature as the brine solutions. Iron precipitates that formed in the samples after extraction from the borehole for both sites were included in the samples when the weight measurements were made as the iron was originally dissolved in the borehole water when it was extracted from the borehole. Differences between the density of the precipitated iron oxide phase and the influence of dissolved iron on the fluid density are presumed to be negligible with regards to the density determinations. The low total concentration of iron in the solution (approximately 10 ppm) supports this assumption.

CALIBRATION CHECK ON THE ION CONDUCTIVITY PROBE AND ION CONDUCTIVITY MEASUREMENTS

Converting measured conductivity to salinity values involves the application of an empirically derived multiplication factor, with that factor being dependent on valence charge of ions (e.g., $Ca^{2+} = 2 * Na^{+}$), differential mobility of various ion species, and temperature. In order to test the relative effect of different ion species and their influence on the measured conductivity and the applicability of the multiplication factor, a set of eight ionic solutions were prepared from salts containing four different chloride and four different carbonate complexes. All solutions were prepared to produce a solution with both cation and anion species present at a milliequivalent concentration of 0.0893 (milliNormal = milliequivalent per liter, where milliequivalent = valence charge of ion * molar concentration). These solutions included: NaCl, KCl, $MgCl_2$, $CaCl_2$, Na_2CO_3, K_2CO_3, $CaCO_3$, and $MgCO_3$ (Table 5.1). Deionized water was measured as a calibration reference at 23°C and the lab prepared solutions also were also measured against a known commercial standard of 6,660 ppm KCl ("One-Shot" brand conductivity standard). One kilogram (kg) of deionized water was prepared for each sample into which each salt compound was added and vigorously shaken until all solids were dissolved. Each vessel was allowed to sit for a day at ambient room temperature (approximately 20^{o}C) before the first conductivity reading was taken. Vessels were then brought as close to 23°C as possible and measured for conductivity. A laboratory-prepared solution of KCl also was placed in an oven set to 25°C to match the factory calibration of the "One-Shot" brand standard. Conductivity was measured using a WTW TetraCon 330i handheld probe which also measures temperature and has an internal program that calculates salinity and TDS from the measured conductivity values. Salinity in milligrams per kilogram (mg/kg) was calculated directly from the conductivity values as a quality control check by using an empirical multiplication factor. For alkali chloride solutions such as the "One-Shot" KCl standard, a multiplication factor of 0.667 is recommended (Boyd, 2002). Although comparison of the in-house standards suggests a multiplication factor of 0.550 to 0.575 may be more appropriate, the manufacturer's suggested value of 0.667 was used for this study because the determined multiplication factor was based on only a limited data set.

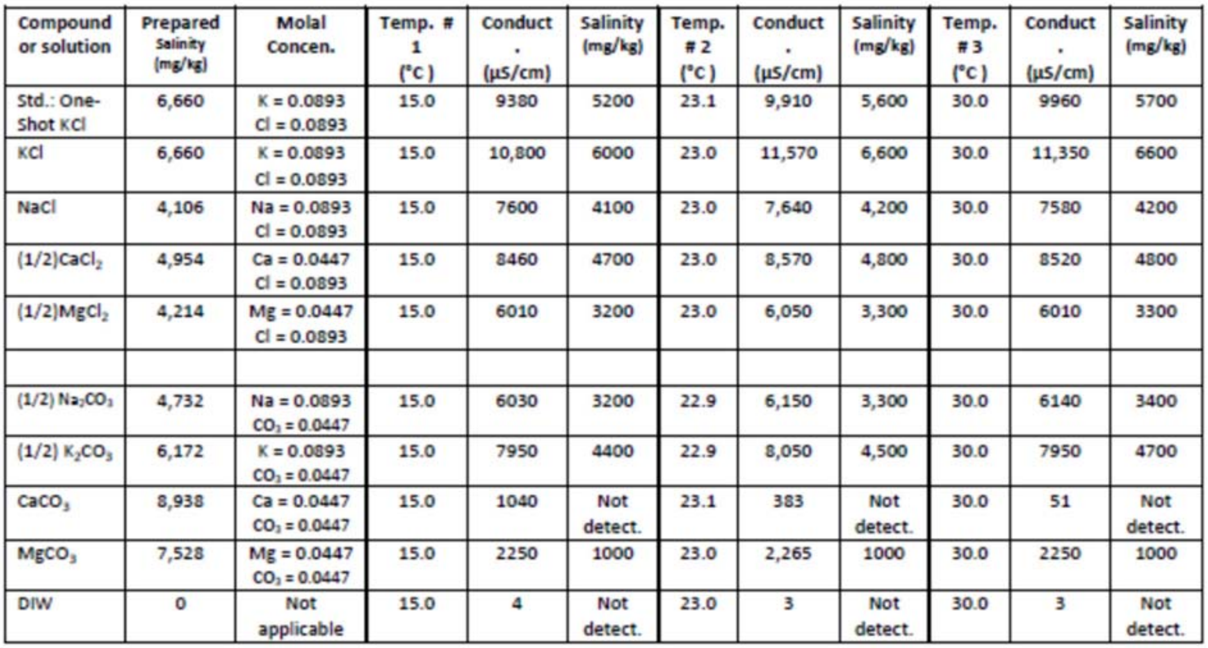
The ratio between the measured concentration using the conductivity probe versus the as- prepared concentration were generally highest (closest to 1.00) for Na^+, K^+, Ca^{2+}, and Cl^- solutions, while the presence of Mg^{2+} and/or CO_3^{2-} tended to result in lower ratios (Table 5.1). A marked difference in conductivity also was detected between the two KCl solutions (the Missouri S&AT laboratory prepared KCl sample and the "One-Shot" brand standard) despite being at the same temperature and concentration. A probable cause for this difference may be related to the presence of propanol-1 as a stabilizer in the "One-Shot" standard.

Conductivity measurements also vary by temperature, as ionic diffusion rates in solution are temperature dependent. The temperature effect on conductivity can be quite large. The manufacturer supplied certificate of analysis that accompanied the "One-Shot" brand KCl standard suggests that a temperature increase of 1°C will correlate to a positive conductivity shift of approximately 1.9%. The WTW brand Cond. 330i probe that was used in the conductivity measurements applies an automated non-linear temperature correction factor to the conductivity readings. However, in these experiments, a temperature dependent shift in conductivity values was still detected, despite the temperature compensation control (Table 5.2). Experiments were conducted to correlate conductivity readings with temperature to determine the accuracy of the conductivity meter under potential field conditions. The same eight ionic solutions discussed above that were prepared for both cation and anion species to a milliNormal value of 0.0893 for NaCl, KCl, $MgCl_2$, $CaCl_2$, Na_2CO_3, and K_2CO_3 were used in these experiments (Table 5.1).

Experiments with deionized water and the "One-Shot" brand KCL standard were also evaluated for conductivity at temperatures of approximately 0, 5, 10, 15, ~23, 30 and 40°C (Figure 5.2; Table 5.1).

Most of the solutions displayed a small decrease in conductivity with increasing temperature (Figure 5.2). The major decreases generally, though not universally, occurred over a temperature range of 0 to 5°C. Laboratory prepared KCl solutions differed from most of the other experimental solutions in showing a decrease in conductivity between 0 and 5°C, then increased between 5 and 23°C, and then were generally flat upon further temperature increase. The conductivity response of the "One-Shot" brand KCl standard matches very closely to the NaCl ionic solution, especially over the range of 15 to 40°C (Figure 5.2). Since the Lamotte Sandstone waters are NaCl dominated, and are extracted at underground temperatures of approximately 20°C, these results indicate that the conductivity measurements that were made from the THEC and SPP sites will match closely with the standardized value. The One-Shot calibration standard that was used to measure conductivity in the field was kept at ambient room temperature on all nights before field testing and then transported to the sampling site in an insulated cooler to minimize temperature changes. Field conductivity measurements were also made in the water trap bath that collected the groundwater shortly after removal from the well so as to minimize temperature changes of the formation water before readings were made (Figure 5.1). Conductivity readings for many of the other solutions prepared with salts containing ions other than Na^+ and Cl^- fell below the expected conductivity values over the entire temperature range of measurements. The $CaCl_2$ and K_2CO_3 values were approximately 20% below their expected values, Na_2CO_3 was approximately 40% below, while $MgCl_2$, $MgCO_3$, and $CaCO_3$ solutions were all more than 60% below their expected conductivity values. Interestingly, the laboratory prepared KCl solution gave conductivity values that were approximately 20% higher than the "One-Shot" l standard. The One-Shot standard also contains propanol-1, and the addition of this ingredient in the commercial standard is likely responsible for the difference in conductivity.

TABLE 5 1. RECORDED CONDUCTIVITY DATA AS IONIC SOLUTION COMPOSITION AND TEMPERATURE WERE VARIED. MOLAR CONCENTRATIONS OF CACL$_2$ AND MGCL$_2$ WERE DECREASED BY HALF TO COMPENSATE FOR THE DOUBLE CHARGE OF THE CATION SPECIES. SIMILARLY, NA$_2$CO$_3$ AND K$_2$CO$_3$ MOLAR CONCENTRATIONS WERE DECREASED BY HALF TO COMPENSATE FOR THE DOUBLE CHARGE ON CO$_3^{2-}$. CONDUCTIVITY WAS MEASURED BY THE WTW COND 330I PROBE ELECTRONICALLY, WHILE SALINITY VALUES WERE CALCULATED FROM THE CONDUCTIVITY READINGS.

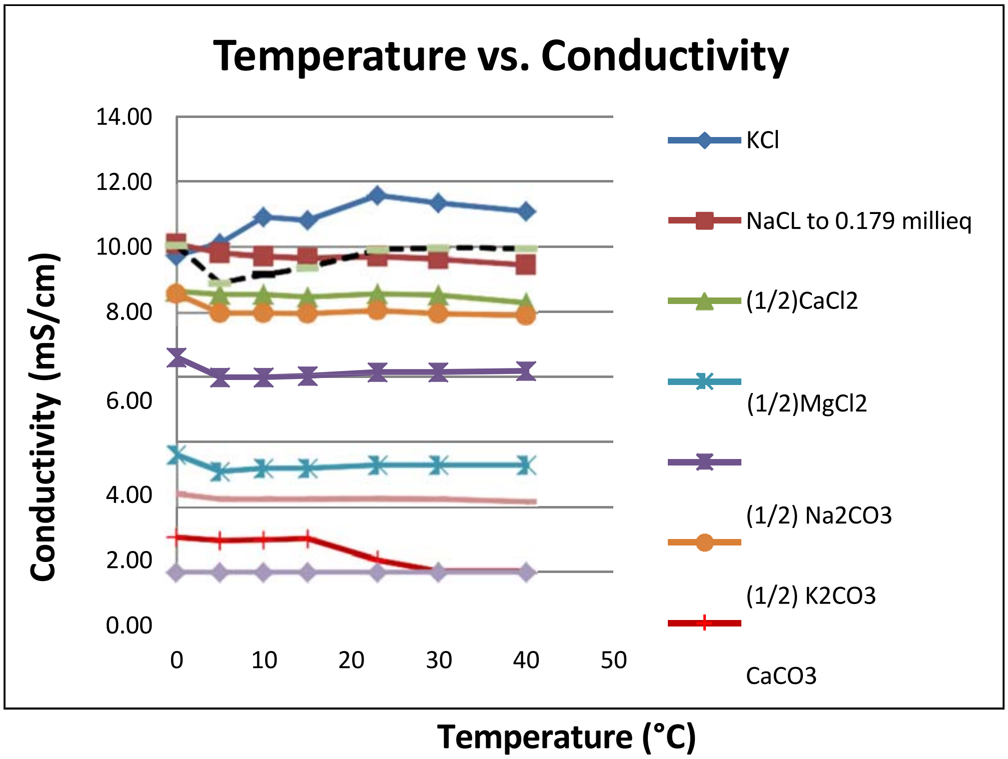


Compound or solution	Prepared Salinity (mg/kg)	Molal Concen.	Temp. # 1 (°C)	Conduct . (µS/cm)	Salinity (mg/kg)	Temp. # 2 (°C)	Conduct . (µS/cm)	Salinity (mg/kg)	Temp. # 3 (°C)	Conduct . (µS/cm)	Salinity (mg/kg)
Std.: One-Shot KCl	6,660	K = 0.0893 Cl = 0.0893	15.0	9380	5200	23.1	9,910	5,600	30.0	9960	5700
KCl	6,660	K = 0.0893 Cl = 0.0893	15.0	10,800	6000	23.0	11,570	6,600	30.0	11,350	6600
NaCl	4,106	Na = 0.0893 Cl = 0.0893	15.0	7600	4100	23.0	7,640	4,200	30.0	7580	4200
(1/2)CaCl$_2$	4,954	Ca = 0.0447 Cl = 0.0893	15.0	8460	4700	23.0	8,570	4,800	30.0	8520	4800
(1/2)MgCl$_2$	4,214	Mg = 0.0447 Cl = 0.0893	15.0	6010	3200	23.0	6,050	3,300	30.0	6010	3300
(1/2) Na$_2$CO$_3$	4,732	Na = 0.0893 CO$_3$ = 0.0447	15.0	6030	3200	22.9	6,150	3,300	30.0	6140	3400
(1/2) K$_2$CO$_3$	6,172	K = 0.0893 CO$_3$ = 0.0447	15.0	7950	4400	22.9	8,050	4,500	30.0	7950	4700
CaCO$_3$	8,938	Ca = 0.0447 CO$_3$ = 0.0447	15.0	1040	Not detect.	23.1	383	Not detect.	30.0	51	Not detect.
MgCO$_3$	7,528	Mg = 0.0447 CO$_3$ = 0.0447	15.0	2250	1000	23.0	2,265	1000	30.0	2250	1000
DIW	0	Not applicable	15.0	4	Not detect.	23.0	3	Not detect.	30.0	3	Not detect.

TABLE 5.2. RATIO OF IONIC CONCENTRATION DETECTED BY THE CONDUCTIVITY PROBE DIVIDED BY PREPARED CONCENTRATION OF IONS. VALUES CLOSEST TO 1.00 RECORD THE IONIC CONCENTRATION MOST ACCURATELY. ALL READINGS WERE AT 23^{O}C

Ionic Solution	Measured concentration (mg/kg) / as prepared concentration (mg/kg)	Ratio
NaCl	4200 / 4106	1.02
KCl	6700 / 6660	1.02
CaCl$_2$	4800 / 4954	0.97
MgCl$_2$	3300 / 4214	0.78
K$_2$CO$_3$	4500 / 6172	0.73
Na$_2$CO$_3$	6170 / 4732	0.72
MgCO$_3$	300 / 7528	0.04
CaCO$_3$	below detection/	Not applicable

FIGURE 5.2. CONDUCTIVITY RESULTS OBTAINED WITH VARIOUS IONIC SOLUTIONS PREPARED IN THE LABORATORY VERSUS THE “ONE-SHOT” BRAND CALIBRATION STANDARD PREPARED WITH KCL + PROPANOL. THE LATTER IS SHOWN WITH THE BLACK DASHED LINE. THE CONDUCTIVITY RESPONSE OF THE “ONE-SHOT” STANDARD MATCHES CLOSELY TO THE NACL IONIC SOLUTION (RED SOLID LINE), ESPECIALLY OVER THE RANGE OF 15 TO 40^{0}C.



Task 3.b. Determine Petrologic and Mineralogic Characteristics of the Confining Layer and Target Formation

EXPERIMENTAL PROCEDURE FOR X-RAY DIFFRACTION ANALYSIS

Samples were selected for XRD analysis from the core collected at three sites based on the importance of a particular horizon as an injection horizon (e.g., Lamotte Sandstone), cap rock (e.g., Derby-Doerun Formation), and/or the uniqueness of a horizon in containing minerals that may corrode to release cations that may complex with dissolved CO_2 to potentially form carbonate minerals.

Preparation of the samples for XRD analysis involved placing 25g of the sample into a beaker with 100mL of deionized water (DIW). More cohesive samples were ground into a paste in an agate mortar and pestle prior to emplacement in the beaker. Mechanical crushing of samples was avoided as this often results in heating of the sample powders, which may potentially cause changes in the structure of clay minerals.

Only the finer clay-sized fraction of particles (< 2.0 micrometers) was analyzed by XRD. This size fraction was concentrated using a water flotation process. After rock material was disaggregated, the sample was stirred into a beaker with deionized water. After 15 seconds of settling time, the suspended particles were decanted off and collected in a second beaker. The finer material in the second beaker was allowed to settle for 10 minutes. This time period allows silt-sized and larger particles to settle by gravity below the top few millimeters of the water column. An aliquot of solution and particles in suspension was then removed from the top of the water column with a pipette and placed upon a glass slide. Evaporation of the water allowed the captured clay particles to lie with the c-axis perpendicular to the glass slide, producing a preferred orientation for proper XRD analysis. The slides produced were thus representative of the fine-grained components of the sediment sample with a preferred particle orientation. Two glass slides were prepared from each sample; one for analysis and one as a backup.

Samples were then analyzed 1) untreated, 2) after an overnight exposure to an ethylene glycol atmosphere, and 3) heated to 375°C. XRD analysis was then performed using a CuK_{alpha} radiation source on an X'Pert PRO XRD system. Scans of the samples were conducted from 2 to 55 degrees two-theta at a scan speed of two degrees two-theta per minute. Detected XRD peaks were compared against peaks from a known sample library or standards run in the laboratory. A quantification procedure was used to calculate the proportion of clays present. This is a modified procedure attributed to a routine developed from the Minnesota Geological Survey:

Prepared clay-mineral mounts were scanned on the XRD instrument in three ways.

1. Scan A - Untreated (i.e. non-glycolated and not heat treated)
   No treatment – rapid scan; approximately 3° to 38° 2θ at 2°2θ/minute,
   No treatment – slow scan; 24° to 26° 2θ at 0.4° 2θ/minute (an optional run that may be needed to differentiate chlorite from kaolinite)
2. Scan B – to be run after untreated scan and overnight exposure in ethylene glycol atmosphere
   Ethylene Glycol treated 2° to 15° 2θ at 2°2θ/minute
3. Scan C – Heat Treated ½ hour at 375°C, to be run after ethylene glycol treatment
   Heat treated - 2° to 15° 2θ at 2°2θ/minute.

Slides of oriented clay were analyzed on a diffractometer at 2° 2θ/minute from approximately 3° to 38° 2θ with monochromatic radiation. Record radiation source type (e.g., Cu Kα). Subsequent runs varied depending on the mineralogy and nature of the information needed. Note that many non-clay minerals have refraction peaks at 30° - 70° 2θ.

The following peak heights over background should be recorded. The positions of these peaks may vary slightly from these angles.

1. No treatment rapid scan run at 12.4° 2Ø – $K_{(1)}$; kaolinite
2. No treatment rapid scan run 17.8° 2θ – $I_{(2)}$; illite
3. No treatment rapid scan run 18.4°to 18.9° 2θ- $C_{(3)}$; chlorite
4. No treatment slow scan run at 24.9° 2θ – $K_{(2)}$; kaolinite
5. No treatment slow scan run at 25.1° 2θ – $C_{(4)}$; chlorite
6. Ethylene glycol treated run at 5.2° 2θ – $M_{(1)}$; montmorillonite (smectite)
7. Ethylene glycol treated run at 8.8° 2θ – $I_{(1G)}$; illite
8. Heated run at 8.8° 2θ – $I_{(1H)}$; illite

The above data can be used to calculate the approximate proportions of illite, montmorillonite, chlorite, mixed-layer clay minerals, and kaolinite within approximately +/- 10% accuracy. Clay mineral present in proportions <5 to 10% may not be detected. The presence or absence of chlorite is quite important in the calculations and is most easily recognized by a peak at 6.1 2θ on the heated slide. The results from this technique do not allow for the differentiation between the various types of montmorillonite, mixed-layer clays, and vermiculite, etc., and calculated clay contents are only accurate to within +/- 10%. The approximate basal spacings and two-theta (2θ) diffraction peak positions used for identifying the various clay mineral groups are given in Table 5.3.

The method for quantification of clays is as follows:

Illite = $\frac{I_{(1G)}}{T} \times 10$

Montmorillonite = $\frac{M_{(1)}}{4T} \times 10$

Chlorite = $\frac{C_{(3)}}{I_{(2)}} \times \frac{I_{(1G)}}{T} \times 10$

Mixed-layer clay minerals = $\frac{I_{(1H)} - \left[I_{(1G)} + \frac{M_{(1)}}{4}\right]}{T} \times 10$

Kaolinite = $\frac{K_{(1)}}{T} \times 10$

or kaolinite, if chlorite is present

= $\frac{K_{(2)}}{2C_{(4)}} \times \frac{C_{(3)}}{I_{(2)}} \times \frac{I_{(1G)}}{T} \times 10$

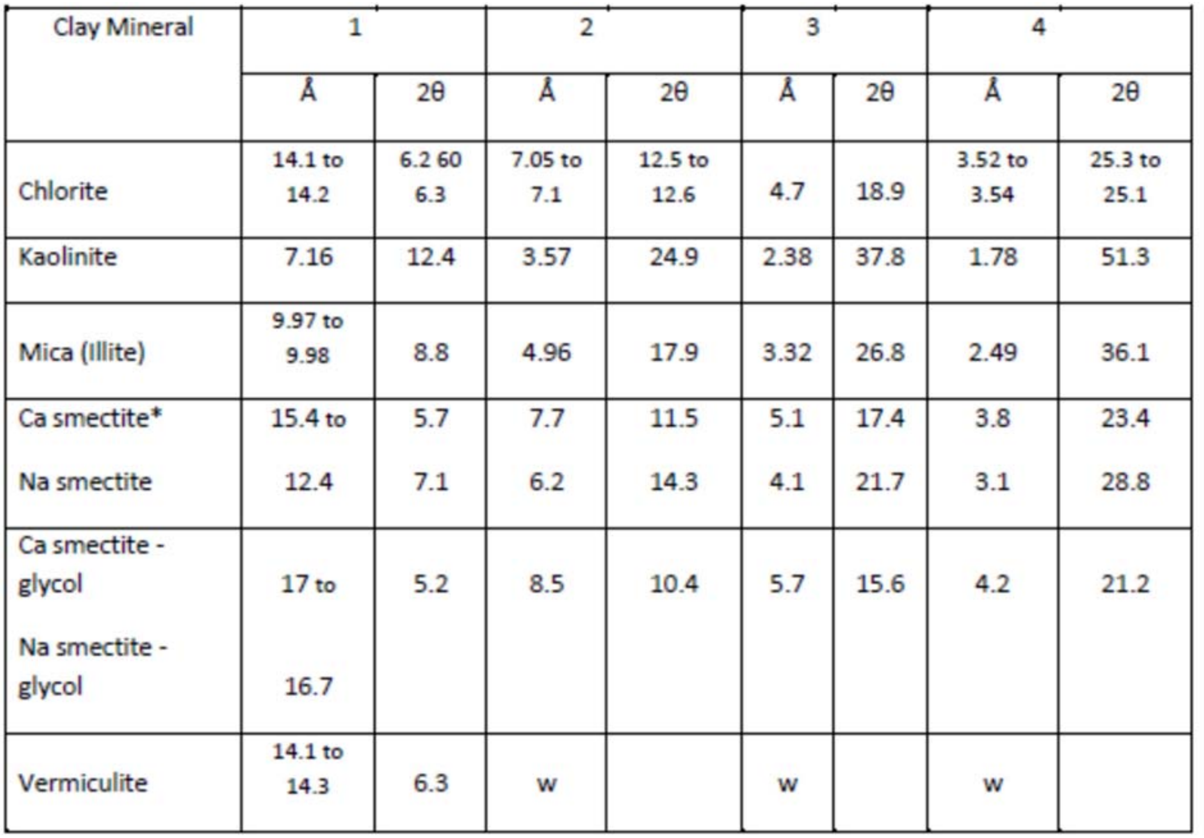
where T is equal to “total counts”

T = $I_{(1H)} + K_{(1)}$

or, if chlorite is present

T = $I_{(1H)} + \left\{\frac{[C_{(3)}][I_{(1G)}]}{I_{(2)}}\right\} + \left\{\frac{[K_{(2)}][C_{(3)}][I_{(1G)}]}{[2C_{(4)}][I_{(2)}]}\right\}$

TABLE 5.3. BASAL SPACINGS (D) IN Å AND 2Θ FOR A CU K-ALPHA RADIATION X-RAY DIFFRACTION ENERGY SOURCE.



Clay Mineral	1		2		3		4	
	Å	2θ	Å	2θ	Å	2θ	Å	2θ
Chlorite	14.1 to 14.2	6.2 60 6.3	7.05 to 7.1	12.5 to 12.6	4.7	18.9	3.52 to 3.54	25.3 to 25.1
Kaolinite	7.16	12.4	3.57	24.9	2.38	37.8	1.78	51.3
Mica (Illite)	9.97 to 9.98	8.8	4.96	17.9	3.32	26.8	2.49	36.1
Ca smectite*	15.4 to	5.7	7.7	11.5	5.1	17.4	3.8	23.4
Na smectite	12.4	7.1	6.2	14.3	4.1	21.7	3.1	28.8
Ca smectite - glycol	17 to	5.2	8.5	10.4	5.7	15.6	4.2	21.2
Na smectite - glycol	16.7							
Vermiculite	14.1 to 14.3	6.3	w		w		w	

Other diffraction peaks that are commonly encountered in sedimentary samples:

- Calcite 29.5° 2θ
- Dolomite 30.9° 2θ
- Quartz 20.8° 2θ and 26.6° 2θ
- Albite and Microcline 27.7° 2θ
- Pyrophyllite 9.6, 19.3, and 29.1° 2θ

Task 3.c. Determine Permeability of the Confining Layer and Target Formation

Porosity and permeability measurements required cores samples 1 inch in diameter. Hence, a one inch core plug was drilled from each of the collected 2.5 inch diameter core samples using a core drill. To drill the samples, the 2.5 inch diameter core samples were secured with a bar clamp and a 4x4 wood beam that had been cut in half and that had a 2.5 inch diameter round opening in it.

The setup is shown in Figure 1. Once the core plugs had been drilled, the ends of the sample were cut flat. All cores were cut at Missouri S&T with the exception of cores taken from THEC, which were cut commercially because the university's equipment was being repaired.

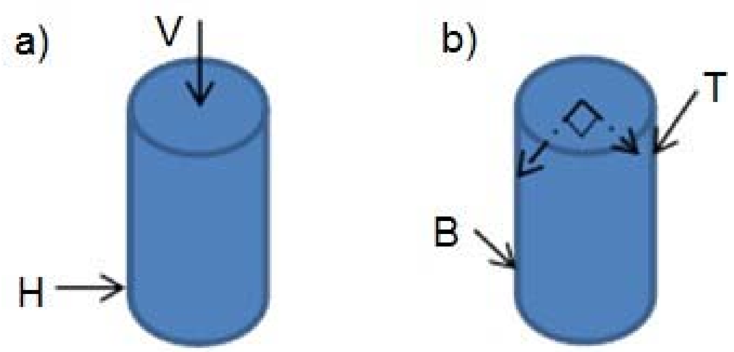
CORE SAMPLE ORIENTATION

Core samples taken from the JTEC well were drilled to measure horizontal permeability. The one inch core plugs of THEC and SPP sites were obtained using a core drill (Figure 5.3) by drilling in two directions, to investigate formation anisotropy. These oriented specimens were drilled from the vertical direction and horizontal direction as shown in Figure 5.4a. Vertical direction was marked as V while horizontal direction as H. A few samples were drilled both from horizontal directions but have a 90 degree angle shown in Figure 5.4b. Samples taken at the top of the core were marked as T, and those taken at the bottom one were marked as B. Each core was also measured for permeability from a positive direction and a negative direction.

FIGURE 5.3. CORE DRILL

All samples were taken in core areas with few fractures to ensure the samples would be stable while drilling for specimens.

FIGURE 5.4. SKETCH OF SPECIMEN MARKER



a) Vertical and horizontal directions b) Horizontal directions

All cut core samples were dried in an oven at 110°C until the core reached a stable weight, indicating that the core had no more water in the pore spaces, and the specimens were completely dry.

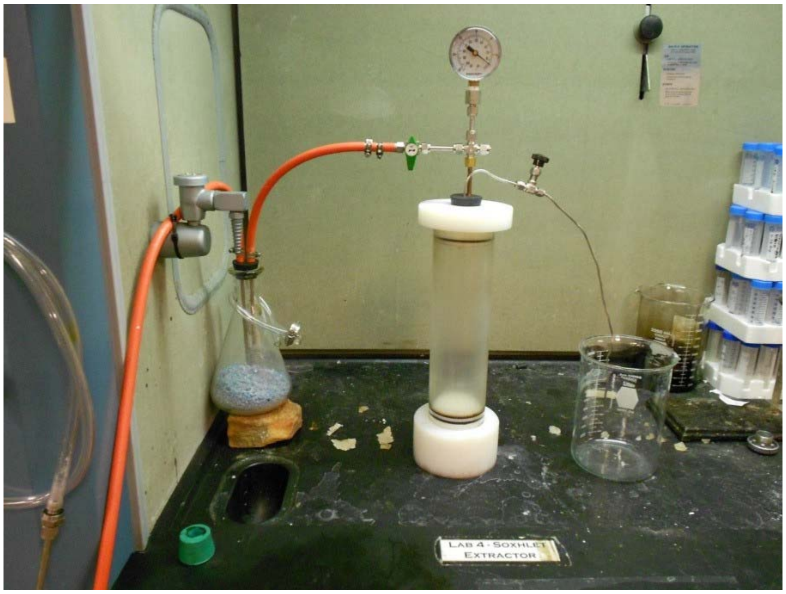
Two methods were used to measure porosity in this study. Porosity of cores taken from the JTEC well was measured using the Saturation Method (vacuum saturation test). Some samples also were sent to a commercial laboratory to verify results obtained by the Saturation Method.

Porosity measurement with the Saturation Method requires an accurate knowledge of formation water density. Two water samples, one from the Reagan Formation and one from the Lamotte Sandstone, were used in calculating porosity. Water density at laboratory conditions was determined by measuring the mass of the fluid at 10 ml intervals, with increasing volumes from 10 to 100 ml. This process was repeated four times for each sample, yielding 40 mass readings. The mass readings were converted to densities in grams per cubic centimeter (g/cc) and an average of the densities was used for the porosity calculation.

The average density of the Reagan Sandstone fluid sample was 0.9865 g/cc, and the average density of the Lamotte Sandstone fluid sample was 0.992 g/cc. Both samples were found to have relatively fresh water composition. At the laboratory temperature of 25°C, fresh water should have a density of 0.99g/cc, so the values found for the samples were deemed to be correct.

Bulk volume for each core plug was determined by using calipers to measure length and width for each core. The mass of the dry core plug was then measured and the sample was placed into a sealed chamber connected to a vacuum pump, which removed all remaining air from the pore space. The core was then saturated with the appropriate native water sample. Reagan Sandstone water was used for the Davis Formation confining layer and samples with depths below 1,900 ft were saturated with Lamotte Sandstone water. After saturation, each core was removed and a final saturated mass was recorded. The volume of water in the pore space was then calculated, knowing the difference between saturated and dry plug masses and fluid density. Pore volume is equal to the water volume, which is converted to porosity by dividing by the bulk volume of the plug sample. The vacuum apparatus for the experiment is shown in Figure 5.5.

FIGURE 5.5. VACUUM SATURATION CHAMBER



The grain volume was calculated by subtracting the pore volume from the bulk volume for each core plug. Grain density was then determined by dividing the grain volume by the dry mass of the sample.

Porosities of the core samples from the THEC and the SPP sites were measured by a Helium Porosimeter. The Helium gas expansion porosimeter is based on the Boyle's and Charles' law expansion of helium gas and is used for direct grain volume and pore volume measurement in an auxiliary cell at isothermal conditions. Subsequently, porosity and grain density can be derived from the direct measurements. A data acquisition computer allows for data logging and calculation of parameters and also calibration data. The device is shown in Figure 5.6. Helium is a stable gas and has a low adsorptivity on most rocks. It consists of small molecules and has a low mass which means helium will penetrate the tiny rock capillaries and low permeability rock that is why it is used.

Boyle's Law equations used in the calculations are,

$$\mathrm{PV} = \mathrm{const}$$

$$\mathrm{P_1 V_{cup+sample}} = \mathrm{P_2 V_{cup}}$$

$$\emptyset = \frac{\mathrm{V_b - V_{HP}}}{\mathrm{V_b}}$$

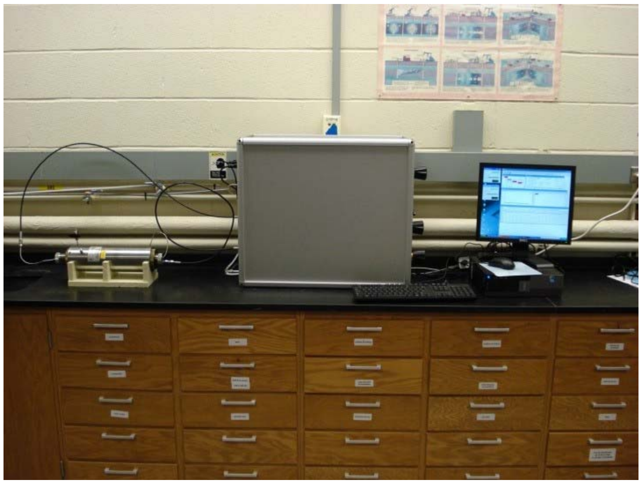
V_b -- Bulk volume
V_{HP} --The volume measured by Helium Porosimeter

FIGURE 5.6. HELIUM POROSIMETER

PERMEABILITY

Permeability for all core plugs was determined by a Klinkenberg test using a gas permeameter. Mass flow meters and pressure transducers were used to accurately measure steady-state gas permeability of the core plug samples. The Ultra-Perm 600 was manufactured by Core Laboratories/Temco Instruments, and the experimental setup can be seen in Figure 5.7. The constant pressure method for testing gas permeability is used with this instrument. For each pressure desired, the upstream pressure is held constant, while the flow rate of gas through the core and the differential pressure across the core are measured.

FIGURE 5.7. EXPERIMENTAL SETUP WITH ULTRA-PERM 600



A dry core plug was loaded into the core holder and 1,000 pounds per square inch (psi) confining pressure was applied. The nitrogen gas flows into the upstream side of the sample at a specified pressure. A differential pressure transducer monitors the difference between the pressure on the upstream side of the sample and the pressure on the downstream side of the sample while the gas is flowing through the sample. The mass flow meter measures the velocity of the nitrogen gas as it passes through the sample. Once the flow rate and both upstream and downstream pressures are stable, the permeability can be calculated using Darcy's Law for gas flow.

$$K_a = 2000 P_m \mu Q_1 L / (P_1^2 - P_2^2) A$$

K_a -- Permeability (md)
μ -- Viscosity (centipoise)
L -- Sample Length (cm)
A -- Sample Cross-Section Area (cm2)
P_1 -- Upstream Pressure (atm)
P_2 -- Downstream Pressure (atm)

Several single point permeability readings are required for a Klinkenberg test. The upstream pressure was changed between readings so that several readings were taken for each core sample. Once these single point readings are found, a graph of permeability (k) versus the inverse of mean pressure (Pmean) is made. The y-intercept is read as the absolute permeability.

The absolute permeability for cores taken from THEC and SPP sites provided directional permeability according to the orientation of the samples measured.

CAPILLARY PRESSURE

Capillary pressure data are required for three main purposes:

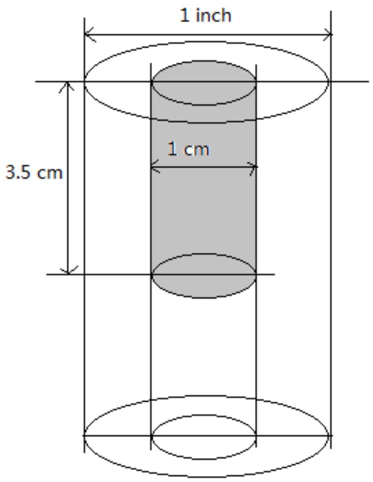
- The prediction of reservoir initial fluid saturations.
- Cap-rock seal capacity (displacement pressures).
- As ancillary data for assessment of relative permeability data.

Capillary pressures are generated where interfaces between two immiscible fluids exist in the pores (capillaries) of the reservoir rock. It is usual to consider one phase as a wetting phase and the other as a non-wetting phase. The *drainage* case, i.e. a non-wetting phase displacing a wetting phase applies to hydrocarbon migrating into a previously brine saturated rock. *Imbibition* data is the opposite to drainage, i.e. the displacement of a non-wetting phase by a wetting phase. Thus, the drainage data can usually be used to predict non-wetting fluid saturation at various points in a reservoir, and the imbibition data can be useful in assessing the relative contributions of capillary and viscous forces in dynamic systems.

In this study, the Mercury Injection Capillary Porosimeter (MICP) measurement is used to monitor the volume of mercury that is injected into a dried core sample at each pressure step. The MICP data are used to determine the CO_2 entry pressure and the pore distribution of the rock. Mercury is the non-wetting phase and it can only access interconnected pores in the core sample. The mercury injection volume is limited by the maximum pressure of the device which is up to 60,000 psi.

Representative samples were taken from the core specimens, and a smaller sample (diameter of 1 cm and a length of 3.5 cm) was drilled to fit the sample cell of Poremaster (r=1 cm, L=3.5 cm) as shown in Figure 5.8.

FIGURE 5.8. SCHEMATIC OF ONE INCH CORES AND ONE CENTIMETER CORES



The theory of the mercury porosimeter is that a non-reactive, non-wetting liquid will not invade the pores until the pressure is sufficient. The equation is:

$$\mathrm{Pc} = \frac{2\sigma\cos\theta}{r}$$

P_c -- Capillary pressure, psi
σ -- Interfacial tension, dynes/cm
θ -- Contact angle, degrees
r -- Pore radium, µm

The mercury saturation is calculated by:

$$S_{Hg} = \frac{V_m}{VP}$$

S_{Hg} -- Mercury saturation
V_m -- Total injection volume of mercury, cc
VP -- Pore volume $PV = \pi r^2 L\emptyset$, cc

The initial pressure at which the mercury first displaces the air is referred as the entry pressure. An estimate of the mercury entry pressure is obtained by drawing a P_c vs. S_{Hg} curve. To consider the seal capacity and reservoir CO_2 storage capability, this entry pressure can be converted to a subsurface CO_2/brine system by using the following equation:

$$P_{bCO_2} = P_{a/m}\frac{(\sigma_{bCO_2}\cos\theta_{b/CO_2})}{\sigma_{a/m}\cos\theta_{a/m}}$$

P_{bco_2}=Capillary pressure in the brine/CO_2 system, psi
$P_{a/m}$ =Capillary pressure in the air mercury system, psi
σ_{bCO_2} = Interfacial tensions of the brine/CO_2 system, 25 dynes/cm
$\sigma_{a/m}$ = Interfacial tensions of the air mercury system, 480 dynes/cm
θ_{b/CO_2} = Contact angles of the brine/CO_2/solid system, 0˚
$\theta_{a/m}$ = Contact angles of the air/mercury/solid system, 140°

To convert to the subsurface CO_2/brine system, the water saturation is shown as:

$$S_w = 1 - S_{Hg}$$

BOREHOLE LOG ANALYSIS

A standard suite of openhole logs (Self Potential, Gamma Ray, Electric, Density, Neutron, Caliper, Sonic) were run in the JTEC and THEC boreholes. No logs were run over the zones of interest in the SPP borehole. JTEC well logs were analyzed manually, recording readings in Excel and determining porosity from the steps outlined here. The commercial well log analysis software, LESA, was used to analyze logs from the THEC borehole.

SHALE VOLUME

A Gamma Ray Log was run in combination with the Density Log, Resistivity Log and Neutron Porosity Log. From the Gamma Ray Log reading, the volume of shale present in the formation was calculated using the Steiber equation:

$$\mathrm{V_{shale}} = \frac{\mathrm{I_{GR}}}{3 - (2 * \mathrm{I_{GR}})}$$

where: $\mathrm{I_{GR}} = \frac{\mathrm{GR} - \mathrm{GR_{min}}}{\mathrm{GR_{max}} - \mathrm{GR_{min}}}$

The minimum gamma ray value (GRmin) is selected as the GR reading for a clean sand formation, indicating there isn't any shale, and the maximum gamma ray value (GRmax) is selected as the GR reading for a 100% shale formation.

POROSITY

The porosity of the target formation was estimated from three logs where possible, including the Density, Neutron Porosity and Sonic Logs. The density porosity can be calculated when the rock matrix density and the drilling fluid density is known. Density log interpretation can be affected by shale in the formation, so a shale correction value is also calculated as follows:

$$\phi_{\mathrm{D,\ shale\ corrected}} = \frac{\rho_{\mathrm{ma}} - \rho_{\mathrm{b}}}{\rho_{\mathrm{ma}} - \rho_{\mathrm{fl}}} - \mathrm{V_{shale}} * \phi_{\mathrm{shale}}$$

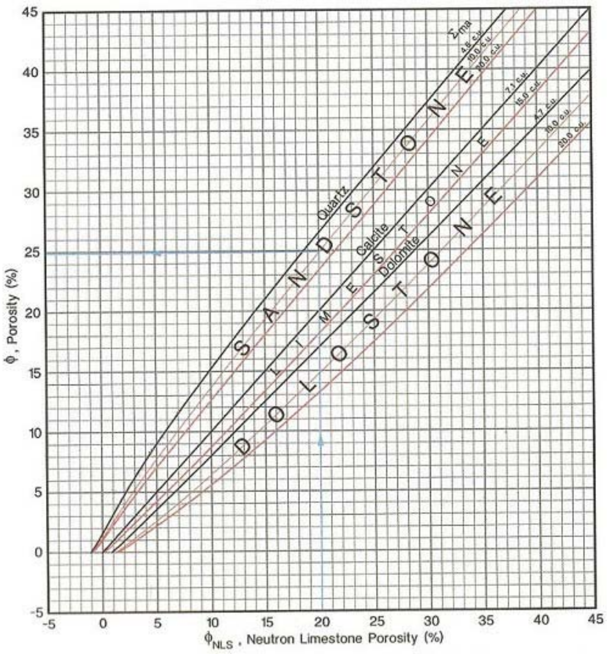
where: $\phi_{\mathrm{shale}} = \frac{\rho_{\mathrm{ma}} - \rho_{\mathrm{shale}}}{\rho_{\mathrm{ma}} - \rho_{\mathrm{fl}}}$

Reagan and Lamotte Sandstone matrix density was set equal to 2.65 g/cc and the fluid density was set equal to 1.0 g/cc. For the ☐$_{\mathrm{shale}}$ calculation, the shale density was selected by taking the density value from the density log in the sections of the confining layer that were determined to be 100% shale by the gamma ray log, which made ☐$_{\mathrm{shale}}$ equal to 0.0005445. The bulk density in the target formation was taken from the short spaced density log in the target formation. The average density porosity of each five foot section was used for calculations.

NEUTRON POROSITY

The Neutron Porosity Log was taken in Limestone Porosity Units (LPU). To convert to formation porosity from this log, readings must first be corrected for lithology. Readings (ϕ_{NLS}) were averaged over each five foot intervals and corrected for lithology according to Figure 5.9.

FIGURE 5.9. CHART FOR CORRECTING HALLIBURTON DSN-II NEUTRON-POROSITY CURVE FOR LITHOLOGY



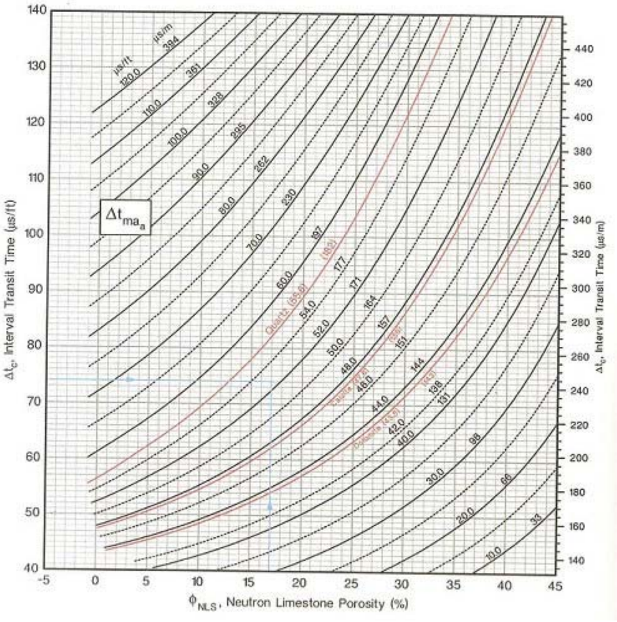
SONIC POROSITY

The sonic porosity was calculated using the Raymer-Hunt-Gardner (ϕ_{RHS}) equation:

$$\phi_S = \frac{5}{8} * \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_{log}}$$

This equation requires the interval transit time of the rock matrix to be known. This can be found if both the neutron porosity and sonic logs are compared. Using Figure 5.10, the average apparent matrix interval transit time was found for each five foot section in both the Reagan and Lamotte Sandstones.

FIGURE 5.10. DETERMINATION OF APPARENT MATRIX INTERVAL TRANSIT



Sustained water/ CO_2 injection was not possible during this project at any of the sites, and the water injections performed in the Lamotte Sandstone were relatively small volumes. Additionally, water injection was only possible in the JTEC borehole. Ten pump-in tests were conducted at the JTEC site to measure hydraulic conductivity. Two straddle packers were used to isolate each section, using open hole, inflatable packers. These pump-in, pressure tests included hydrofrac and hydrojack tests, as explained under task 4a.

Long term CO_2 injection was modeled for the JTEC site using the compositional simulator CMG- GEM. Several cases were evaluated, varying assumptions of injection rate, volume, fixed reservoir volume, completion methods, and reservoir brine withdrawal. These cases provide insight regarding three aspects of CO_2 storage potential in the Lamotte Sandstone: 1) the effect of reservoir properties and injection rate on CO_2 storage and injectivity, 2) the effect of completion techniques and reservoir heterogeneity on CO_2 storage and injectivity, and 3) water withdrawal and influencing factors.

Task 3.e. Retrieve and Analyze Fluid Samples from the Target Formation

EXPERIMENTAL PROCEDURE FOR GOLDICH MINERAL STABILITY TESTS

A large suite of single mineral samples were tested following immersion in a nitric acid (HNO_3) leachant solution prepared to a pH of approximately 3.78 (1.66×10^{-4} M). These experiments were performed with minerals that were obtained from the mineral museum collections at Missouri S&T's Geology and Geophysics Program so that the behavior of each mineral phase could be evaluated individually. No experiments were performed on rock samples from any of the borehole sites as these contained mixed mineral lithologies and in many cases only small percentages of minerals that react at faster rates. Results can be extrapolated from the individual mineral phase tests to the rock samples where phases identified in the rock samples are similar. The 3.78 pH represents both the lowest value expected in soils enriched in organic-acidic decay products and the approximate pH of a dilute aqueous groundwater solution following saturation of the water in the presence of a pure CO_2 gas at atmospheric pressure. These experiments were used to simulate the effect of carbonic acid ($H_2CO_{3(aq)}$) exposure on mineral dissolution rates in order to compare mineral reaction rates as a function of acid neutralization, with observations of minerals in natural weathering environments (Goldich, 1938). The use of HNO_3 rather than $H_2CO_{3(aq}$ offers an advantage in that the former does not readily volatilize and transfer into a gas phase. Nitric is also a stronger acid that more readily dissociates to release H^+ ions into solution for reaction.

The different mineral samples were prepared for testing by crushing and then sieving to collect the -200 mesh sized fraction (<74 micrograms [µm]). The individual mineral samples used in these tests are listed in Figures 5.105 and 5.106. Mineral samples were obtained from the Missouri S&T's mineral museum collections. A 0.20 gram batch of each powdered sample was added into a pre-cleaned 250 ml polyethylene vial to which, 200 ml of HNO_3 solution was added to initiate the tests. Experiments were conducted at ambient room temperature (approximately 20°C) in closed vials, however, the atmosphere above the test solution in the vials was periodically replenished with fresh air each time the vessels were opened and pH measurements were made. Solution readings for the first pH sample were taken following two hours of exposure, and then readings were taken in repetition again, after approximately doubling the previous reaction time up to the point where pH readings were taken approximately two weeks apart. The pH meter used in the testing was routinely calibrated with pH 4.00, 7.00, and 10.00 standards to ensure that accurate and repeatable pH measurements were being made.

EXPERIMENTAL PROCEDURE FOR FLUIDIZED BED REACTOR TESTS

The test procedure for the "fluidized bed reactor" involves CO_2 being passed through a curved glass funnel containing crushed particles of a rock or mineral sample that were emplaced into deionized water at ambient laboratory temperature (approximately 20°C; Figures 5.11a and b). The CO_2 gas entered the glass reaction chamber and the slowly bubbling gas kept the crushed mineral samples aggitated and exposed to fresh solution. The sample remained in contact with water and the CO_2 gas phase throughout the testing process at atmospheric pressure. Dissolved components from the rock mass were released into the water and that solution was periodically sampled and chemically analyzed to evaluate the rate of mineral reactions. These experiments were performed only with rock samples from the JTEC site.

Prior to each run, the fluidized bed reactor column apparatus was soaked for one hour in dilute (3- 5%) HNO_3 solution, and then rinsed three times with high purity deionized water. All mineral and rock samples used in the experiments were crushed with an agate mortar and pestle and sieved to collect a size fraction of 500-850µm (18-35 mesh). The surface area for each crushed sample was geometrically estimated from sieved separated samples by weight measure and assuming a spherical geometry for the particles. Since the particles are never completely spherical, nor smooth surfaced, we likely underestimated the true surface area using this method. The crushed samples were washed and quickly decanted with deionized water to remove any fine powders.

The grains were then dried and five grams of sample were weighed out and placed in the reaction vessel with 50 ml of deionized water. Once the mineral sample and water were in the reaction vessel, "food-grade" CO_2 gas was passed into the flow column and the flow rate was adjusted with a needle valve to produce slow bubbling through the mineral sample (gas flow = 60-80 cm^3/min). The solution pH was periodically checked and recorded with an Accumet Portable AP62 pH/mV/°C meter. After the pH was checked, 20 ml of the sample fluid was removed with a disposable syringe and passed through a disposable 0.45 cellulose acetate filter to remove any suspended particles.

The fluid level in each vessel was then replenished with a new aliquot of deionized water to replace the 20 ml of fluid removed by sampling plus any water lost due to evaporation. At the conclusion of the experiments, the final water sample was collected by decanting, and the reacted solids were recovered and any excess solution was removed by gently touching the corners of the samples to a paper towel. The samples were allowed to air dry and then examined using optical microscopy techniques and a Hitachi S570 Scanning Electron Microscopy-Energy Dispersive Spectroscopy (SEM-EDS) system to look for alteration patterns and precipitated phases.

The approximately 20 ml leachate aliquots that were collected were acidified with analytical grade HNO_3 to a pH of 2 or lower to prevent precipitation of any minerals, which is expected as CO_2 comes out of solution and the pH rises. Solutions were then analyzed on an Optima 2000 DV Inductively Coupled Plasma Optical Emission Spectrograph (ICP-OES) for their dissolved element concentrations.

FIGURE 5.11A. SKETCH OF REACTION CHAMBER FOR FLUIDIZED BED REACTOR TEST ILLUSTRATING MINERALS IN CONTACT WITH CO2 (G) AND DEIONIZED WATER.

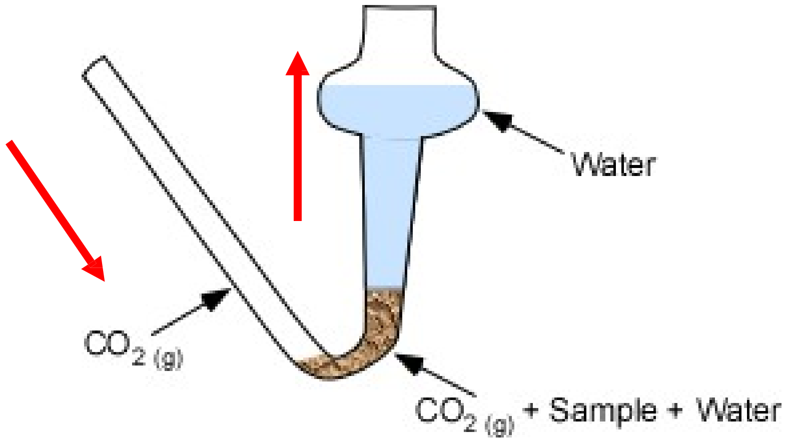
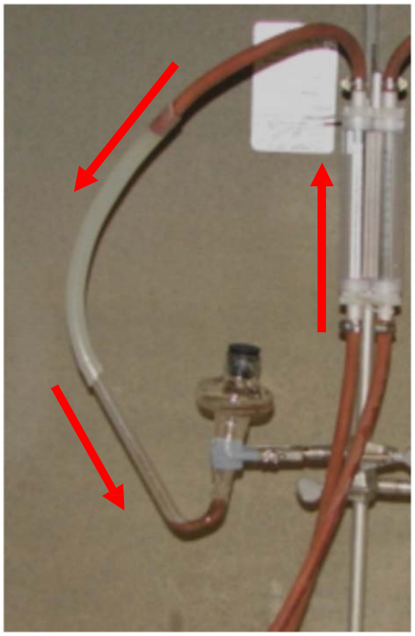


FIGURE 5.11B. IMAGE SHOWS ACTUAL APPARATUS CONNECTED TO CO_2 INJECTION LINES WITH SECOND FLUIDIZED BED REACTOR ON RIGHT NOT SHOWN. THE U-SHAPED GLASS VESSEL IS APPROXIMATELY SIX INCHES TALL. THE DUAL COLUMNS TO UPPER RIGHT ARE THE GAS FLOW VALVES. RED ARROWS DENOTE GAS FLOW DIRECTION. THE RUBBER CORK WAS LOOSELY INSERTED IN THE OUTFLOW OPENING TO MINIMIZE EVAPORATIVE LOSS OF WATER.



EXPERIMENTAL PROCEDURE FOR HIGH PRESSURE AND TEMPERATURE $CO_2 + H_2O$ TESTS

High pressure $CO_2 + H_2O$ tests were conducted in Teflon-lined stainless steel bombs in order to simulate the conditions for reactions between CO_2 and rock samples. The samples were obtained from cores samples extracted from Exploratory Boreholes #1, #2, and #4. Samples for the high pressure and temperature tests with $CO_2 + H_2O$ were prepared by first cutting one-inch diameter cylinders from the two inch diameter field cores then sectioning wafers of individual samples into monoliths approximately two millimeters thick. The mineral samples were typically sectioned directly from hand specimens. These monoliths were polished on their flat surfaces to a uniform surface finish using a 600-grit carbide paper. After polishing, the samples were then washed with deionized water and placed in an oven at 45^oC for two hours for drying. The polished samples were weighed on a scale accurate to 0.0001g before and after the experiment to note any weight change. This will allow for a check to determine if the Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) data supports the weight loss from mineral dissolution (assuming that the formation of hydrated, OH^-, and/or CO_2 phases have not increased sample weights).

Some of the polished samples were broken into two or more pieces prior to testing with each fragment designated with a letter “a, b, c…, etc.” The purpose of having different halves per vessel was to be able to perform SEM testing on one, while leaving another which had been subject to an identical reaction environment for alternative analyses. Twelve vessels were set up for the experiment with the THEC and SPP site samples. The remaining eleven vessels are currently continuing the corrosion process for longer term analysis.

The high pressure - temperature tests with $CO_2 + H_2O$ were conducted in Parr™ 4749 stainless steel vessels with Teflon liners (Figure 5.12). The Teflon liners were pre-cleaned by soaking in HNO_3 at 90^oC and then rinsing with deionized water three times and allowed to dry. The cleaning procedure followed the American Society of Testing and Materials method for the Product Consistency Test (ASTM-C1285-94, 1995). Several grams of dry ice ($CO_{2(s)}$) were added to each vessel, and the vessels were then hermetically sealed to prevent loss of gas components. The evaporation of the dry ice and storage time was used to saturate the pore spaces in the Teflon.

After a minimum of 24 hours, the bombs were opened and weighed. The mineral or rock sample monoliths were then added to the bomb along with 10 ml of deionized water and then the assembly was reweighed. Approximately 2.5 g of dry ice was then added and the vessel was hermetically sealed again and reweighed one more time to determine the actual mass of CO_2 contained in the vessel. Depending on the type of experiment, samples were either kept at ambient room temperature (approximately 20^oC) or placed in an oven at 90^oC. The 90^oC temperature was used to accelerate reactions, and does not necessarily represent any exposure temperature of any hypothetical CO_2 injection repository. Reaction rates typically double for every 10^oC rise in reaction temperature, thus reactions occurring after 6 months at 90^oC would replicate a reaction interval time for a disposal horizon that was equivalent to approximately 16 years at a temperature 40^oC.

The assembled vessels were periodically weighed during the testing interval to determine volatile loss. The experiments were terminated either after a weight loss of one gram or greater had occurred, or when a predetermined test interval time had been achieved. The vessels reacted at 90^oC were placed into a shallow metal pan with approximately 1 inch of tap water to cool down the vessels upon termination. After the vessels were opened, an aliquot of solution approximately ml in volume was withdrawn from the vessel and checked for pH and Eh with an Accumet Portable AP62 pH/mV/Temperature meter. The remaining water was removed via syringe and filtered through a

0.45µm cellulose acetate filter into an acid cleaned and pre-weighed polyethylene bottle. The filtered water sample was then acidified with analytical grade HNO_3 to produce a pH of 2 or lower to prevent the precipitation of any carbonate or other minerals as CO_2 comes out of solution and the pH rises. Solutions were analyzed by ICP-OES. Sample aliquots were typically diluted 1:2 with 1% HNO_3solution to provide enough solution for analysis of eight elements: Ca, Mg, K, Na, Mn, Fe, Si, and Al. Elemental release rates for the samples were calculated in micromoles per day per square meter of surface area to compensate for differences in sample surface area. The monolith sample was removed with clean forceps and placed in a plastic petri dish and allowed to dry. These samples were later examined for corrosion features and secondary phase precipitation using optical microscopy and SEM-EDS techniques. Both reacted and unaltered samples were prepared for SEM-EDS analysis by mounting on Al-stubs using a carbon tape and silver paint, and then the samples were sputter coated with gold (Au) and Pd to minimize charging effects that occur when samples were exposed to the electron beam in the SEM.

All 21 experiments using samples from the JTEC have been completed. Of the 23 vessels initially set up for the THEC and SPP sites, twelve were removed for analysis for inclusion in this report (seven THEC and six SPP site samples).

FIGURE 5.12. HIGH PRESSURE BOMB COMPONENTS. A) PHOTOGRAPH WITH THE TEFLON INSERT AND CAP VISIBLE AS THE WHITE COMPONENTS. B) SIMPLIFIED CROSS SECTION OF THE BOMB ILLUSTRATING SAMPLE PLACEMENT WITH RESPECT TO WATER AND CO_2.

Task 4.b. Determine Porosity, Permeability, Grain Size Distribution, Pore Throat Size and Shape, and Minerals Present in Representative Core Samples at the Four Missouri Power Plant Sites.

LABORATORY INSTRUMENT CALIBRATION AND DATA COLLECTION

Trace element cation determinations for solutions samples were determined by Inductively Coupled Plasma – Mass Spectroscopy (ICP-MS). This included the analysis for Al, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Sr, As, Se, Mo, Ag, Cd, Sn, Sb, Ba, Tl, and Pb. These analyses were performed using a Perkin-Elmer ELAN DRC II – ICP-MS following EPA Procedure 200.8. Standards of known concentration at 1.0 and 10 ppb (parts per billion or micrograms/liter) were analyzed at a minimum of once every 10 samples. Trace element analysis by ICP-MS could only be performed on the JTEC water samples. Total ion concentrations in brine water samples collected from the THEC and SPP sites were too high to allow for ICP-MS analyses as the high salinity for these samples will over-saturate the mass detector signal. For the ICP-MS analyses, accuracy values at the 10 ppb concentration level were better than 3% for Ti, As, Ag, Cd, Sn, Tl, and Pb; between 3 and 5% for V, Cr, Sr, and Ba; between 5 and 10% for Mn, Co, Ni, Cu, and Se; and between 10 and 20% for Al, Zn, Mo, and Sb.

The major elements (Si, Fe, Ca, Mg, K, Na, and Mn) also were measured by Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES) using a Perkin-Elmer Optima 2000 DV – ICP-OES equipped with a Scanning Charged Coupled Detector, ultrasonic nebulizer, and duel view plasma optics system. Standards of known concentration at 1.0 and 10 ppm (part per million or milligrams/liter) were also analyzed at a minimum of once every 10 samples, as well as several runs were conducted with 0.1 and 0.001 ppm standards to determine the instrument accuracy at low concentrations and its detection limits. Duplicate samples were also run for ICP-OES samples to determine analytical precision. For major elements precision was always better than 1.5% for all elements at concentrations of 1 ppm or higher. For Fe, at concentrations of <1 ppm, the precision was always 5% or better.

Accuracy values at the 1.0 ppm concentration level were better than 5% for Si, Ca, and Mg; and between 5 and 10% for Fe, K, and Na for the ICP-OES analyses of the exploratory well samples and fluidized bed reactor tests. At the 10 ppm concentration level accuracies were better than 5% for Si, Mg, K, and Na; and between 5 and 10% for Fe, and Ca. Accuracies fall off below the 1 ppm level on the ICP-OES unit. For a 0.1 ppm standard accuracies were determined at better than 10% for only Fe and Mg, while 10-20% accuracies were determined for Si, and 20-50% accuracies were determined for Ca, K, and Na. The ICP-OES instrument was able to detect, but not accurately quantify Si, Fe, and Mg at 0.01 ppm levels, while Ca, K, and Na could not be detected at this level. The ICP-OES analyses of the solutions collected from the high-pressure vapor tests (reactions between drill core samples, H_2O, and CO_2) were slightly lower than the runs with the formation waters collected from the field sites. Analyses for Ca, Mg, Mn, & Fe were accurate to 15-20% or better, while K, Na, Si, and Al accuracy ranged from 5-15% or better based upon standards QC checks run at 1.0 and 10 ppm concentrations.

Duplicate samples for the ICP-MS samples were generally higher (i.e. less repeatable) for the trace element components that tend to exhibit limited solubility in water, and thus tend to form particulate phases. Precision values of 20 to 30% were detected for some duplicate samples of Cr, Ni, Cu, Zn, and Se when the overall concentrations were < 1 ppb. We also had high values for Zn (up to 22%) and Mo (up to 56%) even though both of these elements were present at ppb to tens of ppb concentration levels in the duplicate samples runs.

Analysis of anion species (Fl^-, Cl^-, PO_4^{3-}, NO_3^-, PO_4^{3-}) were determined by Ion Chromatography (IC) using a Dionex DX-120 Ion Chromatograph in the Missouri S&T labs. Both lab and field blanks were all at concentrations of <0.2 ppm or lower. Accuracies determined using a 5 ppm standard were between 4 and 11% for all anion components. However, the Missouri S&T instrument was recently refurbished and was displaying variable reproducibility between analyses. Because the instrument did not have a recent track record of quality analysis, samples splits were sent to VHG Laboratory in Manchester, New Hampshire. The two most abundant anion components, Cl and SO_4^{2-} were analyzed and used as the preferred values for this project.

Carbon analyses were attempted using a Shimadzu TOC-5000A Total Organic Carbon analyzer for total carbon (TC), dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC). The instrument failed to produce any reliable analyses for these components that were within acceptable QA/QC limits. Most of the difficulty appears to lie within the highly saline sample matrix and/or failure of the instrument hardware. As all fluids were consumed in the several attempt to analyze the samples replication of the data set was not possible. The DIC values can be derived from the alkalinity titration test data. It was initially expected that the DOC contents would be very low in the subsurface waters as they are far removed from any surface water infiltration points, oil, and gas reservoirs. The very low turbidity water and lack of dark organic coloration in the rock and water samples obtained from the JTEC borehole supports this hypothesis, but it was not possible to confirm this with quantitative data.

Task 4.a. Determine the Permeability of Core Samples from the Confining Layer and Target Formation at the Four Missouri Power Plant Sites

Core samples from the JTEC, THEC and SPP sites were tested to understand the strength and geomechanical properties of the formation. Britt Rock Mechanics, LLC, evaluated geomechanical rock properties (Young's modulus, Poisson's ratio). The geomechanical measurements were made using triaxial compression tests. Each of the triaxial compression tests were performed by applying an axial load with a servo-controlled actuator. Confining pressure and pore pressure were hydraulically generated. Axial forces are applied to the 1 inch x 2 inch core samples. Axial stress is monitored with a load cell. Confining pressure and pore pressure were monitored with conventional pressure transducers. Axial and radial strains were measured using strain extensometers.

The cylindrical core samples were cut to a length-to-diameter ratio of two (1" x 2") with an inert fluid and end ground flat and parallel, in accordance to ISRM standards (recommended tolerance in end parallelism is ± 0.001 inches). Each sample was installed between hardened steel end caps and this assembly was sealed with a thin, deformable, heat shrink jacketing material. The jacket prevents confining fluid from penetrating into the sample and allows independent control and monitoring of the confining and pore pressures during testing. The end caps were ported to allow application of pore pressure and/or flow if permeability is measured.

Standardized procedures for conducting the triaxial compression test were followed in making all measurements as follows:

Fill the pressure vessel with hydraulic confining fluid. Raise the confining pressure to a nominal value (100 psi) at a servo-controlled rate (1 psi per second [psi/s]). This initial confining pressure is applied so that there will always be at least a small difference between confining pressure acting outside of the jacket and pore pressure in the rock (inside the jacket). Otherwise leakage will occur.

The axial stress difference is increased at a rate corresponding to an axial strain rate of 10^{-5}/s. Alternatively, rather than controlling the axial strain rate, the axial stress rate can be controlled.

The sample is unloaded slowly, the pressure vessel is emptied and the sample assembly is disassembled.

Triaxial testing is a destructive testing method. Hence, all core samples tested in this manner were destroyed.

By definition, the triaxial measurements are referred to as 'static' moduli. It is also possible to calculate moduli from a sonic log. Values of moduli calculated from the elastic-wave velocity (sonic log) and density are referred to as 'dynamic' moduli.

Young's Modulus and the Poisson's Ratio were calculated from the compressional and shear velocities found with the sonic log, as well as the bulk density found with the density log. The dynamic Young's modulus and the Poisson's Ratio were calculated as follows:

$$\mathrm{E} = \frac{\rho(3\mathrm{V}_\mathrm{P}^2 - 4\mathrm{V}_\mathrm{S}^2)}{(\mathrm{V}_\mathrm{P}/\mathrm{V}_\mathrm{S})^2 - 1}$$

$$\mathrm{v} = \frac{1}{2}\frac{\left(\frac{\mathrm{V}_\mathrm{P}}{\mathrm{V}_\mathrm{S}}\right)^2 - 2}{\left(\frac{\mathrm{V}_\mathrm{P}}{\mathrm{V}_\mathrm{S}}\right)^2 - 1}$$

Since the dynamic Young's modulus, also called the log based Young's Modulus, typically overestimate moduli values, correlations are used to correct the dynamic moduli to a static stress- strain modulus. STIMPLAN software was used for these calculations and to correct the dynamic Young's Modulus to the static Young's modulus.

FORMATION PRESSURE TEST ANALYSIS

Hydrojack and hydrofrac tests were performed on ten intervals in the JTEC borehole. This procedure uses two straddle packers set in an open hole to seal off the test interval. With the packers anchored to the borehole wall, the formation test interval is pressurized hydraulically by pumping at a constant flow rate. The general principle is to affect hydrofracturing with a minute or so from the beginning of interval pressure rise. Packer pressure must be maintained during testing to minimize leakoffs. As the rock hydrofractures, a critical (or breakdown pressure is reached. When pumping is then stopped the pressure will drop to the instantaneous shut in pressure (ISIP). Repeated cycling of the pressurization procedure using the same flow rate will yield the secondary breakdown pressure (the pressure required to reopen a pre-existing fracture) and additional values of the shut in pressure.

These pump-in, pressure tests recorded pressure as a function of increasing injection pressure. The data were analyzed using the commercial hydraulic fracturing software, STIMPLAN, and the well log data for JTEC.

Task 4.b. Determine Porosity, Permeability, Grain Size Distribution, Pore Throat Size and Shape, and Minerals Present in Representative Core Samples at the Four Missouri Power Plant Sites

CAPILLARY PRESSURE ANALYSIS

In this study, the Mercury Injection Capillary Porosimeter (MICP) measurement is used to monitor the volume of Hg that is injected into a dried core sample at each pressure step. The MICP data can be used to determine the pore distribution of the rock. The capillary pressure equations were described in Task 3c. The following method is used to determine the pore distribution:

$$\mathrm{Pc} = \frac{2\sigma\cos\theta}{\mathrm{r}}$$

P_c -- Capillary pressure, psi
σ -- Interfacial tension, dynes/cm
θ-- Contact angle, degrees
r -- Pore radium, µm

The mercury saturation is calculated from:

$$S_{Hg} = \frac{V_m}{VP}$$

S_{Hg} -- Mercury saturation
V_m -- Total injection volume of mercury, cc
V_P -- Pore volume $PV=\pi r^2 L\Phi$, cc

If dV is the volume element of all pores with radii between r and r+dr, then

$$dV = \ D_v(r)dr$$

Where $D_v(r)$ is the volume pore size distribution function defined as the pore volume per unit interval of radius.

Assuming constancy of σ and θ , gives

$$Pr = const$$

$$Pdr + rdP = 0$$

Then

$$-dV = D_v(r)\frac{r}{P}dP$$

Since the change in volume is measured as a decreasing volume, the negative sign can be eliminated to give

$$D_v(r) = \frac{P}{r}\frac{dV}{dP}$$

The curve $D_v(r)$ vs. D represents the pore size distribution curve which gives the pore volume per unit radius interval.

This method has been applied to the selected samples evaluated in the study.

SCANNING ELECTRON MICROSCOPY – ENERGY DISPERSIVE SPECTROSCOPY (SEM-EDS) ANALYSIS

Scanning electron microscopy (SEM) analysis was carried out on both pre-and post-reacted samples from the high pressure and temperature CO_2 + H_2O tests with the JTEC, THEC, and SPP site samples. Samples were examined first by optical microscopy to identify areas of interest for further analysis. Samples were sputter-coated with a thin film of gold-palladium prior to analysis to ensure electrical conductivity. This procedure will result in electron dispersive spectroscopy (EDS) background counts for these elements. A Helios Nanolab 600 SEM was used at 15.0 kV and 0.17 nA of current. The EDS analyses were quantitatively calibrated during the initial installation of the instrument, but not prior to each instrumentation session. The analytical results obtained by the EDS analysis are thus only semi-quantitative in nature.

C. RESULTS AND DISCUSSIONS

1. JOHN TWITTY ENERGY CENTER

Task 4.a. Determine the Permeability of Core Samples from the Confining Layer and Target Formation at the Four Missouri Power Plant Sites

Task 4.b. Determine Porosity, Permeability, Grain Size Distribution, Pore Throat Size and Shape, and Minerals Present in Representative Core Samples at the Four Missouri Power Plant Sites

POROSITY AND PERMEABILITY

Table 5.4 summarizes the porosity and permeability values obtained for the Davis Formation and Bonneterre Formation, to the top of the Reagan Sandstone (1,460.8 feet through 1,770.7 feet) for the JTEC borehole. Core Laboratory (an external vendor) measurements are included in the table for comparison. Figures 5.13 and 5.14 present this data graphically.

TABLE 5.4. DAVIS FORMATION CONFINING LAYER POROSITY AND PERMEABILITY, MISSOURI S&T AND CORE LAB RESULTS COMPARISON

Missouri S&T Results				Core Lab Results		
Depth	**Porosity (%)**	**Permeability (md)**	**Grain Density (g/cc)**	**Porosity (%)**	**Permeability (md)**	**Grain Density (g/cc)**
1460.8	1.08	0.005	2.824			
1480.6	1.35	0	2.777			
1487.2	0.90	0	2.763			
1501.9	5.83	0.156	2.834			
1528.2	9.65	0.185	2.838			
1532.0	0.46	0	2.774			
1536.6	1.81	0	2.778	3.17	0.001	2.81
1558.9	1.52	0	2.755			
1563.6	-	-	-	1.81	0	2.807
1568.4	2.12	0	2.852			
1574.0	1.22	0	2.766			
1578.1	3.36	0	2.795			
1586.1	-	-	-	6.48	0.001	2.785
1593.4	2.92	0	2.697			
1596.4	3.69	0.009	2.753			
1601.0	0.67	0	2.710	1.3	0	2.737

1612.0	0.89	0	2.732			
1615.8	1.25	0	2.681			
1620.1	0.54	0	2.732	0.34	0	2.729
1625.1	1.30	0	2.697			
1634.6	0.65	0	2.747	0.53	0	2.733
1658.6	-	-	-	0.57	0	2.726
1669.3	-	-	-	1.07	0.001	2.725
1684.4	3.26	0	2.772			
1688.4	2.27	0	2.732			
1693.9	3.13	0	2.677	6.91	0.001	2.773
1700.3	2.98	0	2.688			
1703.7	1.76	0	2.790			
1709.1	0.88	0	2.825	1.43	0.001	2.834
1713.7	1.07	0	2.800			
1718.4	1.41	0	2.826			
1724.4	1.45	0	2.792			
1725.9	1.46	0	2.783			
1727.9	0.55	0	2.735			
1731.0	0.81	-	2.796			
1736.7	0.46	0	2.701			
1740.9	0.66	0	2.697			
1746.2	1.14	-	2.719			
1752.1	1.18	0	2.768			
1755.6	1.95	-	2.702			
1758.9	3.46	-	2.732			
1765.1	0.95	0	2.710	2.11	.0001	2.783
1770.7	2.14	-	2.755			

FIGURE 5.13. DAVIS FORMATION AND BONNETERRE FORMATION POROSITY

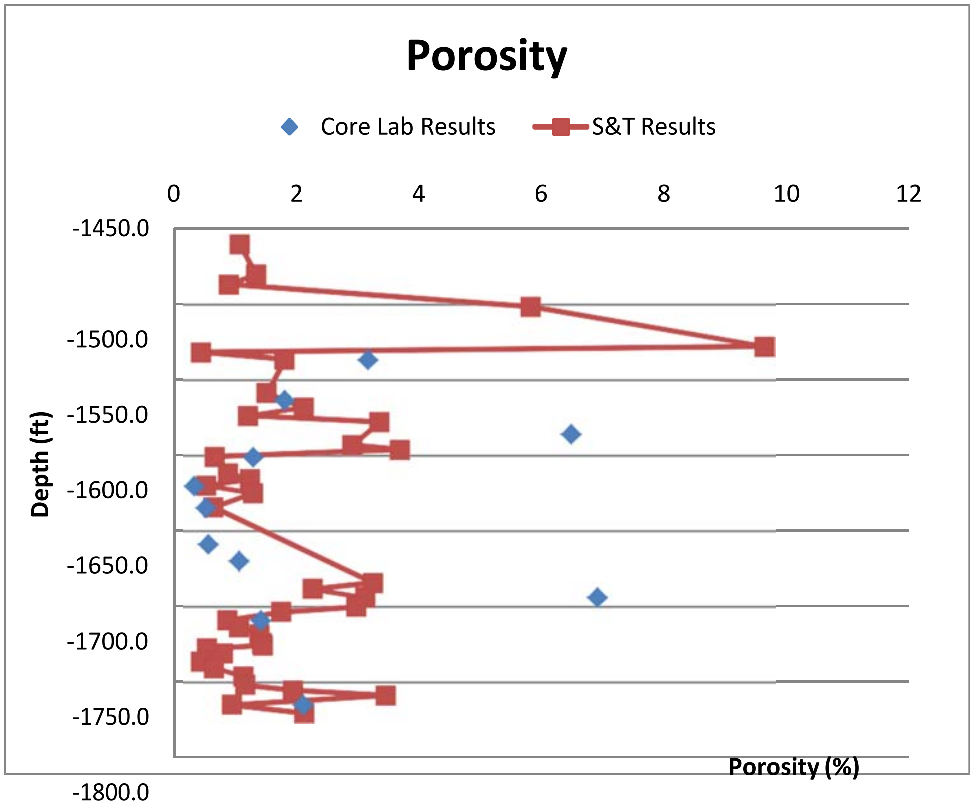
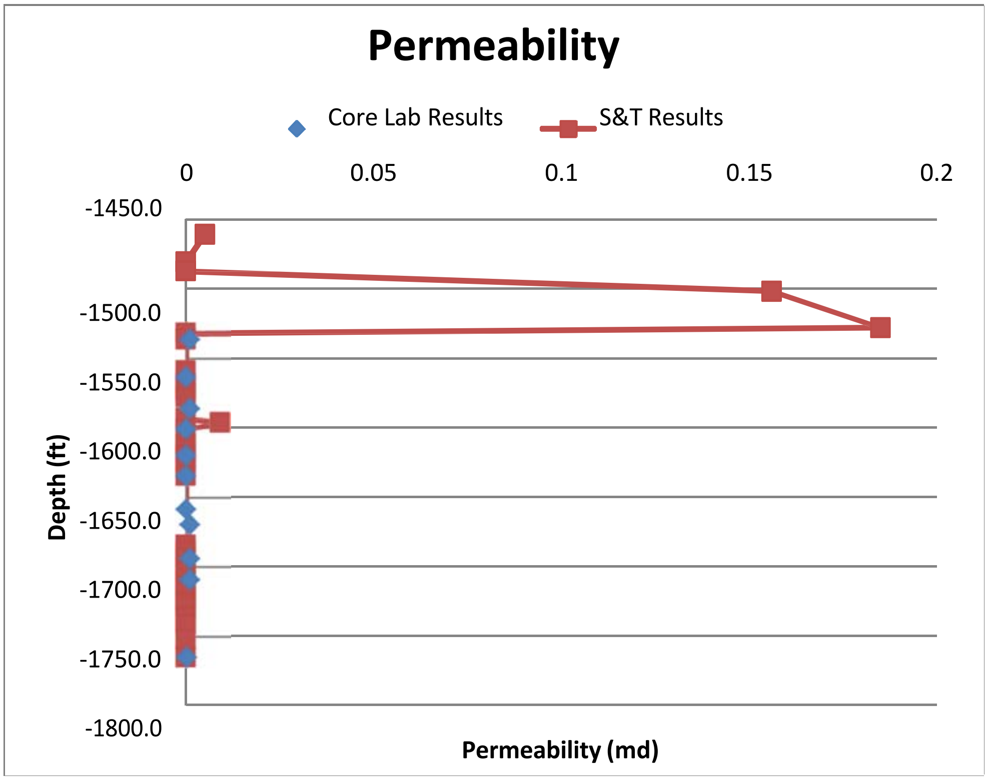


FIGURE5. 14. DAVIS FORMATION AND BONNETERRE FORMATION PERMEABILITY



Missouri S&T measurements of porosity and permeability are generally in agreement with measurements made at Core Laboratories. In the confining layer, maximum porosity is 10%, with an average of 2.1%. The permeability measurements indicate a majority of the zones <0.001 md. The zone of higher porosity (1,502-1,528 feet) also has a corresponding higher permeability (0.15-0.19 md). However, the formation has almost no permeability below 1,528 ft. It should be noted that limits of the permeability measurement are such that the value is an upper bound, and that the permeability may be significantly less than 0.001 md. Fleury, et. al, 2009, indicate that the most important measurement for cap rock sealing is permeability, but indicated permeability values of microdarcy range to nanodarcy are preferred, though impractical to achieve with standard core analytical method. Capillary pressure measurements were not made on the JTEC borehole, but were included in two other boreholes – THEC and SPP sites.

The Reagan Sandstone and Lamotte Sandstone were cored continuously and core samples were taken at 1,775.3 feet through 2,144.6 feet. Two samples were taken from some depths if there appeared to be a variation in the rock. Table 5.5 summarizes the porosity and permeability measurements taken. Figures 5.15, 5.16 and 5.17 provide graphical representation of the data.

TABLE 5.5. REAGAN SANDSTONE AND LAMOTTE SANDSTONE POROSITY AND PERMEABILITY, MISSOURI S&T AND CORE LAB RESULTS COMPARISON

Missouri S&T Results				Core Lab Results		
Depth	**Porosity (%)**	**Permeability (md)**	**Grain Density (g/cc)**	**Porosity (%)**	**Permeability (md)**	**Grain Density (g/cc)**
1775.3	6.06	0.012	2.818			
1778.2	4.81	0.018	2.810			
1783.2	8.68	207.8	2.663	8.71	427	2.677
1783.8	8.08	10.7	2.686			
1784.9	9.87	265.5	2.634	9.87	1029	2.681
1787.1	11.49	67.1	2.702			
1789.9	11.33	146.2	2.672			
1793.6	13.52	712.8	2.609			
1794.6	12.52	557.5	2.626	12.60	1495	2.643
1798.8	5.95	3.96	2.648			
1803.7	7.81	0.161	2.648			
1811.3	9.15	22	2.648	8.73	89.4	2.645
1813.9	4.82	0.008	2.694			
1815.4	-	759	-	11.97	759	2.645
1817.8	16.03	889.2	2.633	16.22	1637	2.642
1819.6A	15.48	572.6	2.563			
1819.6B	16.16	640	2.592			
1823.8	8.97	4.26	2.704			
1829.1	11.91	219.2	2.634			
1833.4	11.03	10.8	2.606	10.77	31.6	2.652
1834.7	10.21	6.64	2.659			
1840.4	8.45	18.3	2.597	8.37	47.1	2.646
1841.5	9.46	40.5	2.652			
1847.9	10.70	43	2.642			
1852.7	13.20	5.71	2.640			
1861.4	10.00	4.11	2.643			

1865.5A	1.55	0.005	2.632			
1865.5B	1.69	0.004	2.691			
1879.4	12.06	-	2.635			
1890.9	0.97	0	2.729			
1892.3	5.05	0.008	2.675			
1907.4	8.93	-	2.755			
1918.5	3.13	-	2.671			
1920.6	1.67	0	2.666			
1936.7	2.10	-	2.642			
1944.6	3.93	0	2.615	6.63	.001	2.735
1951.4	5.02	0	2.615			
1956.8A	10.77	2.1	2.715			
1956.8B	13.09	8.83	2.814			
1967.1	3.88	0.07	2.646			
1972.6	4.43	0.09	2.609	4.44	.044	2.644
1978.3	9.47	-	2.648			
1983.3	8.40	0.18	2.640			
1989.0A	9.11	3.31	2.578			
1989.0B	9.35	2.51	2.498	9.83	4.06	2.648
1995.2	17.94	0.379	2.611			
2001.1	11.06	11.5	2.551	11.40	16.7	2.641
2004.9A	9.80	-	2.602			
2004.9B	12.99	-	2.590			
2010.9	9.06	7.38	2.631			
2013.80	7.89	3.44	2.624			
2020.1	9.50	6.3	2.615			
2027.1A	5.48	-	2.500			
2027.1B	3.52	0.052	2.474			
2033.6	11.25	4.99	2.611			
2040.8	3.76	0.022	2.522			
2047.5	4.54	0.029	2.559			
2052.4	8.61	1.43	2.599	8.35	1.17	2.643
2061.2	8.46	0.118	2.624			
2079.5	8.48	0.174	2.577			
2083.9A	6.90	0.056	2.584			
2083.9B	10.14	0.054	2.367	10.81	.026	2.653
2088.4	1.61	0.014	2.553	4.30	.002	2.661
2094.1A	16.76	0.103	2.578			
2094.1B	12.02	0.067	2.570			
2097.9	9.51	0.024	2.408	9.82	.005	2.649
2103.8	12.54	-	2.572			
2120.4	11.98	1.3	2.605	11.52	.560	2.643
2125.5A	8.34	2.29	2.562			
2125.5B	10.14	4.95	2.603			
2133.1A	8.78	1.14	2.593			
2133.1B	10.36	0.625	2.586			
2137.4	11.23	1.09	2.563	11.56	.821	2.661
2139.9A	11.77	0.867	2.510	11.93	2.50	2.649
2139.9B	11.30	0.808	2.586			
2144.6	10.00	7.24	2.565			

FIGURE 5.15. LAMOTTE SANDSTONE POROSITY

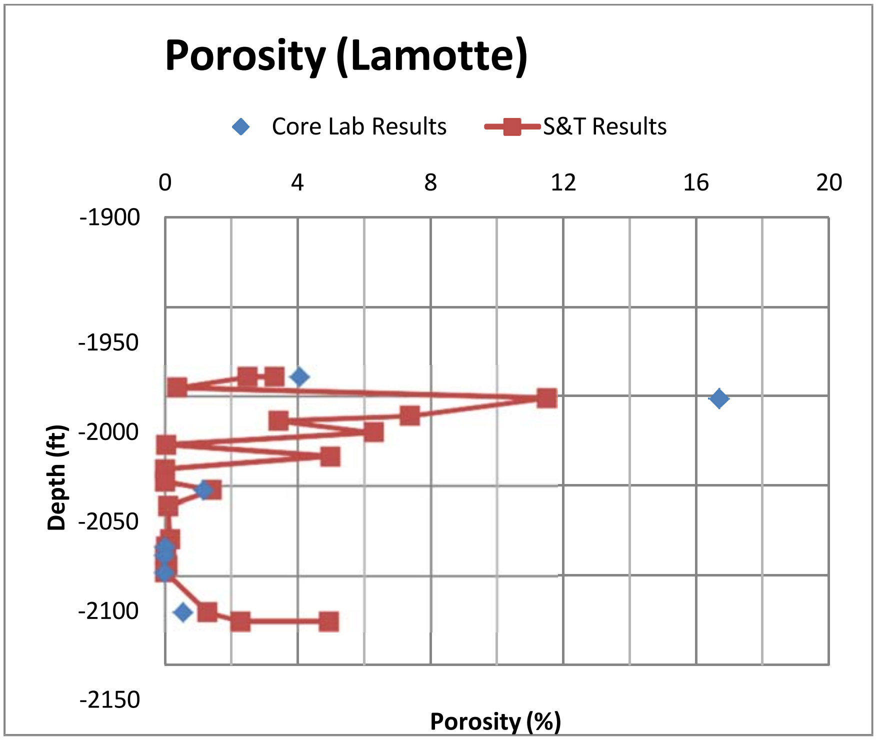


FIGURE 5.16. REAGAN AND LAMOTTE SANDSTONE PERMEABILITY

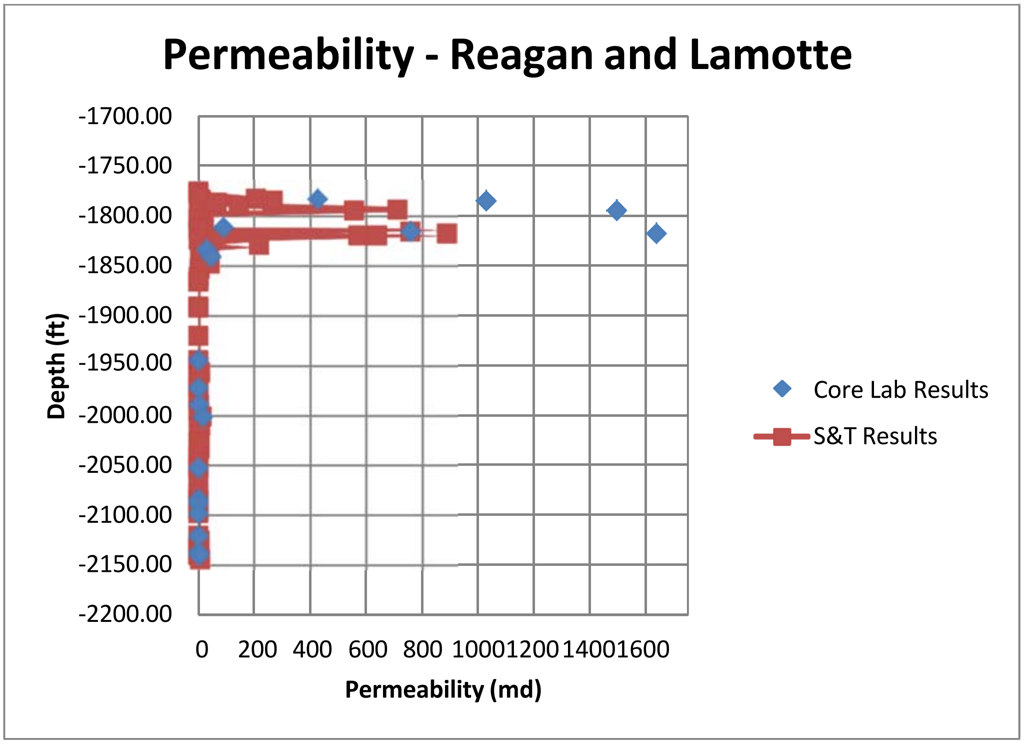
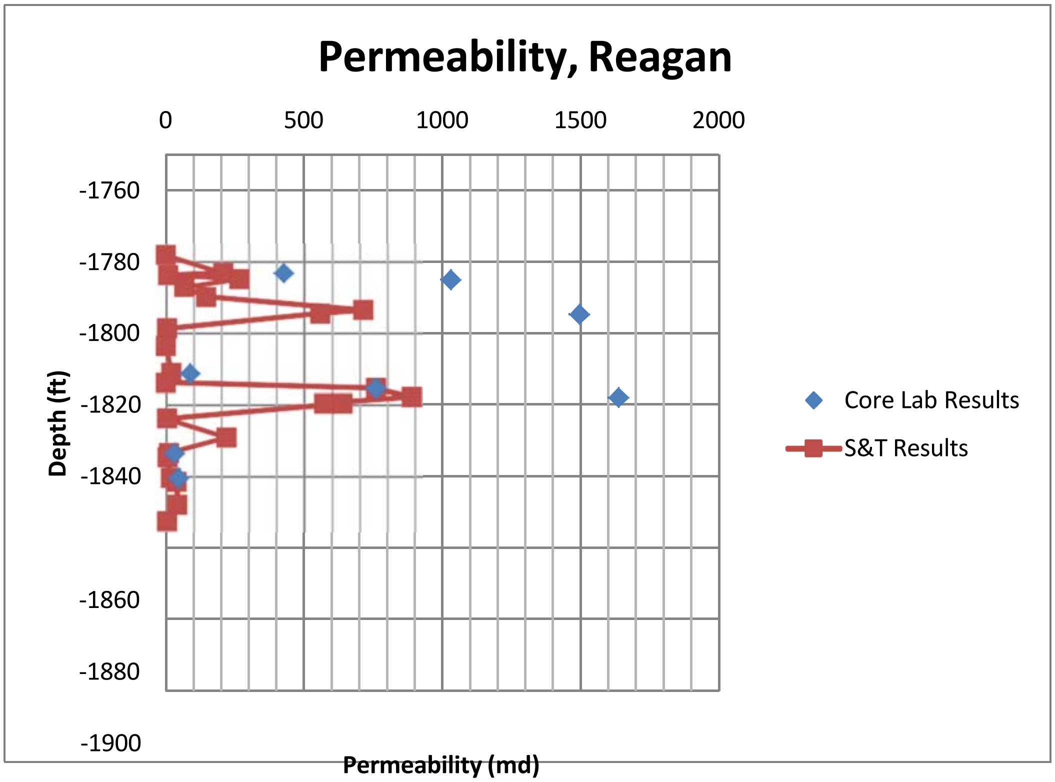


FIGURE 5.17. REAGAN AND LAMOTTE SANDSTONE PERMEABILITY



In the Reagan Sandstone, found from 1,780 feet to 1,850 feet, the average porosity is 10.78% with a range from 6% to 17%. The average porosity in the Lamotte Sandstone, found from 2,000 feet to 2,120 feet is slightly lower, with an average of 8.9%, and a range from 4% to 17%. The permeability results from Core Laboratories were higher on several samples (1-16. Darcy permeability) compared to permeability measured by Missouri S&T. Missouri S&T values (hundreds of md permeability) are in better agreement with values of Reagan Sandstone permeability found in Kansas.

The permeability of the Reagan Sandstone ranged from near 0 md to 900 md. The average permeability over the interval was 236 md. In the Lamotte Sandstone, the permeability was significantly lower. From 2,000 feet to 2,150 feet, permeability from almost 0 md to 11.5 md, and the average permeability over that interval was 2.16 md.

Both the Reagan Sandstone and Lamotte Sandstone exhibit storage capacity for CO_2, although the low permeability of the Lamotte Sandstone at this site suggests low injectivity. No CO_2 was injected into the site due to the freshness of the water in these formations, and hence no exact measurements of CO_2 injectivity were made.

Task 3.c. Determine Permeability of the Confining Layer and Target Formation

BOREHOLE LOG ANALYSIS

Open hole logs were run throughout the entire confining layer and target formation, ranging from approximately 1,460 feet to 2,150 feet. The open hole log suite included a Density Log, Gamma Ray Log, Resistivity Log, Neutron Porosity Log and a Sonic Log. The data from these logs were analyzed to determine shale content of the formations as a percentage of total rock grain volume, and to calculate formation porosity according to the procedure described in Task 3.c of the methodology section.

POROSITY

The porosity measured during the core analysis was compared to the porosity calculated from each of three borehole logs. Tables 5.6 and 5.7 summarize the results.

TABLE 5.6. SUMMARY COMPARISON OF REAGAN POROSITY VALUES FROM WELL LOGGING

Start Depth (ft)	End Dept (ft)	ϕ, from Core Analysis	ϕNLS, from neutron log	ϕ, from bulk density log	ϕs, from sonic log
1780	1785	8.97	8.7	8.582	4.974
1785	1790	11.41	9.5	7.128	4.400
1790	1795	13.14	9.1	4.922	5.832
1795	1800	5.95	7.1	5.013	4.312
1800	1805	7.81	3.7	3.661	1.485
1805	1810	-	4.0	2.667	1.785
1810	1815	7.02	5.1	3.726	3.721
1815	1820	16.05	10.9	7.241	9.026
1820	1825	8.97	9.0	4.277	5.416
1825	1830	11.91	7.0	4.514	4.201
1830	1835	10.62	7.8	4.986	6.408
1835	1840	-	7.0	3.890	4.161

1840	1845	8.95	7.0	4.667	4.959
1845	1850	10.7	6.8	4.972	4.295

TABLE 5.7. SUMMARY COMPARISON OF LAMOTTE POROSITY VALUES FROM WELL LOGGING

Start Depth (ft)	End Depth (ft)	ϕ, from Core Analysis	ϕNLS, from neutron log	ϕ, from bulk density log	ϕs, from sonic log
1995	2000	17.94	7.9	4.927	5.739
2000	2005	11.28	7.0	4.564	4.879
2005	2010	-	5.2	3.975	3.136
2010	2015	8.46	5.8	4.640	3.826
2015	2020	-	5.1	4.094	4.670
2020	2025	9.50	4.5	3.707	2.618
2025	2030	4.50	4.0	3.284	1.922
2030	2035	11.25	7.0	5.602	4.160
2035	2040	-	6.1	4.269	4.444
2040	2045	3.76	5.8	4.366	5.319
2045	2050	4.54	5.5	3.856	3.222
2050	2055	8.61	4.3	3.729	2.222
2055	2060	-	5.8	4.296	4.526
2060	2065	8.46	8.3	4.501	6.418
2065	2070	-	10.9	5.481	8.296
2070	2075	-	8.5	3.804	6.532
2075	2080	8.48	6.8	3.874	4.409
2080	2085	8.52	6.7	4.497	5.713
2085	2090	4.30	7.0	3.739	6.164
2090	2095	14.39	7.0	4.847	5.218
2095	2100	9.51	6.2	4.218	6.001
2100	2105	12.54	9.0	5.302	7.269
2105	2110	-	8.8	5.334	6.798
2110	2115	-	5.6	4.189	3.727
2115	2120	11.98	5.5	3.681	4.402

Tables 5.6 and 5.7 compare porosity from laboratory measurement against and the estimated porosity from borehole log analysis. As shown, the lab measured porosity is slightly higher than the borehole log estimated porosity. While the average Reagan Sandstone porosity found in the lab was around 10%, the average porosity from the borehole log analysis was 6%. The average lab measured porosity for the Lamotte Sandstone was around 9%, while the average porosity from the borehole log analysis was 5%. This difference is to be expected, since the measurement techniques are different. In general, core measurements are considered to be more accurate than borehole logging measurements, because borehole logs average readings over a specific interval.

Task 3.d. Determine the injection rate profile for the target formation.

GEOMECHANICS AND ROCK PROPERTIES

A laboratory investigation was conducted to evaluate the geomechanical rock properties of the core samples from the JTEC borehole. Young's modulus (E) and Poisson's ratio (v) were measured for the samples according to the procedure described in Task 4.a. of the methodology. Table 5.8 summarizes the measured values.

TABLE 5.8. SUMMARY OF TRIAXIAL COMPRESSION TESTS FOR THE JTEC BOREHOLE

Sample Depth	Young's Modulus (10^6 psi)	Poisson's Ratio
1460.8	14.890	0.198
1480.6	11.580	0.164
1487.2	11.438	0.215
1501.9	3.722	0.106
1502.1	18.010	0.149
1510.8	6.778	0.094
1515.8	10.048	0.110
1528.2	9.336	0.174
1532.0	8.091	0.077
1536.6	10.705	0.176
1546.1	6.971	0.062
1549.6	11.459	0.170
1555.7	9.064	0.112
1558.9	16.144	0.091
1563.6	10.905	0.155
1568.4	9.600	0.107
1574.0	9.793	0.159
1578.1	8.079	0.133
1586.1	5.554	0.137
1593.4	6.426	0.151
1596.4	9.097	0.108
1601.0	8.366	0.136
1601.0	8.366	0.138
1612.0	10.176	0.200
1615.8	7.509	0.149

Sample Depth	Young's Modulus (10^6 psi)	Poisson's Ratio
1620.1	11.500	0.175
1625.1	6.415	0.151
1634.6	11.193	0.193
1658.6	17.227	0.292
1669.8	10.960	0.217
1684.4	12.928	0.083
1688.4	11.445	0.223
1693.9	3.722	0.106
1700.3	9.795	0.193
1703.7	12.995	0.177
1709.1	12.691	0.186
1713.7	15.397	0.250
1718.4	18.675	0.278
1724.4	3.414	0.059
1725.9	21.774	0.323
1727.9	8.865	0.195
1731.0	11.879	0.156
1740.9	7.756	0.161
1746.2	5.002	0.109
1752.1	5.662	0.127
1755.6	4.023	0.135
1765.1	7.744	0.137
1775.3	13.406	0.166
1778.2	13.598	0.196
1783.2	6.748	0.090
1783.8	6.407	0.081
1784.9	11.789	0.133
1787.1	5.750	0.086
1789.9	7.619	0.100
1793.6	6.077	0.073
1794.5	5.274	0.075
1798.8	6.008	0.070
1811.3	5.335	0.089
1813.9	9.100	0.099
1815.4	4.424	0.111
1817.8	4.860	0.080
1833.4	5.204	0.059
1834.7	6.819	0.090
1840.4	5.582	0.082
1841.5	5.786	0.087
1847.9	5.441	0.092

Sample Depth	Young's Modulus (10^6 psi)	Poisson's Ratio
1852.7	4.689	0.112
1861.4	4.816	0.115
1879.4	5.363	0.149
1890.9	6.714	0.141
1907.4	2.996	0.130
1918.5	6.053	0.146
1920.6	8.622	0.177
1936.7	7.936	0.244
1944.6	5.856	0.107
1951.4	6.299	0.153
1967.1	5.590	0.070
1972.6	5.149	0.082
1978.3	6.125	0.107
1983.3	3.535	0.083
1989.0	4.672	0.099
1995.2	5.389	0.093
2001.1	4.677	0.053
2010.9	5.669	0.105
2013.8	4.445	0.057
2020.1	3.853	0.082
2033.6	5.051	0.113
2040.8	3.830	0.083
2047.4	5.357	0.082
2052.4	5.384	0.115
2088.4	3.346	0.082
2103.8	4.140	0.091
2120.4	3.505	0.091
2125.5	5.831	0.176
2137.4	5.036	0.125

Initial results of the tests indicate the average Young's modulus for the six tests in the Potosi Formation was 9.95 x 10^6 psi. The average Young's modulus for the thirteen Davis Formation tests was 10.33 x 10^6 psi. Similarly, the average Young's modulus for the five Bonneterre Formation samples was 14.39 x 10^6 psi. All of these measurements indicate a brittle, or tough rock, meaning the rock will fail under an applied stress without significant strain deformation.

By definition, the triaxial measurements are referred to as 'static' moduli. It also is possible to calculate moduli from a Sonic Log. Values of moduli calculated from the elastic-wave velocity (Sonic Log) and density are referred to as 'dynamic' moduli.

Young’s modulus and the Poisson’s ratio were calculated from the compressional and shear velocities found with the Sonic Log, as well as the bulk density found with the Density Log. The dynamic Young’s modulus and the Poisson’s ratio were calculated with the equations below.

$$E = \frac{\rho\,(3V_P{}^2 - 4V_S{}^2)}{(V_P / V_S)^2 - 1}, \quad \nu = \frac{1}{2}\,\frac{\left(\frac{V_P}{V_S}\right)^2 - 2}{\left(\frac{V_P}{V_S}\right)^2 - 1}$$

Since the dynamic Young’s modulus, also called the log based Young’s modulus, typically overestimates moduli values, correlations are used to correct the dynamic moduli to a static stress-strain modulus. STIMPLAN software was used for these calculations and to correct the dynamic Young’s modulus to the static Young’s modulus. These results are shown in Figure 5.18.

Figure 5.19 compares the static moduli from tri-axial testing to the static modulus corrected from the Sonic Log using STIMPLAN. There is relatively good agreement in the values with the exception of approximately 1,620 to 1,700 feet. It is not clear why the values do not match over this interval.

Figure 5.20 provides a comparison of the triaxial Poisson’s ratio to the static log derived Poisson’s ratio. In this figure, there are similar trends, but the log derived values are still characteristically high.

FIGURE 5.18. LOG DERIVED STATIC MODULI AND POISSON'S RATIO

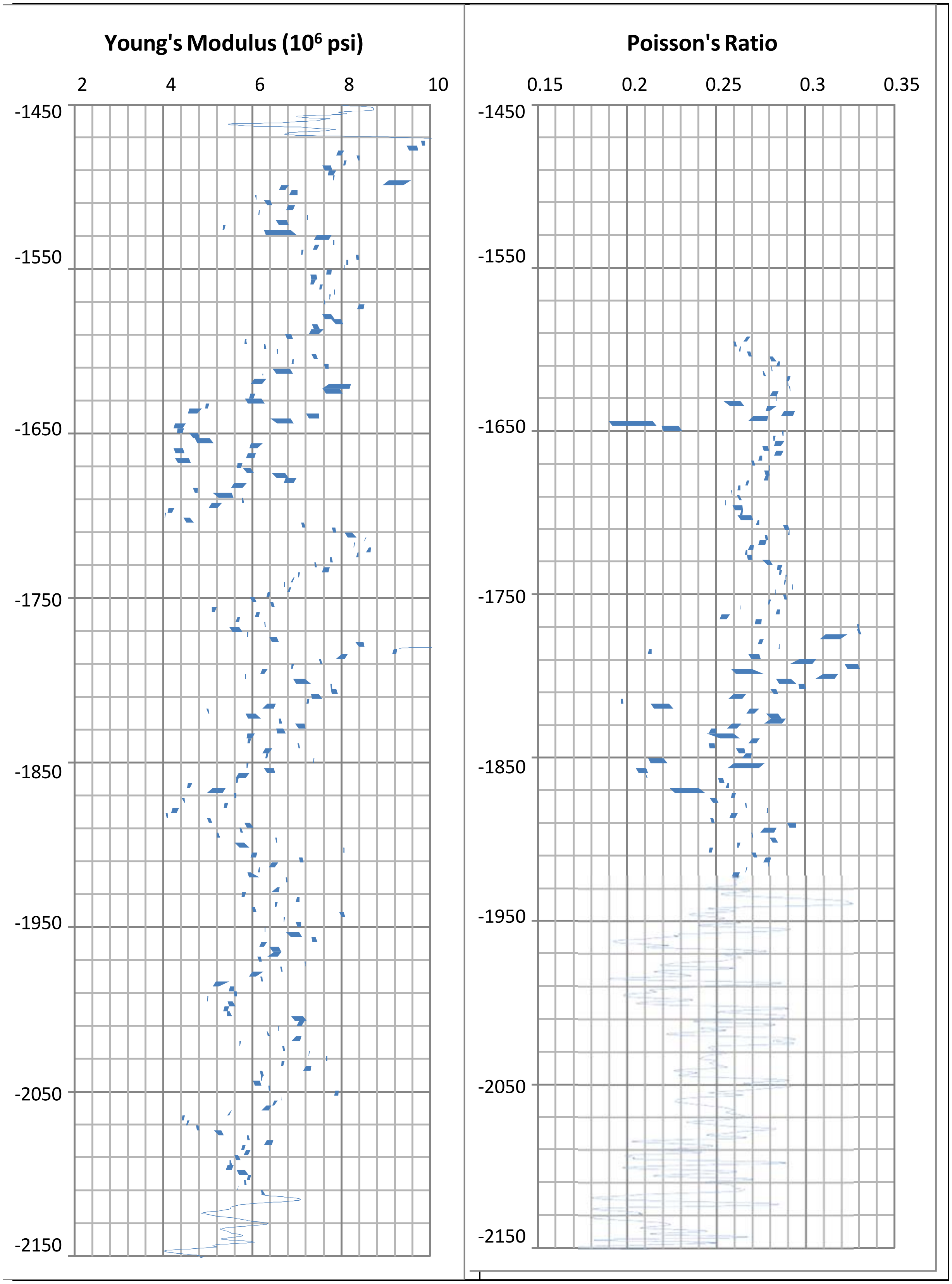


FIGURE 5.19. COMPARISON OF TRIAXIAL STATIC MODULI WITH STATIC LOG-DERIVED MODULI

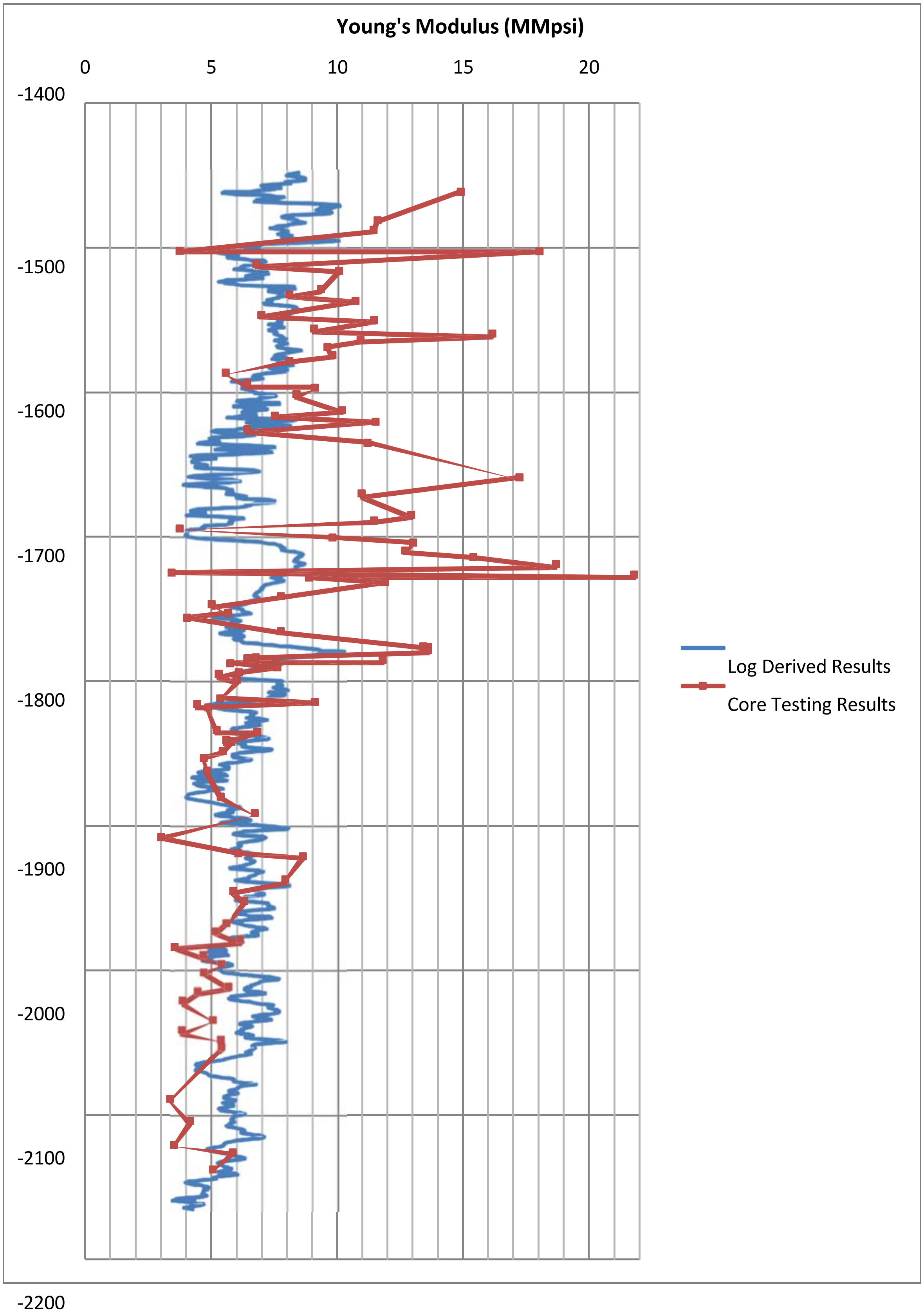
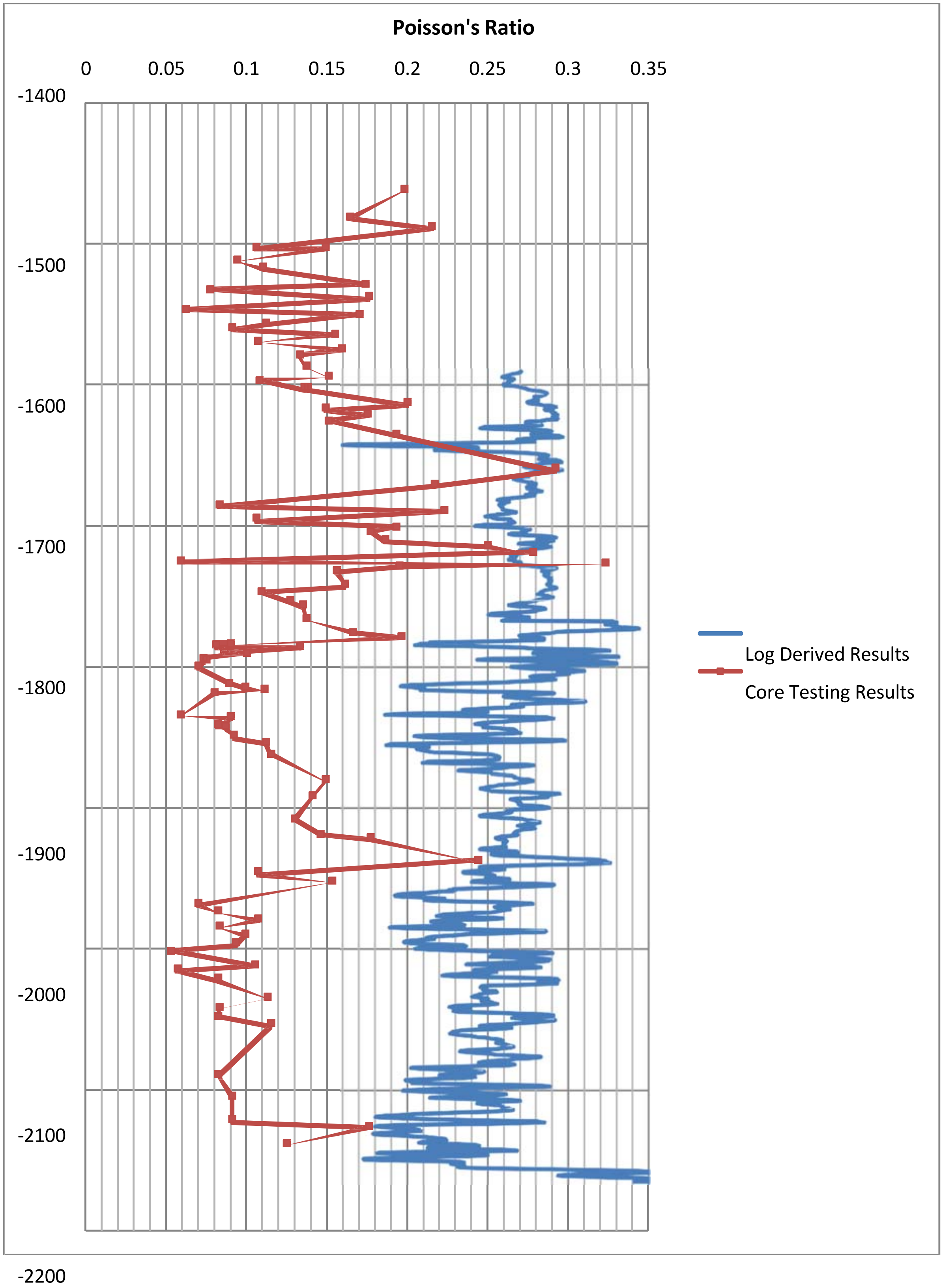


FIGURE 5.20. COMPARISON OF TRIAXIAL POISSON'S RATIO WITH LOG-DERIVED POISSON'S RATIO



Task 3.c. Determine Permeability of the Confining Layer and Target Formation

FORMATION PRESSURE TEST ANALYSIS

Geomechanical testing shows that the formations studied all exhibit high moduli, indicating that the formations are relatively tough. Other geomechanical parameters of interest are the formation breakdown pressure, and the minimum in situ stress. Formation breakdown pressure provides an indication of the maximum allowable injection pressure without breaking down the formation, assuming no adjustments for injection fluid cooling. The minimum in situ stress is an important parameter in hydraulic fracturing design, as in situ stresses control fracture azimuth and orientation (vertical and horizontal), fracture height growth, fracture width, treatment pressures and fracture conductivity. Induced fractures propagate perpendicular to the minimum in situ stress. Minimum in situ stress is also synonymous with closure stress.

Ten intervals within the Lamotte Sandstone were selected for pressure breakdown testing. The general principle is to affect hydrofracturing within a minute or so from the beginning of interval pressure rise. As the rock hydrofractures, a critical (or breakdown) pressure is reached.

When pumping is then stopped the pressure will drop to the instantaneous shut in pressure (ISIP). Repeated cycling of the pressurization procedure using the same flow rate will yield the secondary breakdown pressure (the pressure required to reopen a pre-existing fracture) and additional values of the shut-in pressure.

These ten zones were tested according to ASTM D4645 standards, as described in Task 4.a of the methodology section. Results of these analyses were detailed in the final report for the JTEC well (JTEC, 2012) and a summary is presented here. Representative graphs and their interpretation are included for one interval (Interval 3, Lamotte, 2,022 feet – 2,026.3 feet).

INTERVAL 3 LAMOTTE SANDSTONE, 2,022 – 2,026.3 FEET

The hydrofracture and hydrojack tests carried out for interval 3 are as shown in Figures 5.21 and Figure 5.21 indicates an initial surface breakdown pressure.

As can be seen in Figure 5.22, the maximum surface pressure reached with every cycle decreased with each successive reopening and draining cycle. Generally, multiple tests tend to reduce any influence of wellbore and rock strength because the fracture is no longer being extended, but only reopened. And the test is repeated to several times so that a value is reproduced. For interval 3, the formation breakdown pressure has been determined to be approximately 1,443 psi. This would mean that bottom hole injection pressure should be less than this value throughout injection into the zone.

A square root time analysis for interval 3 is shown in Figure 5.23. Closure pressure for interval 3 is calculated to be 159.76 psi. In this interpretation, there is a clear distinction of trend at a value above 159.76 psi. So, for pressure values below 159.76 psi, it can be concluded that there is no possibility of an induced hydraulic fracture being open.

FIGURE 5.21. HYDROFRACTURE PRESSURE TEST RECORD FOR LAMOTTE INTERVAL 3 (2,022FT – 2,026.3FT)

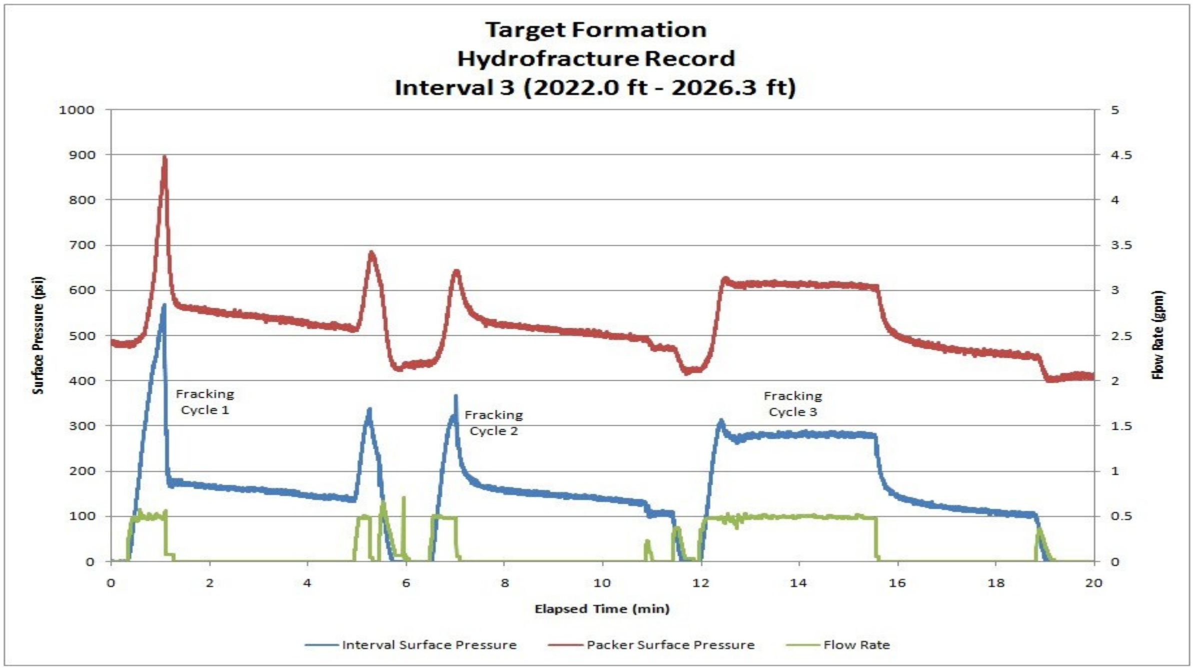


FIGURE 5.22. HYDROJACK PRESSURE TEST RECORD FOR LAMOTTE INTERVAL 3 (2,022 FEET – 2,026.3 FEET)

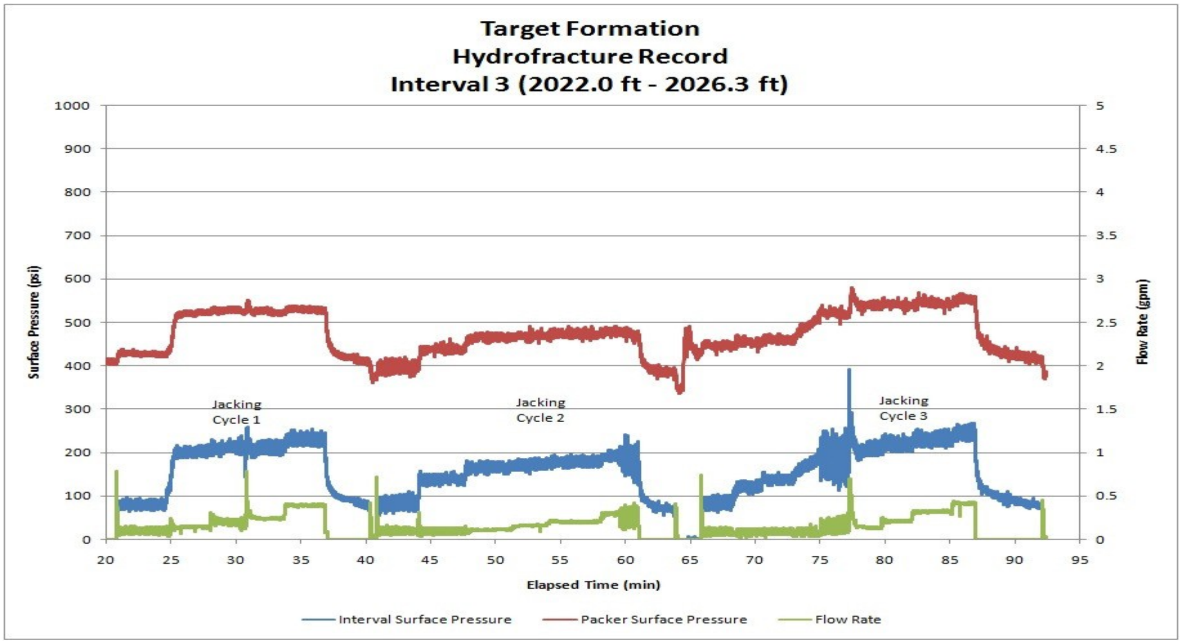


FIGURE 5.23. SQUARE ROOT TIME PLOT FOR LAMOTTE INTERVAL 3 (2,022 FEET – 2,026.3 FEET)

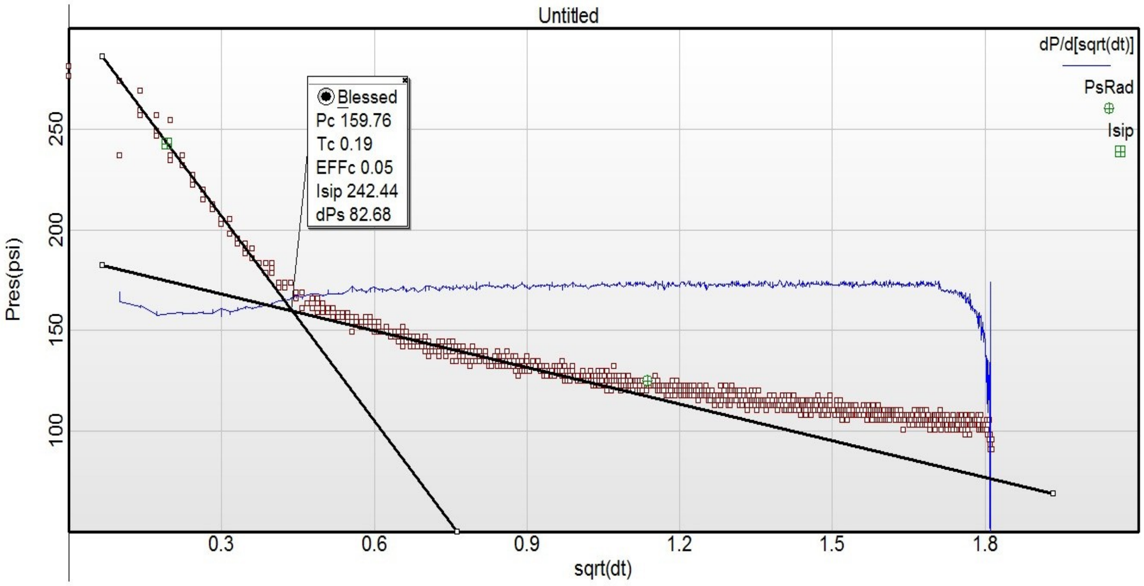


Table 5.9 summarizes the formation breakdown pressure, closure stress and fracture extension pressure found for the 10 intervals tested. Fracture pressure for the Bonneterre is higher, which is expected in a more brittle formation. The fracture gradient varies from 0.71 psi/feet (1,443psi/2,024 feet) to 1.35 psi (2,558 psi/1,882 feet).

TABLE 5.9. SUMMARY OF FORMATION PRESSURE TEST RESULTS & YOUNG'S MODULUS FOR THE JTEC SITE

Interval	Depth (ft)	Formation Breakdown Pressure (psi)	Closure Stress (psi)	Extension Pressure (psi)	Young's Modulus 10^6 psi	Formation
1	2102.0 - 2106.2	1760	1173	1330	4.140	Lamotte
9	2084.3 - 2088.6	1980	1348	1536	3.346	Lamotte
2	2065.3 - 2069.6	1520	1154	1191	~4.8	Lamotte
3	2022.0 - 2026.3	1443	1047	1096	~4.2	Lamotte
10	2013.0 - 2017.3	2553	1157	1880	4.445	Lamotte
4	1995.3 - 1999.6	1713	1064	1068	5.389	Bonneterre DL
5	1942.3 - 1946.6	2300	1571	1662	5.856	Bonneterre DL
6	1880.3 - 1884.6	2558	1647	1696	5.363	Bonneterre DL
7	1864.7 - 1869.0	2416	1718	1970	~5.0	Bonneterre DL
8	1795.0 - 1799.3	Na	1046	1949	6.008	Reagan SS

Task 3.c. Determine Permeability of the Confining Layer and Target Formation

RELATIVE PERMEABILITY

The relative permeability of CO_2 and brine is an important parameter in the simulation. Small change in parameters that characterize relative permeability could lead to a considerable change (up to 20%) in flow rate (Burton et al., 2008).

In this study, the relative permeability curve was generated using the Mohamad Ibrahim/Koederitz method for a water-wet sandstone formation (Koederitz and Ibrahim, 2002). The Mohamad Ibrahim/Koederitz method was chosen because it is reliable and suitable to the Lamotte Sandstone. This method has advantage over the commonly used Corey function because it provides better estimation in the way that it uses an empirical relative permeability correlation based on 416 sets of lab data obtained from published literature and industry sources all over the world.

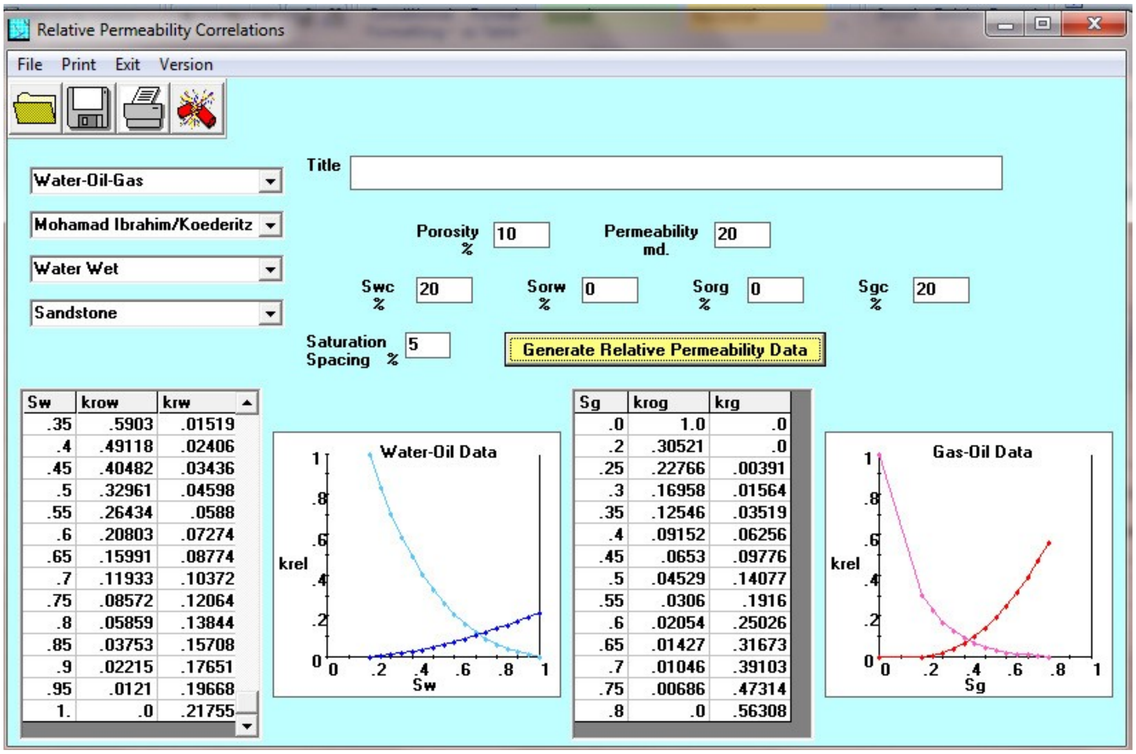
Bennion and Bachu (2005 and 2008) characterized the displacement of CO_2-brine system with laboratory measurements at in-situ pressure and temperature condition on rock samples from the Wabamun Lake area in Alberta, Canada. The results include detailed CO_2-brine relative permeability data for four sandstones with formation top depths ranging from 1,240-2,734 m.

However, the sample and test conditions do not match the current study formation; therefore, it is not feasible to use their results because the relative permeability of CO_2-brine system depends on the in-situ conditions of pressure, temperature, water salinity, and the pore size distribution of the rock (Bachu and Bennion, 2008).

When generating the relative permeability curve for the Lamotte Sandstone model, the residual gas saturation was fixed at 20%, and then the relative permeability of CO_2 and brine can be characterized by the irreducible water saturation. The irreducible water saturation for a strong water-wet medium is usually greater than 20%, whereas that of an oil-wet medium is generally less than 15% (Craig, 1971). Since the study formation is water wet, a base value of the irreducible water saturation was set at 20%. Figure 5.24 shows the relative permeability curve and data with a formation porosity of 10% and permeability of 20 md.

Three phase relative permeability curves were also generated for the reservoir simulation. The Computer Modeling Group (CMG) simulation software requires inputting three phase relative permeability curves because for conventional oil reservoirs the gas phase will condense due to pressure reduction, generating an oil phase and leading to a three phase system. In the Lamotte Sandstone, only water and gas are present, so the liquid-gas relative permeability are used, and the water-oil relative permeability is simply an extra input.

FIGURE 5.24. LAMOTTE RELATIVE PERMEABILITY GENERATED USING THE MOHAMAD IBRAHIM/KOEDERITZ METHOD



Water-Oil-Gas
Mohamad Ibrahim/Koederitz
Water Wet
Sandstone

Title
Porosity % 10
Permeability md. 20
Swc % 20
Sorw % 0
Sorg % 0
Sgc % 20
Saturation Spacing % 5

Sw	krow	krw
.35	.5903	.01519
.4	.49118	.02406
.45	.40482	.03436
.5	.32961	.04598
.55	.26434	.0588
.6	.20803	.07274
.65	.15991	.08774
.7	.11933	.10372
.75	.08572	.12064
.8	.05859	.13844
.85	.03753	.15708
.9	.02215	.17651
.95	.0121	.19668
1.	.0	.21755

Sg	krog	krg
.0	1.0	.0
.2	.30521	.0
.25	.22766	.00391
.3	.16958	.01564
.35	.12546	.03519
.4	.09152	.06256
.45	.0653	.09776
.5	.04529	.14077
.55	.0306	.1916
.6	.02054	.25026
.65	.01427	.31673
.7	.01046	.39103
.75	.00686	.47314
.8	.0	.56308

Task 3.d. Determine the Injection Rate for the Target Formation

RESERVOIR MODELING AND INJECTION SIMULATIONS

CMG-GEM 2010.10 software (Computer Modeling Group- General Equation of State Model) was used to model CO_2 sequestration in saline aquifers, and specifically the Lamotte Sandstone. Two baseline models have been created: 1) general models representing deep and shallow aquifers using publication data, and 2) Lamotte Sandstone model based on data from known formation properties and properties identified in the JTEC borehole. Three aspects of CO_2 storage potential in the Lamotte Sandstone have been addressed: 1) the effect of reservoir properties and injection rate on CO_2 storage and injectivity, 2) the effect of completion techniques and reservoir heterogeneity on CO_2 storage and injectivity, and 3) water withdrawal and influencing factors.

LAMOTTE MODEL

With data available from Exploratory Borehole #1 at the JTEC site, in Springfield, Missouri, a Lamotte Sandstone model was built using data listed in Table 5.10. The aquifer is homogenous, 595 m (1,952 ft) deep and 57 m (187 ft) thick with medium-low porosity (10%) and permeability (20 md). The formation pressure is 4,998 kPa and the temperature is 21.85°C. All the other parameters are the same as the previous cases. The basic aqueous and mineral reactions were included in the models to better mimic the study formation. The effect of geochemical reactions will not be discussed in the results because geochemical reactions has very little effect on CO_2 storage during the injection period because they take effect on a very long period measured in centuries to millennia (Bachu et al, 2007). For borehole constraints, the CO_2 injector is operated under a maximum bottom hole pressure of 8,238 kPa. This value is determined by the product of reservoir depth and maximum bottom hole pressure gradient, which is set to be the average common sedimentary basin fracture pressure gradient 0.71-0.82 psi/feet multiplied by a safety factor of 0.8 (Ecomomides, 2000).

TABLE 5.10. BASE MODEL INPUT DATA

Reservoir Property	Value	Reference & Remarks
Formation Top	595 m 1,952 ft	Explore borehole log file
Formation Thickness	57 m 187 ft	Explore borehole log file
Porosity	10 %	Explore borehole log file
Permeability	20 md	Lab data
Rock compressibility	1E-9 1/kPa	Appold and Garven,2000
Reference pressure	4998 kPa	Explore borehole log file
Reference temperature	21.85°C at 595 m 1,952 ft 22.39°C at 652 m 2,139 ft	Explore borehole log file
Sea level	376.83 m 1,236.31 ft	Explore borehole log file
Maximum residual gas saturation	0.4	Model hysteresis effect in gas relative permeability
Maximum BHP	8238 kPa	Assuming 13.845kPa/m (0.612 psi/ft)

The relative permeability of CO_2 and brine is an important parameter to consider in this simulation. Small changes in parameters that characterize relative permeability could lead to a considerable change (up to 20%) in flow rate (Burton et al., 2008). Bennion and Bachu (2005 and 2008) characterized the displacement of CO_2-brine system with laboratory measurements at in situ pressure and temperature condition on rock samples from the Wabamun Lake area in Alberta, Canada. The results include detailed CO_2-brine relative permeability data for four sandstones with formation top depths ranging from 1,240-2,734 m (4,068 – 8970 feet). However, the sample and test conditions do not match our study formation; we cannot simply use one of their data sets because the relative permeability of CO_2-brine system depends on the in situ conditions of pressure, temperature, water salinity, and the pore size distribution of the rock (Bachu and Bennion, 2008). In this study, the relative permeability curve was generated using the Mohamad Ibrahim/Koederitz method for a water-wet sandstone formation (Koederitz and Ibrahim, 2002).

The Mohamad Ibrahim/Koederitz method was chosen over the commonly used Corey function because it provides better estimation in the way that it uses an empirical relative permeability correlation based on 416 sets of lab data obtained from published literature and industry sources all over the world. In addition, the residual gas saturation was fixed at 20%, so the relative permeability of CO_2 and brine can be characterized by the irreducible water saturation. The irreducible water saturation for a strong water-wet medium is usually greater than 20%, whereas that of an oil-wet medium is generally less than 15% (Craig, 1971). Since the study formation is water wet, a base value of the irreducible water saturation was set at 20%.

Task 3.d. Determine the Injection Rate Profile for the Target Formation

EFFECT OF INJECTION RATE

The effect of injection rate on CO_2 storage capacity was studied using a Lamotte Sandstone model. The injection rates studied were set at 15,000, 10,000, and 5,000 m3/day. Figures 5.25 and 5.26 show the effect of injection rate on CO_2 storage potential.

FIGURE 5.25. INJECTION RATES VS. TIME AT DIFFERENT MAXIMUM INJECTION RATES

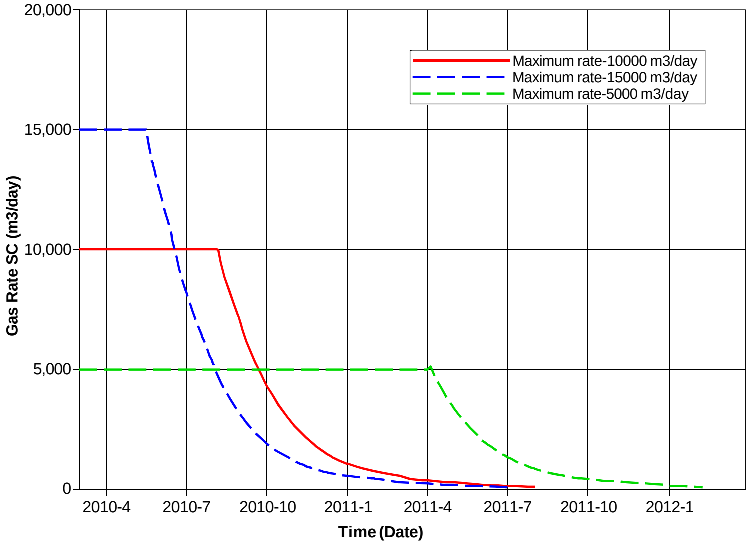
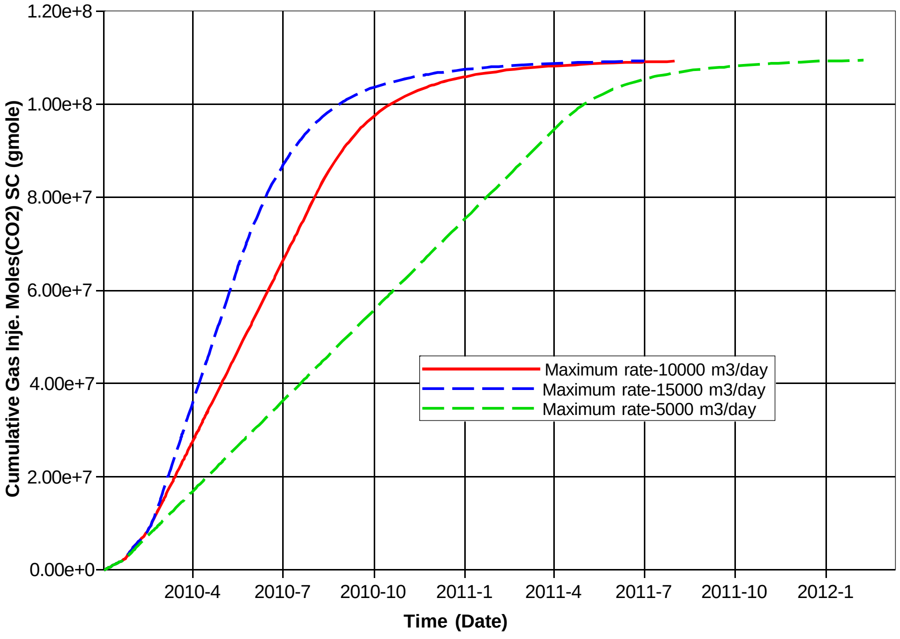


FIGURE 5.26. TOTAL CO_2 INJECTED AT DIFFERENT MAXIMUM INJECTION RATES



As shown in Figures 5.25 and 5.26, CO_2 storage capacity was almost the same for all three cases, but the case with highest injection rate reached the capacity within the shortest time, thus it had the highest injection efficiency. For a given formation, a relatively high injection rate within the formation limits would benefit the injection process.

For all simulation cases, injection rate declines with time as reservoir pressure builds within the closed boundary injection volume. For this reason, it is very important to have an understanding of the regional characteristics of the formation, and any fluid movement. In the simulation work, it was decided to also investigate the effect of water withdrawal.

WATER WITHDRAWAL AND INFLUENCING FACTORS

Shallow sequestration is more effective when water is withdrawn from the storage formation. Water withdrawal can increase storage capacity, reduce formation pressure, and control free- phase CO_2 movement (McNemar, 2009; Court et al., 2011). The extracted water can be re- injected as a Water Alternating Gas (WAG) process, treated for beneficial use, or reused depending on the initial water quality, regional water needs, and treatment costs. Many researchers have pointed out a potential link between electric power production, water supply, and carbon sequestration. The latter can increase water usage; for example, a coal-fired power plant utilizing carbon sequestration would require twice as much cooling water as the original plant. Extracting water from the storage formation and treating it for beneficial use provides a means to offset increased power plant water demands associated with carbon capture and sequestration (Leonenko and Keith, 2008; Hassanzadeh et al., 2009; Newmark et al., 2010; Kobos et al., 2010; Buscheck et al., 2010; Court et al., 2011; Macknick et al., 2011). The Water Energy and Carbon Sequestration (WECS) model was developed to integrate the full data set of U.S. power plants, geological saline formations, carbon capture and sequestration scenarios, and saline formation water extraction and treatment technologies. The WECS study found that up to 20% of all the existing complete saline formation well data points meet the criteria for combined CO_2 storage and extracted water treatment systems, which shows the potential and feasibility of water withdrawal (Kobos et al., 2010).

Water withdrawal was included in the Lamotte Sandstone model to slow the pressure buildup and allow more CO_2 to be stored. The simulation work starts with determining a reasonable reservoir size, well pattern, and injection rate for various models. Cases without water withdrawal were compared to cases with water withdrawal, for which two typical well patterns—5 spot and inverted 9 spot—were addressed. Once the reservoir size and well pattern were selected, an optimal injection rate could be determined by varying the injection rate within the reasonable range for that certain case.

EFFECT OF RESERVOIR SIZE AND WELL PATTERN

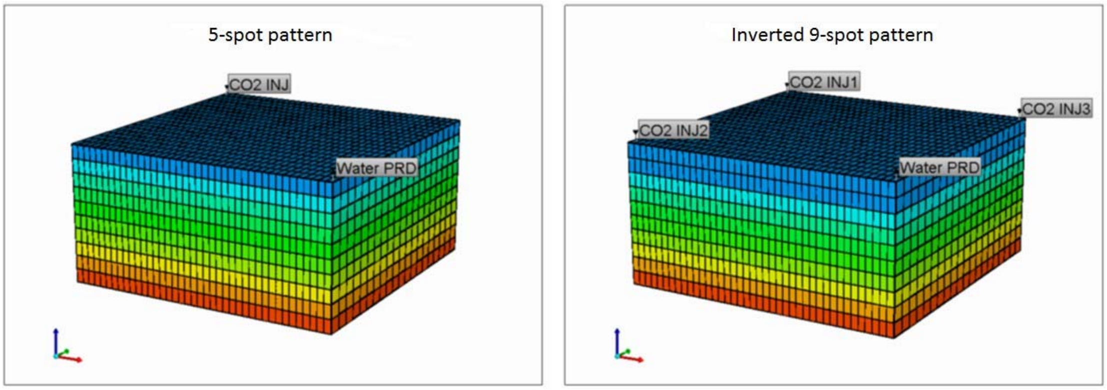
This section addresses the following cases:

1. Reservoir length varied from 400 m to 2,000 m with no water withdrawal
2. Reservoir length varied from 400 m to 2,000 m with 5-spot water withdrawal
3. Reservoir length varied from 400 m to 2,000 m with inverted 9-spot water withdrawal

To select a proper reservoir size for simulation, this work built cases with a reservoir length (set equal to width) varying from 400 to 2,000 m. Constant size grids were used to remove the effect of grid size on CO_2 solubility trapping and vertical segregation. For each reservoir size, two scenarios were discussed: (a) CO_2 injection with simultaneous water withdrawal and (b) CO_2 injection with no water withdrawal. For the water withdrawal scenario, two different well patterns were considered (Figure

5.27): 5-spot pattern (one CO_2 injector and one water producer at the opposite corners) and inverted 9-spot pattern (three CO_2 injectors and one water producer at all corners). Both the injection and production were set at the maximum possible rate with all aquifer layers perforated. The water producer was shut in immediately after CO_2 broke through, while the CO_2 injection continued. For the no water withdrawal scenario, the injector was placed in the center of the reservoir. Initially, the CO_2 injection rate was high; it then decreased to maintain the reservoir's pressure within the limit for both scenarios. The injection ceased when no more CO_2 could be injected.

FIGURE 5.27. 5-SPOT AND INVERTED 9-SPOT WELL PATTERN



Once a proper reservoir size and well pattern were selected, a reasonable injection rate could be determined. For an 800 m long and 800 m wide reservoir with a 5-spot well pattern, the maximum injection rate for the Lamotte Sandstone aquifer lies between 40 and 70 m^3/day under reservoir conditions (about 36-56 tons/day under surface conditions). Therefore, the effect of the injection rate on CO_2 storage ability was studied by varying the maximum injection rate from 40 to 70 m^3/day at reservoir conditions (RC), when the reservoir length is fixed at 800 m and the well pattern is fixed to be 5 spot.

Figure 5.28 compares the CO_2 storage capacity of the water withdrawal and no water withdrawal cases. The dashed line represents cumulative CO_2 injected in percent pore volume (% pv). Figure 5.29 compares the CO_2 storage efficiency of these cases. Figure 5.30 shows the time at which CO_2 starts to break through from the producer for water withdrawal cases. The dashed line represents the change of breakthrough time over the distance between injector and producer as reservoir size changes. It reflects how quickly CO_2 spreads laterally and breaks through.

As shown in Figure 5.28, the CO_2 storage capacity increases as the reservoir size increases. As would be expected, a larger reservoir has more pore space and allows CO_2 injection for a longer time. However, the portion of CO_2 volume accounted for actually decreases and it decreases significantly when water is withdrawn. Also, the portion of CO_2 volume (%pv) in per unit of pore volume (m^3) decreases sharply as the reservoir size increases, suggesting a decrease in storage efficiency (Figure 5.29). This indicates that the larger the reservoir size, the more total CO_2 can be injected, but a lower percentage of CO_2 will be stored in the pore volume. This is because the reservoir size is controlled by varying the reservoir's length or width with a fixed reservoir thickness and top depth, so the maximum injection pressure that limits the CO_2 storage capacity does not change. When the reservoir size increases, the pore volume increases faster than the injected CO_2 volume. Moreover, water withdrawal greatly benefits the storage capacity, especially when the reservoir is small, because it releases the reservoir's pressure and pore volume, resulting in a longer CO_2 injection period, and this effect is more obvious for a small reservoir. Compared to cases with no water withdrawal, 5-spot withdrawal increases the CO_2 storage capacity and efficiency 34-70 times, and inverted 9-spot withdrawal increases 16-40 times (Figure 5.31).

FIGURE 5.28. CUMULATIVE CO_2 INJECTED FOR CASES WITH AND WITHOUT WATER WITHDRAWAL

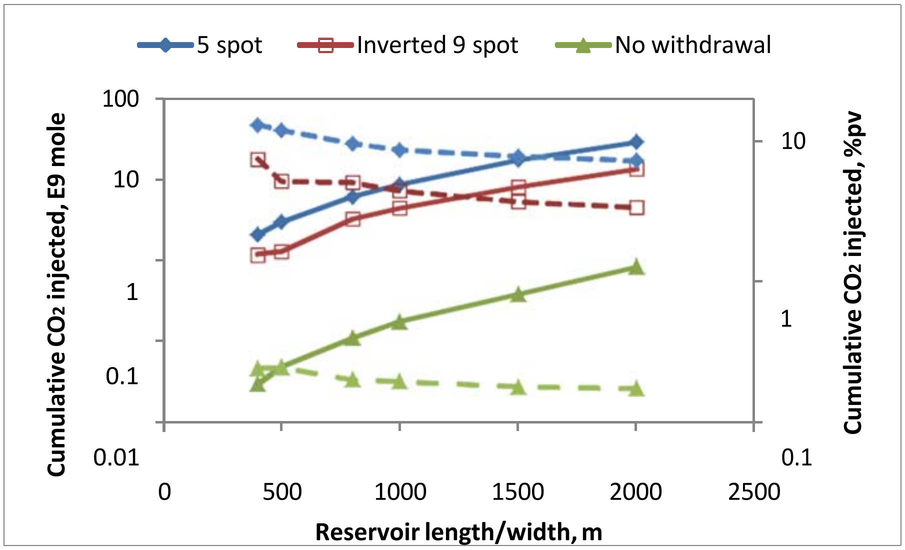


FIGURE 5.29. CO_2 STORAGE EFFICIENCY FOR CASES WITH AND WITHOUT WATER WITHDRAWAL

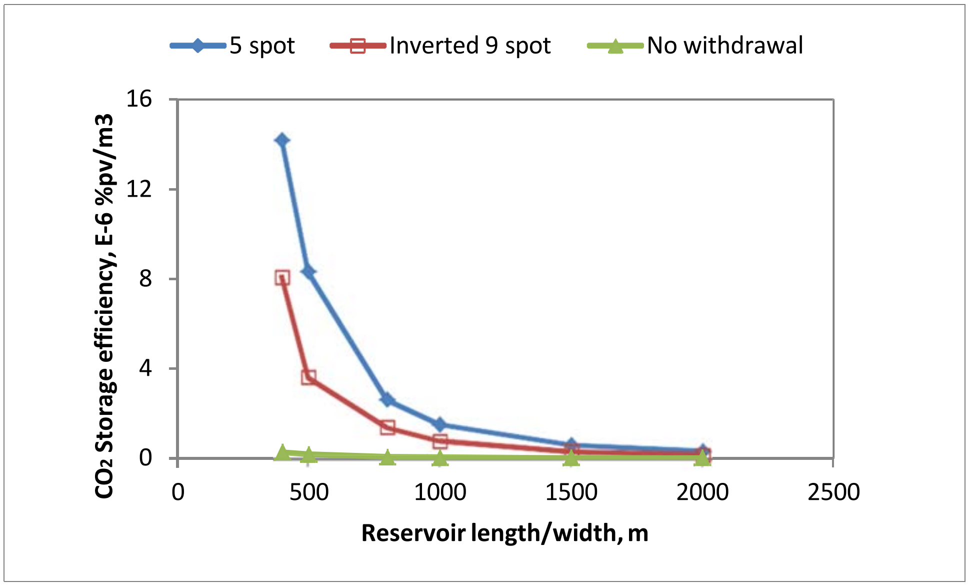


FIGURE 5.30. CO_2 BREAKTHROUGH/INJECTION TIME AND RELATIVE BREAKTHROUGH TIME

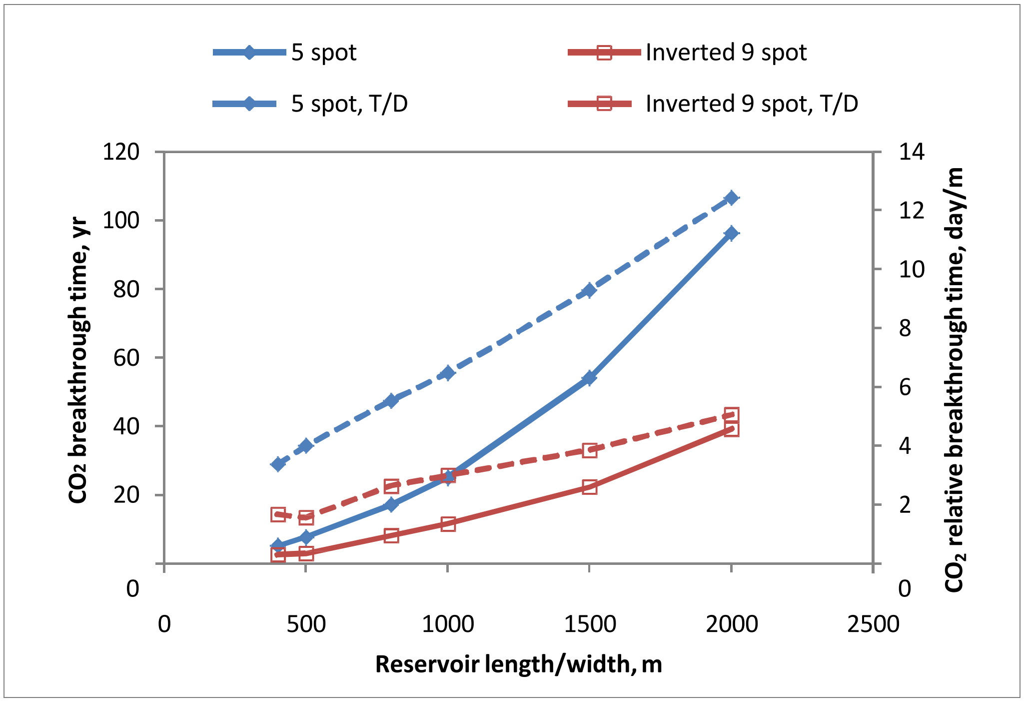
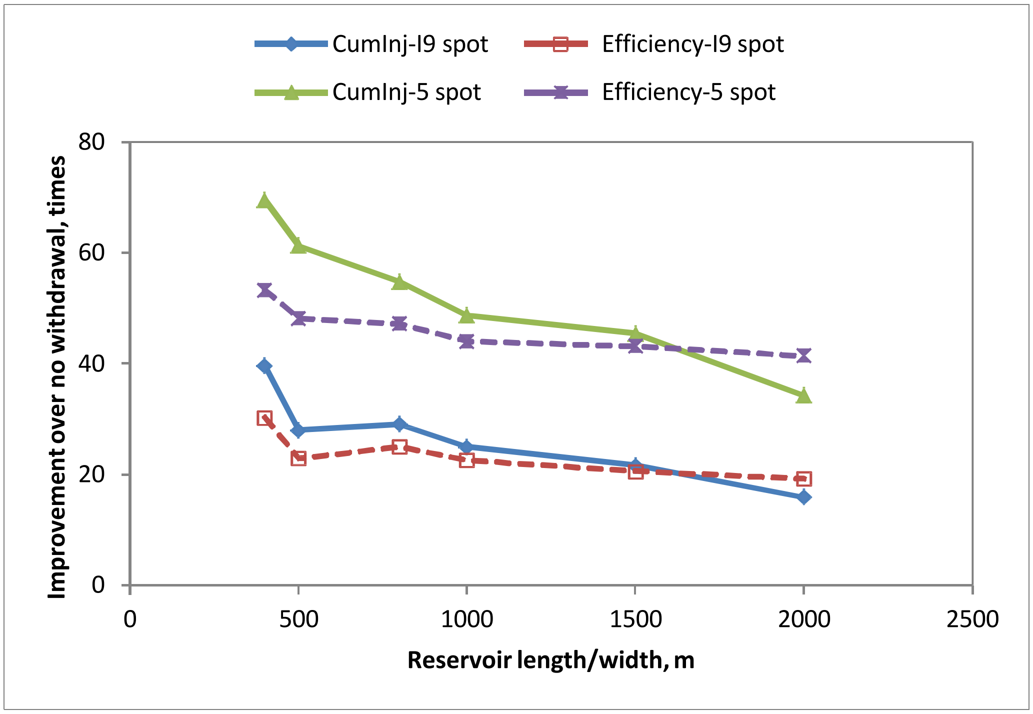


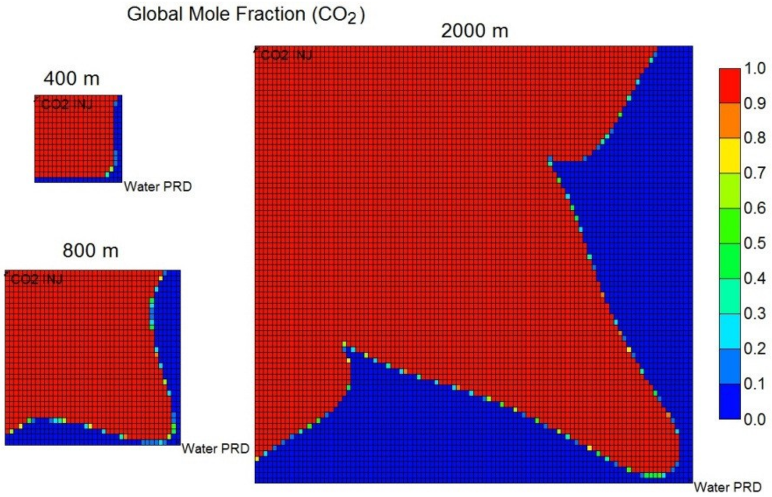
FIGURE 5.31. CO_2 STORAGE CAPACITY AND EFFICIENCY INCREASE WITH WATER WITHDRAWAL



In order to have more CO_2 stored efficiently, a proper reservoir size (referred to as well distance in this study) needs to be determined. If the reservoir is too small, a very little amount of CO_2 can be injected and the maximum injection time is limited; on the other hand, if the reservoir is too big

CO_2 storage efficiency will be low, which means only a small portion of CO_2 will be stored in every pore space unit (see Figure 5.29), and the lateral movement of CO_2 will be relatively slow (see Figure 5.30). In addition, CO_2 tends to accumulate along the cross section of the injector and producer where the maximum pressure drop occurs and eases the CO_2 flow in this direction. This directional movement effect becomes more prominent as the reservoir size increases, which actually reduces the CO_2 sweep efficiency (Figure 5.32).

FIGURE 5.32. CO_2 MOLE FRACTION IN THE TOP LAYER AT THE END OF SIMULATION



Based on the results above, 800-1,000 m (2,625 – 3,281 ft) is a turning point when the storage efficiency tends to be stable and low. Also, a reservoir of this size range has considerable storage capacity (5-spot: 5.92×10^8 -8.34×10^8 lb; inverted 9-spot: 3.1×10^8 -4.27×10^8 lb), good sweep efficiency, as well as favorable injection time (Figure 5.30, 5-spot: 17-25years; inverted 9-spot: 8- 12 years). Therefore, 800 m (2,624 feet) is a good start value for reservoir length in models when the actual data is unknown. Clearly, water withdrawal with the 5-spot well pattern provides better results, so it is also set as the input for the following studies.

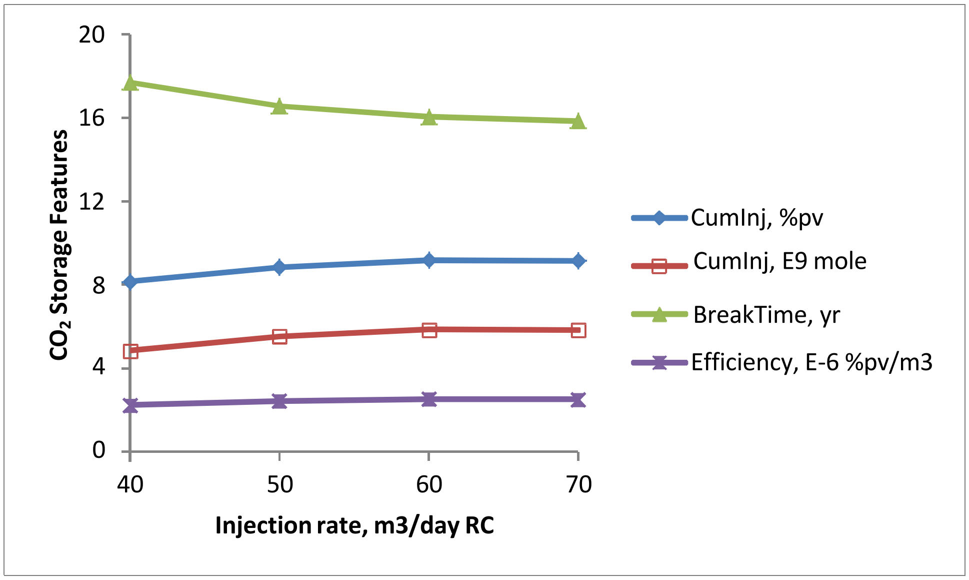
It is important to note that CO_2 injection is limited by the pressure build-up that occurs later in the case with no water withdrawal and after the producer shut-in in the case with withdrawal, so the injection rate will decrease to a point that is not economically feasible for the operation. Because of this, there is a minimum feasible injection rate, which prevents CO_2 injection in some cases even when there is still space available for storage. This minimum feasible CO_2 injection rate was not considered in the simulation for the purpose of investigating the maximum storage capacity. In reality, this minimum feasible injection rate should be included in determining the optimal well pattern and well distance.

EFFECT OF INJECTION RATE

This section addresses cases with maximum injection rates varying between 40 and 70 m^3/day RC for an 800 m x 800 m (2,624 feet x 2,624 feet) reservoir with 5-spot withdrawal. Figure 5.33 shows how the CO_2 injection rate affects storage capacity, efficiency, and breakthrough time for an 800 m long reservoir with 5-spot water withdrawal. The CO_2 storage capacity and efficiency increased 20.9% and 12.5% respectively as the maximum injection rate increased from 40 to 60 m^3/day RC, and then dropped 1.4% and 3.2 % when the maximum injection rate reached 70 m^3/day RC. The CO_2 breakthrough time decreased within 10.5% as the injection rate increased. This suggests that 60 m^3/day RC is the optimal maximum injection rate for the case studied considering the cumulative CO_2

injected and CO_2 storage efficiency. Injection at this rate gets the most CO_2 stored efficiently and it can last for the injection period studied (typically years).

FIGURE 5.33. EFFECT OF CO_2 INJECTION RATE ON STORAGE CAPACITY AND EFFICIENCY

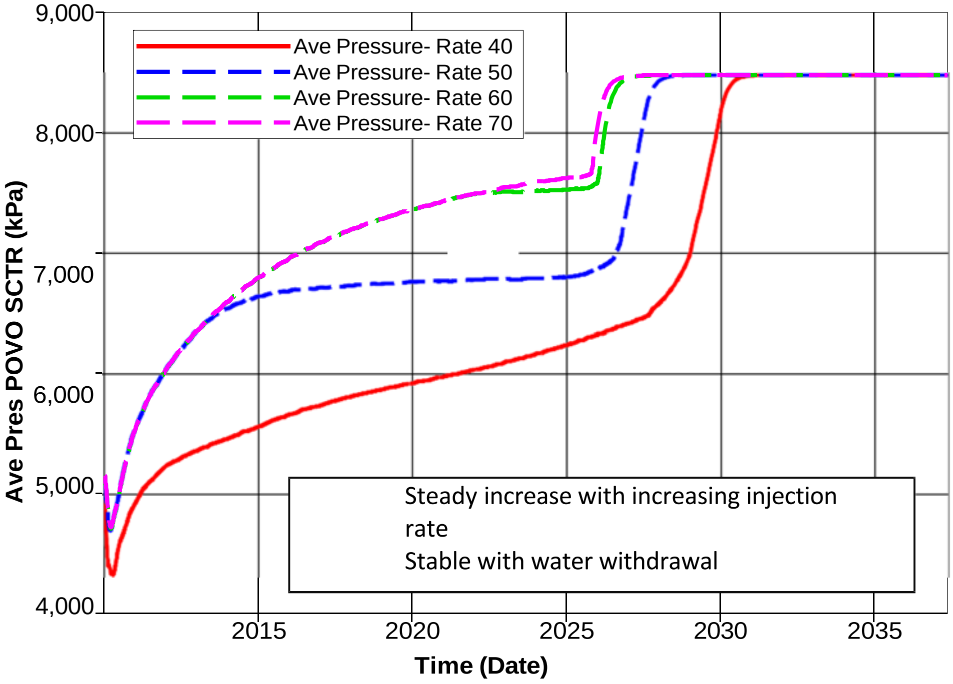


Figures 5.34 and 5.35 explain the existence of an optimal maximum injection rate. As shown in the simulation work, the average reservoir pressure increases steadily as an increasing amount of CO_2 is injected. It tended to stabilize when the withdrawal of water balanced the pressure buildup from the CO_2 injection, and rose sharply after the water withdrawal stopped due to the CO_2 breakthrough from the producer. Accordingly, the actual injection rate experienced three stages during the whole injection process. First, the injection rate increased to the maximum value from a low initial value and the length of this period increased as the maximum injection pressure constraint increased. Next, injection rate remained stable at the maximum value until CO_2 breakthrough. Finally, the injection rate dropped until no more CO_2 could be injected, which was controlled by the pressure constraint of the formation – the maximum bottom-hole pressure.

Clearly, higher injection rates allow more CO_2 to be injected early in the injection period, but lower injection rates postpone the CO_2 breakthrough time, so more CO_2 could be injected during the extended period. The optimal maximum injection rate can be determined by comparing the CO_2 mass difference in the early injection period and the later extended period.

Considering the CO_2 storage capacity alone, 60 m^3/day RC was the optimal rate for our case. A practical optimal rate could be adjusted by considering the high rate generation and the longer injection operation cost resulting from the lower rate.

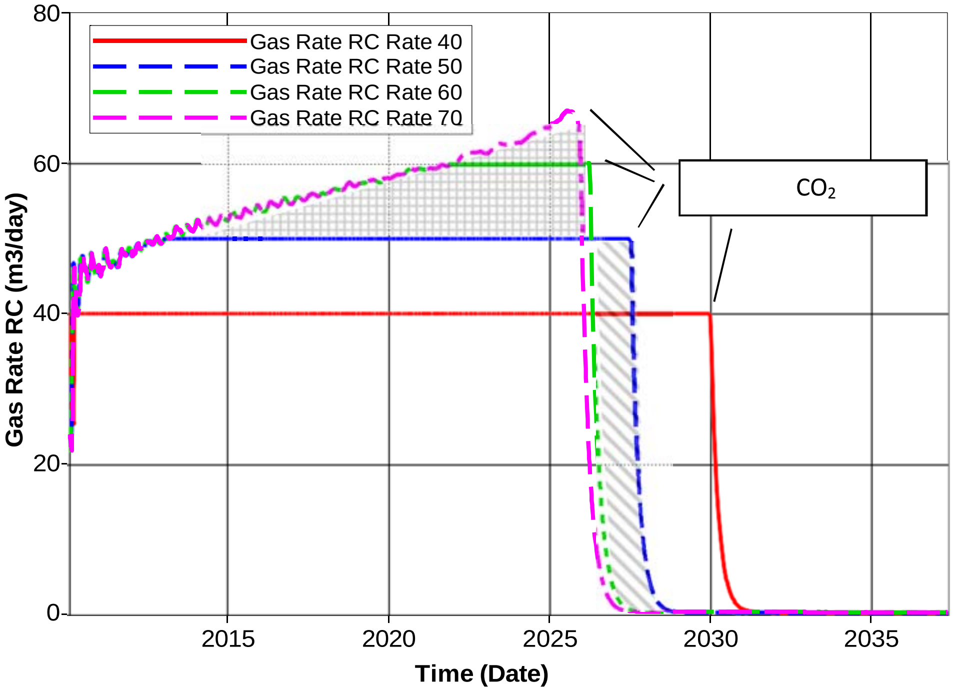
FIGURE 5.34. AVERAGE RESERVOIR PRESSURE CHANGE WITH TIME UNDER DIFFERENT MAXIMUM RATES



Steady increase with increasing injection rate

Stable with water withdrawal

FIGURE 5.35. INJECTION RATE CHANGE WITH TIME UNDER DIFFERENT MAXIMUM RATE CONSTRAINTS



In summary, an 800 m x 800 m (2,624 feet x 2,624 feet) reservoir is proper for this study because it allows a considerable amount of CO_2 (5.63×10^8 lb) to be stored relatively efficiently (2.5%pv/m^3) in a fairly long injection period (15.8 years). Water withdrawal greatly improves the CO_2 storage capacity and efficiency, especially with the 5-spot well pattern. The optimal injection rate for an 800 m (2,624 feet) long reservoir with a 5-spot withdrawal is 60 m^3/day RC.

The simulations shown here illustrate the importance in modeling a specific site, as storage capacity and injectivity will be dependent on formation characteristics at a particular location, in addition to the manner in which the well is completed.

Simulation results show that CO_2 storage capacity is dominated primarily by thickness, porosity, depth, and fracture pressure, whereas CO_2 injectivity is dominated primarily by permeability but also affected to a smaller extent by other factors.

In summary, various factors were studied to investigate their effect on CO_2 storage potential in the Lamotte Sandstone in the study area, including formation depth, thickness, porosity, permeability, salinity, pressure gradient, fracture pressure gradient, temperature gradient, and injection rate.

The results show that CO_2 storage capacity and injectivity increase as these factors increase, but the CO_2 stability decreases due to the increasing percentage of free phase CO_2. CO_2 storage capacity is dominated primarily by thickness, porosity, depth, and fracture pressure, whereas CO_2 injectivity is dominated primarily by permeability, thickness, depth, and salinity. The injection time depends largely on formation thickness, porosity, fracture pressure, and depth. Higher permeability and temperature could decrease injection time. Detailed relationships between factors and CO_2 storage potential can be demonstrated using contour maps and surface maps.

More data points enable better results.

Generally, formation depth, thickness, and porosity greatly affect CO_2 storage capacity and injectivity, whereas formation pressure gradient and temperature gradient had little effect on both. Formation permeability, fracture pressure gradient, salinity, and injection rate affect CO_2 injectivity much more than CO_2 storage capacity. For a given formation, a relatively high injection rate is desirable for an injection process.

Shallow sequestration is even more promising with water withdrawal. This greatly improves the CO_2 storage capacity and efficiency, especially in the 5-spot well pattern, which increases the CO_2 storage capacity and efficiency 34-70 times over cases with no water withdrawal. Large reservoirs have a high storage capacity but low storage efficiency and sweep efficiency. High injection rates allowed more CO_2 to be injected in a short period of time, but low injection rates postponed the CO_2 breakthrough time, so more CO_2 could be injected during the extended period. An optimal maximum injection rate can be determined through simulation.

TASK 2.d. Determine the Baseline Water Chemistry of the Target Formation at Each of the Four Missouri Power Plant Sites

FORMATION WATER SAMPLING - EXPLORATORY BOREHOLE #1; JOHN TWITTY ENERGY CENTER (JTEC)

Water from the Reagan Sandstone lens was sampled on November 7, 2010, what is believed to be a mixed flow Reagan-Lamotte Sandstone lens was sampled on November 23, 2010, and a Lamotte Sandstone was sampled on January 7, 2011 using a downhole core packer to isolate the Lamotte Sandstone from other aquifer subunits.

The Reagan groundwater samples displayed an average pH of 7.80 +/- 0.06, Eh -53.5 +/- 1.4 millivolts, dissolved oxygen 0.19 +/- 0.14 mg/L, and water temperature 18.0 +/- 0.2^{o}C (Table 5.11a). The water conductivity was a constant 328 microSiemens/cm. Water samples from the isolated Lamotte Sandstone aquifer were similar, with an average pH of 7.92 +/- 0.01, Eh -59.6 +/-millivolts, dissolved oxygen 0.16 +/- 0.02 mg/L, water temperature 17.2^{o}C, and water conductivity 334 microSiemens/cm.

Turbidity values were very low at 0.15 NTU units for the Reagan Sandstone and this corresponded well with a low Total Suspended Solids (TSS) value of only 1.30 mg/L. Turbidity values were slightly higher for the Lamotte samples at 3.82 +/- 0.43 NTU units (Table 5.11a), correlating to a slight increase in TSS (1.48 +/- 0.40). The Lamotte Sandstone water samples also displayed elevated and variable Al concentrations suggesting that the suspended material in the water samples was a clay mineral. We also re-measured the turbidity values for the Lamotte Sandstone samples after a delay of approximately nine hours to see if the loss of CO_2 from the solutions had any effect on mineral precipitation. All three samples displayed a slight increase in turbidity after the incubation period, and shaking the vessels increased the turbidity values even further. This increase in turbidity suggests that small particles of a carbonate mineral were forming as the solutions were losing CO_2, with CO_2 loss inducing a pH rise and lowering of the solubility of Ca^{2+} Mg^{2+} and CO_3^{2-} with respect to carbonate phases.

The water samples collected on all three dates at the JTEC site were low salinity Ca-Mg- bicarbonate solutions (Tables 5.11a and 5.11b). The average molar Ca/Mg ratio for the Reagan Sandstone water was 1.36 (Ca = 33.4 ppm, 0.833 millimolar; Mg = 14.9 ppm, 0.613 millimolar) suggesting the dissolution of a mixed source rock lithology for this water composed of 26% calcite- limestone ($CaCO_3$) and 74% dolomite ($Ca,Mg(CO_3)_2$). The average molar Ca/Mg ratio for the Lamotte Sandstone water was 1.64 (Ca = 22.4 ppm, 0.559 millimolar; Mg = 8.28 ppm, 0.341 millimolar), suggesting the dissolution of a 40% calcite-limestone and 60% dolomite source. These proportions reflect the dissolution ratios of calcite to dolomite and do not necessarily represent the proportions of the mineral in the source rock as calcite tends to dissolve at a faster rate than dolomite, and quartz exhibits a very low solubility in most natural waters.

Reagan Sandstone water concentrations of Si, K, and Na were all between one and five ppm. The Lamotte Sandstone water displayed a significant increase in Na and HCO_3^-, a slight increase in K, and a decrease in Ca and Mg relative to the Reagan. For the minor and trace elements, Fe, Mn, and Sr were enriched, while Ba and SO_4^{2-} were depleted in the Lamotte relative to the Reagan water. In the Reagan water, the trace elements Sr, Ba, and Mn displayed the highest concentrations, averaging 133, 41, and 12 ppb, respectively (Table 5.11c). Zinc concentrations were sporadic, and for one sample (Reagan #2) we detected ~130 ppb. The low concentration of Al is important from a repository standpoint as this element is often indicative of the presence of clay minerals. The low contents in the formation waters indicate that the clay is not being suspended in the groundwater system by the drilling and pumping process. The Lamotte Sandstone water samples displayed a similar trace element pattern with Sr, Al, Mn, Zn, and Ba averaging 208, 59, 38, 13, and 11 ppb, respectively (Table 5.11c). The increase in Al in the Lamotte Sandstone relative to the Reagan Sandstone reflects the dissolution of feldspar minerals in the Lamotte Sandstone and the formation of clay minerals. Filtration through a 0.45 micron filter reduced the Al concentration to an average of 1.7 ppb, indicating that the Al transport in the groundwater is being dominated by particulate material. Movement of these particles can potentially plug pores in the repository host rock, thereby hindering an injection process.

There are four different analytical procedures by which evaluation could be conducted for dissolved solid – salinity content of the Reagan aquifer water:

1. Total Dissolved Solids (TDS) by Evaporation to Dryness: The most direct method is by filtering out any particles greater than 0.45 microns (the TSS fraction), collecting the filtrate in a pre-weighed beaker, evaporating to dryness at 95^{o}C, and weighing the beaker again to determine the accumulated residue (the TDS fraction). The TDS determinations for the Reagan Sandstone aquifer averaged 159.1 +/- 7.5 mg/L, while the Lamotte Sandstone samples averaged 226.5 +/- 13.5 mg/L (Table 5.11a).
2. Tabulating cation and anion analytical determinations: A second method is to tabulate the ppm (mg/L) content of all species detected in solution. This tabulation would include the major ions of HCO_3^- (alkalinity; Table 5.11a); Ca, Mg, Si, Na, K, Fe (ICP-OES; Table 5.11b); Sr (ICP-MS; Table 5.11c); and SO_4^{2-}, Cl, F, NO_3^- (Ion Chromatography; Table 5.11d). Tabulation of all of these species for the Reagan Sandstone water came to 190.5 mg/L, while the Lamotte Sandstone sample average was 195.9 mg/L.
3. HACH Hardness Testing: A third method involves the use of the HACH hardness test kit. This analysis detects the total hardness of Ca^{2+} and Mg^{2+} ions by titration with EDTA and determines their concentration with CO_3^{2-} already included in the weight calculation. The average HACH total hardness determination for the Reagan Sandstone water samples was 185 +/- 36 mg/L for three readings, while the average determination for the Lamotte Sandstone was only 84 +/- 2 mg/L (Table 5.11a).
4. Conductivity Measurements The fourth method uses the conductivity value and a multiplication factor of 0.667 to convert conductivity to TDS (Boyd, 2002). Multiplying the Reagan Sandstone water sample measured conductivity of 328 +/- 0 microSiemens/cm (Table 5.11a) * 0.667 = 219 +/- 0 mg/L. The corresponding values for the Lamotte Sandstone water are 309 +/- 1 microSiemens/cm * 0.667 = 206 +/- 1 mg/L.

TABLE 5.11A. JOHN TWITTY ENERGY CENTER BOREHOLE COLLECTION AND ON-SITE MEASUREMENT DATA.

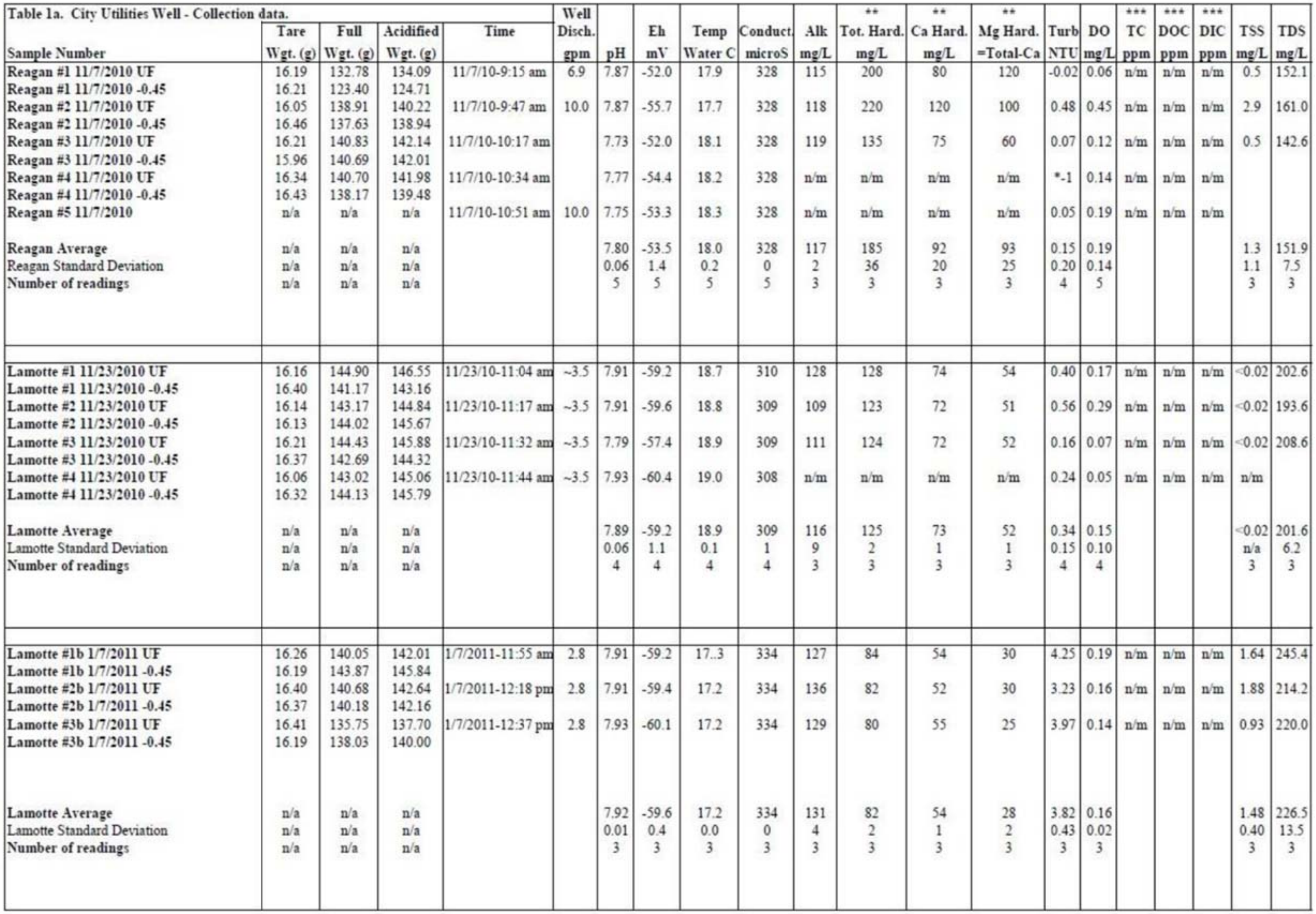


Table 1a. City Utilities Well - Collection data.

Sample Number	Tare Wgt. (g)	Full Wgt. (g)	Acidified Wgt. (g)	Time	Well Disch. gpm	pH	Eh mV	Temp Water C	Conduct. microS	Alk mg/L	** Tot. Hard. mg/L	** Ca Hard. mg/L	** Mg Hard. =Total-Ca	Turb NTU	DO mg/L	*** TC ppm	*** DOC ppm	*** DIC ppm	TSS mg/L	TDS mg/L
Reagan #1 11/7/2010 UF	16.19	132.78	134.09	11/7/10-9:15 am	6.9	7.87	-52.0	17.9	328	115	200	80	120	-0.02	0.06	n/m	n/m	n/m	0.5	152.1
Reagan #1 11/7/2010 -0.45	16.21	123.40	124.71																	
Reagan #2 11/7/2010 UF	16.05	138.91	140.22	11/7/10-9:47 am	10.0	7.87	-55.7	17.7	328	118	220	120	100	0.48	0.45	n/m	n/m	n/m	2.9	161.0
Reagan #2 11/7/2010 -0.45	16.46	137.63	138.94																	
Reagan #3 11/7/2010 UF	16.21	140.83	142.14	11/7/10-10:17 am		7.73	-52.0	18.1	328	119	135	75	60	0.07	0.12	n/m	n/m	n/m	0.5	142.6
Reagan #3 11/7/2010 -0.45	15.96	140.69	142.01																	
Reagan #4 11/7/2010 UF	16.34	140.70	141.98	11/7/10-10:34 am		7.77	-54.4	18.2	328	n/m	n/m	n/m	n/m	*-1	0.14	n/m	n/m	n/m		
Reagan #4 11/7/2010 -0.45	16.43	138.17	139.48																	
Reagan #5 11/7/2010	n/a	n/a	n/a	11/7/10-10:51 am	10.0	7.75	-53.3	18.3	328	n/m	n/m	n/m	n/m	0.05	0.19	n/m	n/m	n/m		
Reagan Average	n/a	n/a	n/a			7.80	-53.5	18.0	328	117	185	92	93	0.15	0.19				1.3	151.9
Reagan Standard Deviation	n/a	n/a	n/a			0.06	1.4	0.2	0	2	36	20	25	0.20	0.14				1.1	7.5
Number of readings	n/a	n/a	n/a			5	5	5	5	3	3	3	3	4	5				3	3
Lamotte #1 11/23/2010 UF	16.16	144.90	146.55	11/23/10-11:04 am	~3.5	7.91	-59.2	18.7	310	128	128	74	54	0.40	0.17	n/m	n/m	n/m	<0.02	202.6
Lamotte #1 11/23/2010 -0.45	16.40	141.17	143.16																	
Lamotte #2 11/23/2010 UF	16.14	143.17	144.84	11/23/10-11:17 am	~3.5	7.91	-59.6	18.8	309	109	123	72	51	0.56	0.29	n/m	n/m	n/m	<0.02	193.6
Lamotte #2 11/23/2010 -0.45	16.13	144.02	145.67																	
Lamotte #3 11/23/2010 UF	16.21	144.43	145.88	11/23/10-11:32 am	~3.5	7.79	-57.4	18.9	309	111	124	72	52	0.16	0.07	n/m	n/m	n/m	<0.02	208.6
Lamotte #3 11/23/2010 -0.45	16.37	142.69	144.32																	
Lamotte #4 11/23/2010 UF	16.06	143.02	145.06	11/23/10-11:44 am	~3.5	7.93	-60.4	19.0	308	n/m	n/m	n/m	n/m	0.24	0.05	n/m	n/m	n/m	n/m	
Lamotte #4 11/23/2010 -0.45	16.32	144.13	145.79																	
Lamotte Average	n/a	n/a	n/a			7.89	-59.2	18.9	309	116	125	73	52	0.34	0.15				<0.02	201.6
Lamotte Standard Deviation	n/a	n/a	n/a			0.06	1.1	0.1	1	9	2	1	1	0.15	0.10				n/a	6.2
Number of readings	n/a	n/a	n/a			4	4	4	4	3	3	3	3	4	4				3	3
Lamotte #1b 1/7/2011 UF	16.26	140.05	142.01	1/7/2011-11:55 am	2.8	7.91	-59.2	17..3	334	127	84	54	30	4.25	0.19	n/m	n/m	n/m	1.64	245.4
Lamotte #1b 1/7/2011 -0.45	16.19	143.87	145.84																	
Lamotte #2b 1/7/2011 UF	16.40	140.68	142.64	1/7/2011-12:18 pm	2.8	7.91	-59.4	17.2	334	136	82	52	30	3.23	0.16	n/m	n/m	n/m	1.88	214.2
Lamotte #2b 1/7/2011 -0.45	16.37	140.18	142.16																	
Lamotte #3b 1/7/2011 UF	16.41	135.75	137.70	1/7/2011-12:37 pm	2.8	7.93	-60.1	17.2	334	129	80	55	25	3.97	0.14	n/m	n/m	n/m	0.93	220.0
Lamotte #3b 1/7/2011 -0.45	16.19	138.03	140.00																	
Lamotte Average	n/a	n/a	n/a			7.92	-59.6	17.2	334	131	82	54	28	3.82	0.16				1.48	226.5
Lamotte Standard Deviation	n/a	n/a	n/a			0.01	0.4	0.0	0	4	2	1	2	0.43	0.02				0.40	13.5
Number of readings	n/a	n/a	n/a			3	3	3	3	3	3	3	3	3	3				3	3

TABLE 5.11B. MAJOR ELEMENT CATIONS FROM THE JOHN TWITTY ENERGY CENTER BOREHOLE, ICP-OES ANALYSIS (VALUES IN PPM).

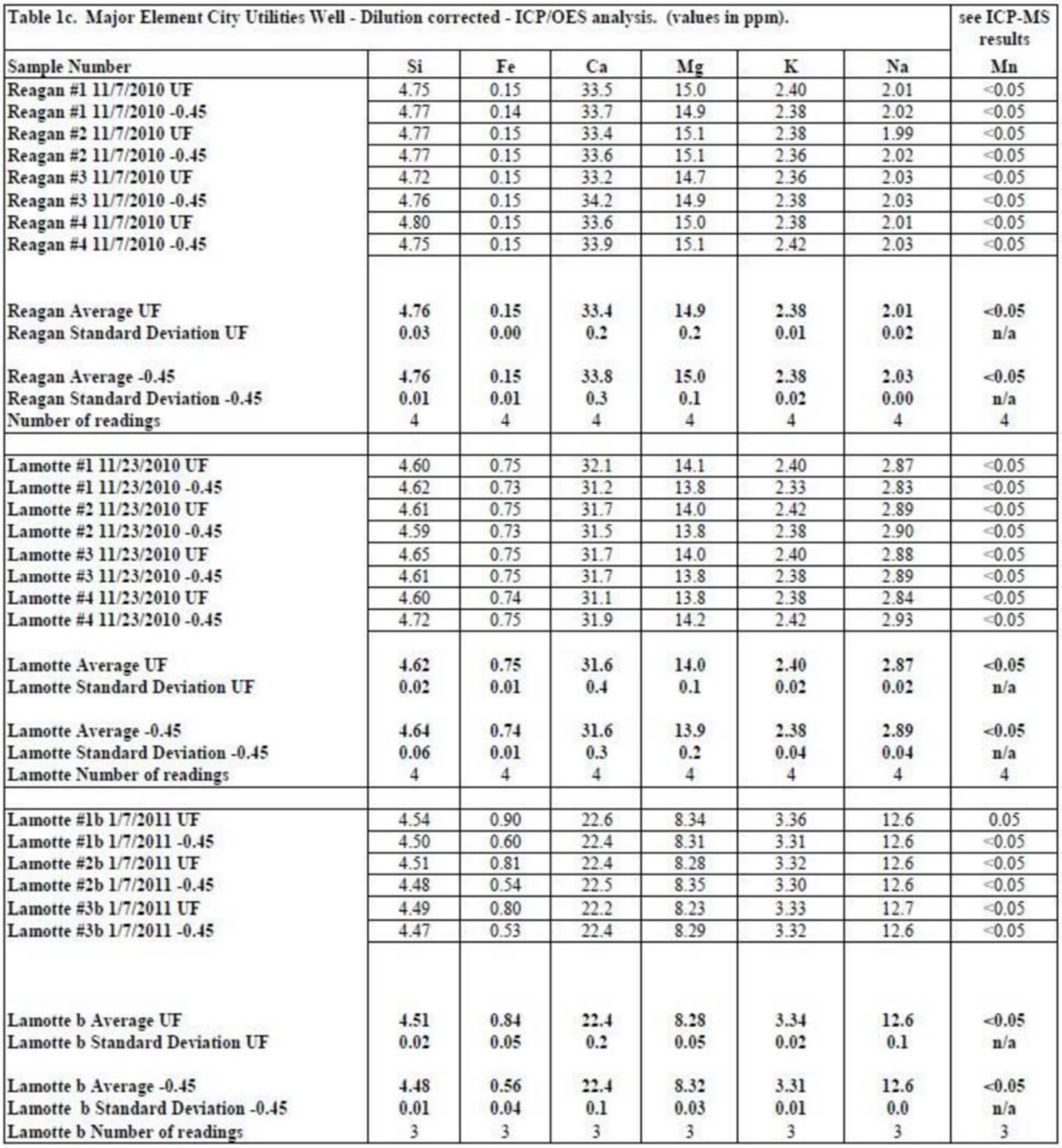


Table 1c. Major Element City Utilities Well - Dilution corrected - ICP/OES analysis. (values in ppm).							see ICP-MS results
Sample Number	Si	Fe	Ca	Mg	K	Na	Mn
Reagan #1 11/7/2010 UF	4.75	0.15	33.5	15.0	2.40	2.01	<0.05
Reagan #1 11/7/2010 -0.45	4.77	0.14	33.7	14.9	2.38	2.02	<0.05
Reagan #2 11/7/2010 UF	4.77	0.15	33.4	15.1	2.38	1.99	<0.05
Reagan #2 11/7/2010 -0.45	4.77	0.15	33.6	15.1	2.36	2.02	<0.05
Reagan #3 11/7/2010 UF	4.72	0.15	33.2	14.7	2.36	2.03	<0.05
Reagan #3 11/7/2010 -0.45	4.76	0.15	34.2	14.9	2.38	2.03	<0.05
Reagan #4 11/7/2010 UF	4.80	0.15	33.6	15.0	2.38	2.01	<0.05
Reagan #4 11/7/2010 -0.45	4.75	0.15	33.9	15.1	2.42	2.03	<0.05
Reagan Average UF	**4.76**	**0.15**	**33.4**	**14.9**	**2.38**	**2.01**	**<0.05**
Reagan Standard Deviation UF	**0.03**	**0.00**	**0.2**	**0.2**	**0.01**	**0.02**	**n/a**
Reagan Average -0.45	**4.76**	**0.15**	**33.8**	**15.0**	**2.38**	**2.03**	**<0.05**
Reagan Standard Deviation -0.45	**0.01**	**0.01**	**0.3**	**0.1**	**0.02**	**0.00**	**n/a**
Number of readings	4	4	4	4	4	4	4
Lamotte #1 11/23/2010 UF	4.60	0.75	32.1	14.1	2.40	2.87	<0.05
Lamotte #1 11/23/2010 -0.45	4.62	0.73	31.2	13.8	2.33	2.83	<0.05
Lamotte #2 11/23/2010 UF	4.61	0.75	31.7	14.0	2.42	2.89	<0.05
Lamotte #2 11/23/2010 -0.45	4.59	0.73	31.5	13.8	2.38	2.90	<0.05
Lamotte #3 11/23/2010 UF	4.65	0.75	31.7	14.0	2.40	2.88	<0.05
Lamotte #3 11/23/2010 -0.45	4.61	0.75	31.7	13.8	2.38	2.89	<0.05
Lamotte #4 11/23/2010 UF	4.60	0.74	31.1	13.8	2.38	2.84	<0.05
Lamotte #4 11/23/2010 -0.45	4.72	0.75	31.9	14.2	2.42	2.93	<0.05
Lamotte Average UF	**4.62**	**0.75**	**31.6**	**14.0**	**2.40**	**2.87**	**<0.05**
Lamotte Standard Deviation UF	**0.02**	**0.01**	**0.4**	**0.1**	**0.02**	**0.02**	**n/a**
Lamotte Average -0.45	**4.64**	**0.74**	**31.6**	**13.9**	**2.38**	**2.89**	**<0.05**
Lamotte Standard Deviation -0.45	**0.06**	**0.01**	**0.3**	**0.2**	**0.04**	**0.04**	**n/a**
Lamotte Number of readings	4	4	4	4	4	4	4
Lamotte #1b 1/7/2011 UF	4.54	0.90	22.6	8.34	3.36	12.6	0.05
Lamotte #1b 1/7/2011 -0.45	4.50	0.60	22.4	8.31	3.31	12.6	<0.05
Lamotte #2b 1/7/2011 UF	4.51	0.81	22.4	8.28	3.32	12.6	<0.05
Lamotte #2b 1/7/2011 -0.45	4.48	0.54	22.5	8.35	3.30	12.6	<0.05
Lamotte #3b 1/7/2011 UF	4.49	0.80	22.2	8.23	3.33	12.7	<0.05
Lamotte #3b 1/7/2011 -0.45	4.47	0.53	22.4	8.29	3.32	12.6	<0.05
Lamotte b Average UF	**4.51**	**0.84**	**22.4**	**8.28**	**3.34**	**12.6**	**<0.05**
Lamotte b Standard Deviation UF	**0.02**	**0.05**	**0.2**	**0.05**	**0.02**	**0.1**	**n/a**
Lamotte b Average -0.45	**4.48**	**0.56**	**22.4**	**8.32**	**3.31**	**12.6**	**<0.05**
Lamotte b Standard Deviation -0.45	**0.01**	**0.04**	**0.1**	**0.03**	**0.01**	**0.0**	**n/a**
Lamotte b Number of readings	3	3	3	3	3	3	3

TABLE 5.11C. TRACE ELEMENT DATA FROM THE JTEC BOREHOLE, ICP-MS ANALYSIS (VALUES IN PPB).

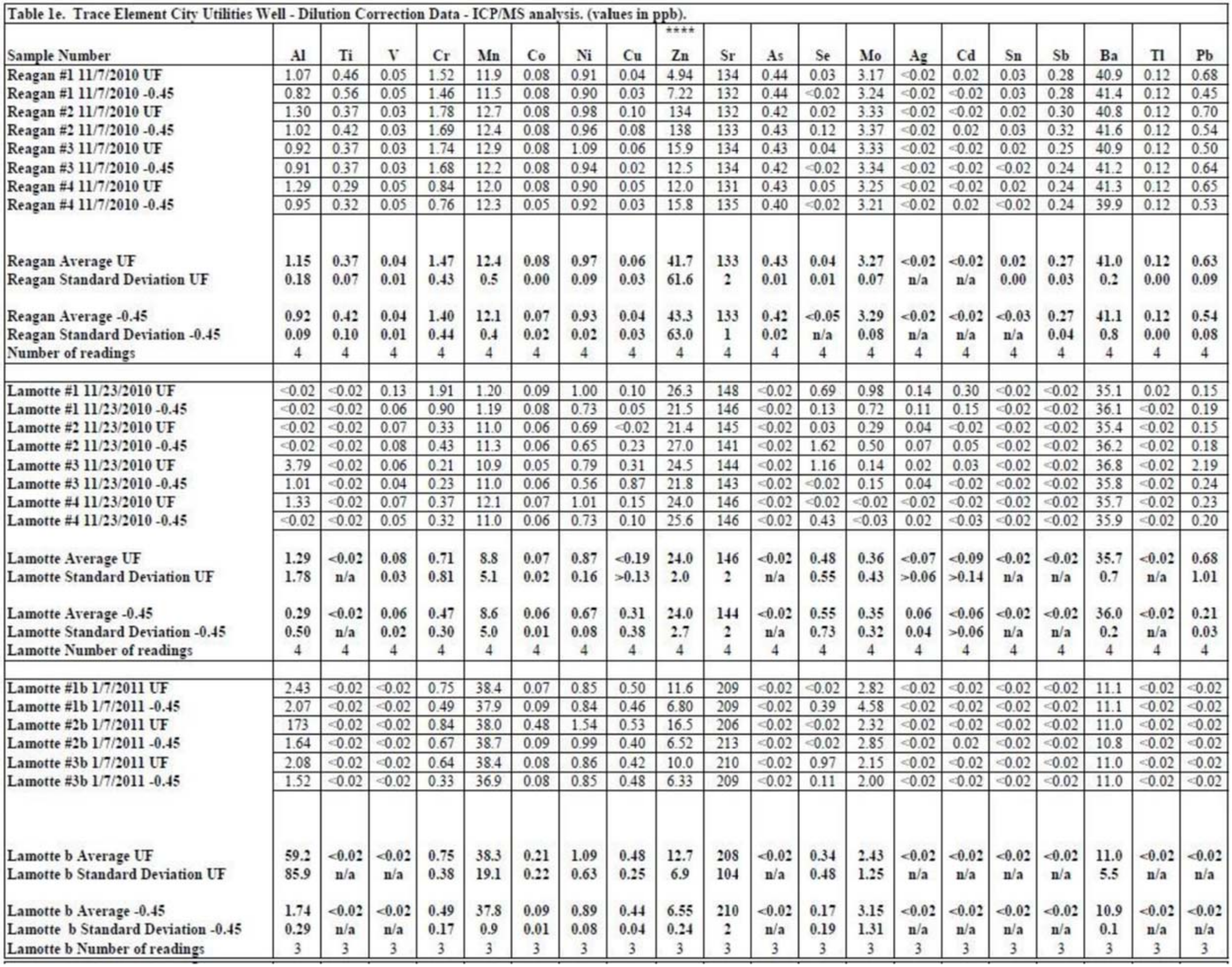


Table 1e. Trace Element City Utilities Well - Dilution Correction Data - ICP/MS analysis. (values in ppb).

Sample Number	Al	Ti	V	Cr	Mn	Co	Ni	Cu	**** Zn	Sr	As	Se	Mo	Ag	Cd	Sn	Sb	Ba	Tl	Pb
Reagan #1 11/7/2010 UF	1.07	0.46	0.05	1.52	11.9	0.08	0.91	0.04	4.94	134	0.44	0.03	3.17	<0.02	0.02	0.03	0.28	40.9	0.12	0.68
Reagan #1 11/7/2010 -0.45	0.82	0.56	0.05	1.46	11.5	0.08	0.90	0.03	7.22	132	0.44	<0.02	3.24	<0.02	<0.02	0.03	0.28	41.4	0.12	0.45
Reagan #2 11/7/2010 UF	1.30	0.37	0.03	1.78	12.7	0.08	0.98	0.10	134	132	0.42	0.02	3.33	<0.02	<0.02	0.02	0.30	40.8	0.12	0.70
Reagan #2 11/7/2010 -0.45	1.02	0.42	0.03	1.69	12.4	0.08	0.96	0.08	138	133	0.43	0.12	3.37	<0.02	0.02	0.03	0.32	41.6	0.12	0.54
Reagan #3 11/7/2010 UF	0.92	0.37	0.03	1.74	12.9	0.08	1.09	0.06	15.9	134	0.43	0.04	3.33	<0.02	<0.02	0.02	0.25	40.9	0.12	0.50
Reagan #3 11/7/2010 -0.45	0.91	0.37	0.03	1.68	12.2	0.08	0.94	0.02	12.5	134	0.42	<0.02	3.34	<0.02	<0.02	<0.02	0.24	41.2	0.12	0.64
Reagan #4 11/7/2010 UF	1.29	0.29	0.05	0.84	12.0	0.08	0.90	0.05	12.0	131	0.43	0.05	3.25	<0.02	<0.02	0.02	0.24	41.3	0.12	0.65
Reagan #4 11/7/2010 -0.45	0.95	0.32	0.05	0.76	12.3	0.05	0.92	0.03	15.8	135	0.40	<0.02	3.21	<0.02	0.02	<0.02	0.24	39.9	0.12	0.53
Reagan Average UF	1.15	0.37	0.04	1.47	12.4	0.08	0.97	0.06	41.7	133	0.43	0.04	3.27	<0.02	<0.02	0.02	0.27	41.0	0.12	0.63
Reagan Standard Deviation UF	0.18	0.07	0.01	0.43	0.5	0.00	0.09	0.03	61.6	2	0.01	0.01	0.07	n/a	n/a	0.00	0.03	0.2	0.00	0.09
Reagan Average -0.45	0.92	0.42	0.04	1.40	12.1	0.07	0.93	0.04	43.3	133	0.42	<0.05	3.29	<0.02	<0.02	<0.03	0.27	41.1	0.12	0.54
Reagan Standard Deviation -0.45	0.09	0.10	0.01	0.44	0.4	0.02	0.02	0.03	63.0	1	0.02	n/a	0.08	n/a	n/a	n/a	0.04	0.8	0.00	0.08
Number of readings	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Lamotte #1 11/23/2010 UF	<0.02	<0.02	0.13	1.91	1.20	0.09	1.00	0.10	26.3	148	<0.02	0.69	0.98	0.14	0.30	<0.02	<0.02	35.1	0.02	0.15
Lamotte #1 11/23/2010 -0.45	<0.02	<0.02	0.06	0.90	1.19	0.08	0.73	0.05	21.5	146	<0.02	0.13	0.72	0.11	0.15	<0.02	<0.02	36.1	<0.02	0.19
Lamotte #2 11/23/2010 UF	<0.02	<0.02	0.07	0.33	11.0	0.06	0.69	<0.02	21.4	145	<0.02	0.03	0.29	0.04	<0.02	<0.02	<0.02	35.4	<0.02	0.15
Lamotte #2 11/23/2010 -0.45	<0.02	<0.02	0.08	0.43	11.3	0.06	0.65	0.23	27.0	141	<0.02	1.62	0.50	0.07	0.05	<0.02	<0.02	36.2	<0.02	0.18
Lamotte #3 11/23/2010 UF	3.79	<0.02	0.06	0.21	10.9	0.05	0.79	0.31	24.5	144	<0.02	1.16	0.14	0.02	0.03	<0.02	<0.02	36.8	<0.02	2.19
Lamotte #3 11/23/2010 -0.45	1.01	<0.02	0.04	0.23	11.0	0.06	0.56	0.87	21.8	143	<0.02	<0.02	0.15	0.04	<0.02	<0.02	<0.02	35.8	<0.02	0.24
Lamotte #4 11/23/2010 UF	1.33	<0.02	0.07	0.37	12.1	0.07	1.01	0.15	24.0	146	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	35.7	<0.02	0.23
Lamotte #4 11/23/2010 -0.45	<0.02	<0.02	0.05	0.32	11.0	0.06	0.73	0.10	25.6	146	<0.02	0.43	<0.03	0.02	<0.03	<0.02	<0.02	35.9	<0.02	0.20
Lamotte Average UF	1.29	<0.02	0.08	0.71	8.8	0.07	0.87	<0.19	24.0	146	<0.02	0.48	0.36	<0.07	<0.09	<0.02	<0.02	35.7	<0.02	0.68
Lamotte Standard Deviation UF	1.78	n/a	0.03	0.81	5.1	0.02	0.16	>0.13	2.0	2	n/a	0.55	0.43	>0.06	>0.14	n/a	n/a	0.7	n/a	1.01
Lamotte Average -0.45	0.29	<0.02	0.06	0.47	8.6	0.06	0.67	0.31	24.0	144	<0.02	0.55	0.35	0.06	<0.06	<0.02	<0.02	36.0	<0.02	0.21
Lamotte Standard Deviation -0.45	0.50	n/a	0.02	0.30	5.0	0.01	0.08	0.38	2.7	2	n/a	0.73	0.32	0.04	>0.06	n/a	n/a	0.2	n/a	0.03
Lamotte Number of readings	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Lamotte #1b 1/7/2011 UF	2.43	<0.02	<0.02	0.75	38.4	0.07	0.85	0.50	11.6	209	<0.02	<0.02	2.82	<0.02	<0.02	<0.02	<0.02	11.1	<0.02	<0.02
Lamotte #1b 1/7/2011 -0.45	2.07	<0.02	<0.02	0.49	37.9	0.09	0.84	0.46	6.80	209	<0.02	0.39	4.58	<0.02	<0.02	<0.02	<0.02	11.1	<0.02	<0.02
Lamotte #2b 1/7/2011 UF	173	<0.02	<0.02	0.84	38.0	0.48	1.54	0.53	16.5	206	<0.02	<0.02	2.32	<0.02	<0.02	<0.02	<0.02	11.0	<0.02	<0.02
Lamotte #2b 1/7/2011 -0.45	1.64	<0.02	<0.02	0.67	38.7	0.09	0.99	0.40	6.52	213	<0.02	<0.02	2.85	<0.02	0.02	<0.02	<0.02	10.8	<0.02	<0.02
Lamotte #3b 1/7/2011 UF	2.08	<0.02	<0.02	0.64	38.4	0.08	0.86	0.42	10.0	210	<0.02	0.97	2.15	<0.02	<0.02	<0.02	<0.02	11.0	<0.02	<0.02
Lamotte #3b 1/7/2011 -0.45	1.52	<0.02	<0.02	0.33	36.9	0.08	0.85	0.48	6.33	209	<0.02	0.11	2.00	<0.02	<0.02	<0.02	<0.02	11.0	<0.02	<0.02
Lamotte b Average UF	59.2	<0.02	<0.02	0.75	38.3	0.21	1.09	0.48	12.7	208	<0.02	0.34	2.43	<0.02	<0.02	<0.02	<0.02	11.0	<0.02	<0.02
Lamotte b Standard Deviation UF	85.9	n/a	n/a	0.38	19.1	0.22	0.63	0.25	6.9	104	n/a	0.48	1.25	n/a	n/a	n/a	n/a	5.5	n/a	n/a
Lamotte b Average -0.45	1.74	<0.02	<0.02	0.49	37.8	0.09	0.89	0.44	6.55	210	<0.02	0.17	3.15	<0.02	<0.02	<0.02	<0.02	10.9	<0.02	<0.02
Lamotte b Standard Deviation -0.45	0.29	n/a	n/a	0.17	0.9	0.01	0.08	0.04	0.24	2	n/a	0.19	1.31	n/a	n/a	n/a	n/a	0.1	n/a	n/a
Lamotte b Number of readings	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

TABLE 5.11D. ION CHROMATOGRAPHY ANION DATA FROM THE JOHN TWITTY ENERGY CENTER BOREHOLE (VALUES IN PPM).

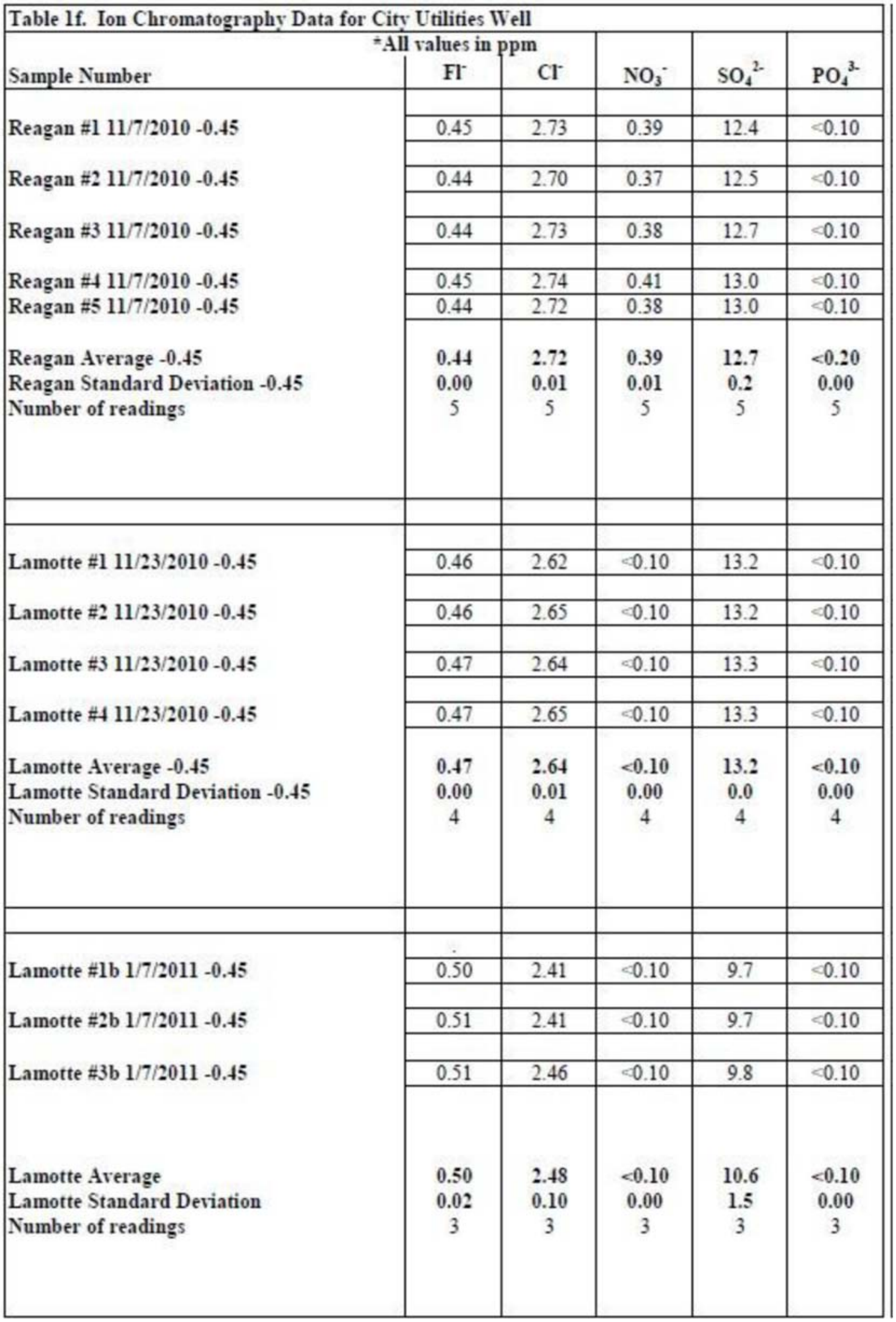


Table 1f. Ion Chromatography Data for City Utilities Well

*All values in ppm

Sample Number	Fl^-	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}
Reagan #1 11/7/2010 -0.45	0.45	2.73	0.39	12.4	<0.10
Reagan #2 11/7/2010 -0.45	0.44	2.70	0.37	12.5	<0.10
Reagan #3 11/7/2010 -0.45	0.44	2.73	0.38	12.7	<0.10
Reagan #4 11/7/2010 -0.45	0.45	2.74	0.41	13.0	<0.10
Reagan #5 11/7/2010 -0.45	0.44	2.72	0.38	13.0	<0.10
Reagan Average -0.45	**0.44**	**2.72**	**0.39**	**12.7**	**<0.20**
Reagan Standard Deviation -0.45	**0.00**	**0.01**	**0.01**	**0.2**	**0.00**
Number of readings	5	5	5	5	5
Lamotte #1 11/23/2010 -0.45	0.46	2.62	<0.10	13.2	<0.10
Lamotte #2 11/23/2010 -0.45	0.46	2.65	<0.10	13.2	<0.10
Lamotte #3 11/23/2010 -0.45	0.47	2.64	<0.10	13.3	<0.10
Lamotte #4 11/23/2010 -0.45	0.47	2.65	<0.10	13.3	<0.10
Lamotte Average -0.45	**0.47**	**2.64**	**<0.10**	**13.2**	**<0.10**
Lamotte Standard Deviation -0.45	**0.00**	**0.01**	**0.00**	**0.0**	**0.00**
Number of readings	4	4	4	4	4
Lamotte #1b 1/7/2011 -0.45	0.50	2.41	<0.10	9.7	<0.10
Lamotte #2b 1/7/2011 -0.45	0.51	2.41	<0.10	9.7	<0.10
Lamotte #3b 1/7/2011 -0.45	0.51	2.46	<0.10	9.8	<0.10
Lamotte Average	**0.50**	**2.48**	**<0.10**	**10.6**	**<0.10**
Lamotte Standard Deviation	**0.02**	**0.10**	**0.00**	**1.5**	**0.00**
Number of readings	3	3	3	3	3

Task 3.b. Determine Petrologic and Mineralogic Characteristics of the Confining Layer and Target Formation

HIGH PRESSURE AND TEMPERATURE CO_2 + H_2O TESTS; JOHN TWITTY ENERGY CENTER (JTEC)

Twenty-one core samples from JTEC were tested using the high pressure and temperature CO_2 + H_2O test apparatus at 90°C. The 90°C temperatures were not representative of any potential CO_2 sequestration site in the subsurface strata of Missouri, but rather were used to accelerate dissolution rate kinetics during reactions. Reaction rates typically double for a temperature rise of approximately 10°C, thus reactions occurring after one month at 90°C would be replicating a reaction process that is equivalent to approximately 32 months for a disposal horizon temperature of 40°C.

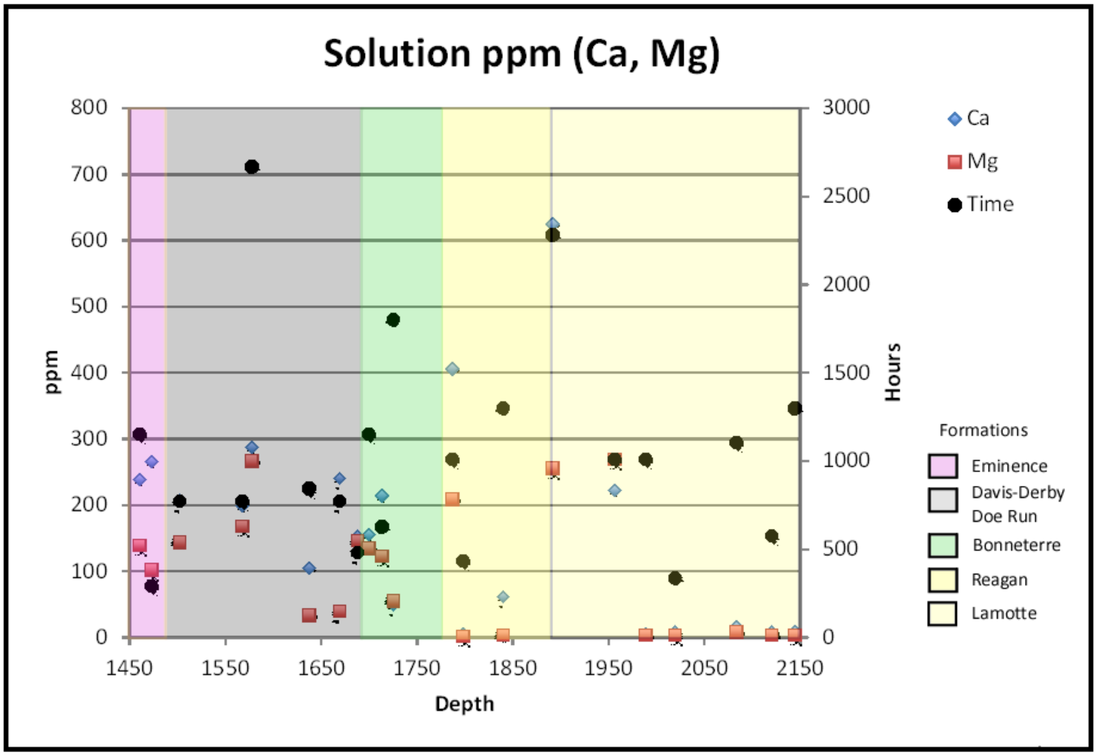
Solutions generated by reacting the sample solids in the CO_2 + H_2O experimental environment were analyzed by ICP-OES and the altered solids were examined by SEM-EDS analysis. The elemental release data is presented in the form of micromolar (μM) release rates of elements normalized to the measured geometric surface area of the sample wafers and reaction time (μM/day/m^2; Figure 5.36). All samples tested from the Eminence, Derby-Doerun, Davis, and Bonneterre Formations had a high release of Ca and Mg. These results were expected because these sedimentary units are dominated by dolomite and calcite minerals. At a depth greater than 1,725 ft there were generally decreasing amounts of Ca and Mg being released to solution, correlating to the transition from the Bonneterre Dolomite to the Reagan Sandstone lens. One exception to this trend was the sample at 1,892 ft (Reagan-Lamotte contact), which also displayed high release rates of Ca and Mg, coincident with glauconite and dolomite being present. Dolomite was detected in the XRD analysis of the samples (Table 5.12). The very high Ca release concentrations for this sample may also indicate some calcite being present. Tests with a 5% HCl solution on the solid sample did reveal a rapid reaction with effervescence of CO_2 gas bubbles, suggesting that calcite also was present, even though it was not detected in the XRD analysis. XRD techniques are only semi-quantitative, and minerals that are present in concentrations less than 5 to 10% may go undetected.

Reacted solid samples from the 90°C high pressure CO_2 + H_2O experiments were examined using the SEM-EDS analytical technique after the alteration experiments were completed. Samples from the Davis and Derby-Doerun confining layer (1,568 ft), the transition zone between the Davis and Bonneterre Formations (1,669.8 ft), and the Bonneterre Formation (1,713 ft; Figure 5.37) all displayed corrosion pitting that commonly was concentrated on along rhombohedral cleavage surfaces of carbonate minerals. All three samples also displayed the formation of minute alteration grains that were too small to obtain either a clear SEM image for morphological evaluation or an accurate EDS chemical analysis. The EDS investigations of these phases did indicate, however, elevated concentrations of Si, Al, and K; and are thus suggestive of the presence of illite clay or K-feldspar in addition to a carbonate phase. These grains may have precipitated during reactions or occurred as residual material, with clay minerals present in the dolomite being left behind and enriched after the original dolomite matrix had been dissolved away. The 1,713 ft Bonneterre sample also displayed scattered blocky grains with the same enrichment of Si, Al, and K that are suggestive of the presence of a low-temperature feldspar (microcline-adularia; $KAlSi_3O_8$).

Reacted solids from the 90°C high pressure CO_2 + H_2O experiments with the Lamotte Sandstone samples at 1,892 ft and 1,956 ft depths displayed the formation of a fine grained and oval shaped alteration phase (Figures 5.38b and 5.38d) and a platy-hexagonal morphology phase believed to be kaolinite (Figure 5.38c). The 1,892 ft Lamotte Sandstone sample was the longest time span test that was completed at 95 days of exposure. Reaction rates double approximately every 10°C rise in temperature, thus the 95-day reaction of the test sample at 90°C is estimated to reflect an equivalent rate of reaction of about 8.5 years at a hypothetical CO_2 repository at 40°C temperature. Overall reaction patterns from all tests from the JTEC core would imply a rapid reaction rate for any carbonate minerals contacted by the $H_2CO_{3(aq}$ enriched injection fluids, but relatively sluggish reactions for any silicate phases exposed to the same environment.

FIGURE 5.36. ELEMENTAL RELEASE FROM CORE SAMPLES FROM THE JTEC SITE AFTER COMPLETION OF THE HIGH-PRESSURE CO_2 + H_2O TESTS AT 90^{O}C. SAMPLES WERE PLOTTED AS A FUNCTION OF CORE DEPTH IN FT. A) CA AND MG RELEASE TO SOLUTION, VALUES IN PPM. B) RELEASE RATES NORMALIZED TO SURFACE AREA OF SAMPLES IN MICROMOLES PER DAY PER SQUARE METER OF SAMPLE SURFACE AREA.

a)



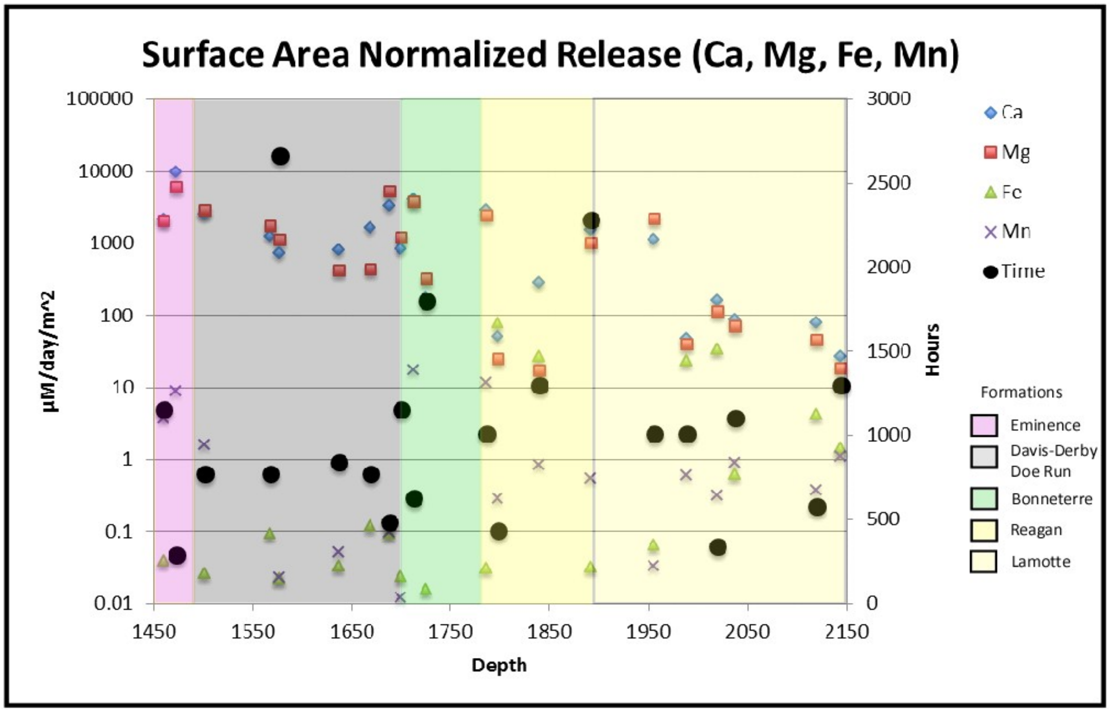


FIGURE 5.37. SCANNING ELECTRON MICROGRAPH IMAGES OF CORE SAMPLE FROM THE BONNETERRE FORMATION FROM THE JTEC SITE AT 1,713 FT AFTER 26 DAYS OF REACTION IN THE HIGH-PRESSURE CO_2 + H_2O TEST ENVIRONMENT AT 90^{O}C. A) SAMPLE DISPLAYED SURFACE ROUGHNESS FOLLOWING DISSOLUTION OF THE DOLOMITE AND SCATTERED DISTRIBUTION OF A RESISTANT BLOCKY PHASE. B) HIGH MAGNIFICATION IMAGE DISPLAYING DISSOLUTION PITS ORIENTED ALONG LINEAR TRACES OF RHOMBOHEDRAL GRAINS OF DOLOMITE.
BOXES SHOW TWO ZONES WHERE THE DISSOLUTION RESISTANT PHASE OCCURS. THIS PHASE IS ENRICHED IN SI-, AL-, AND K, C) ENERGY DISPERSIVE SPECTRUM FOR A BLOCKY PHASE WITH A COMPOSITION AND MORPHOLOGY CONSISTENT WITH THE PRESENCE OF MICROCLINE FELDSPAR ($KALSI_3O_8$).

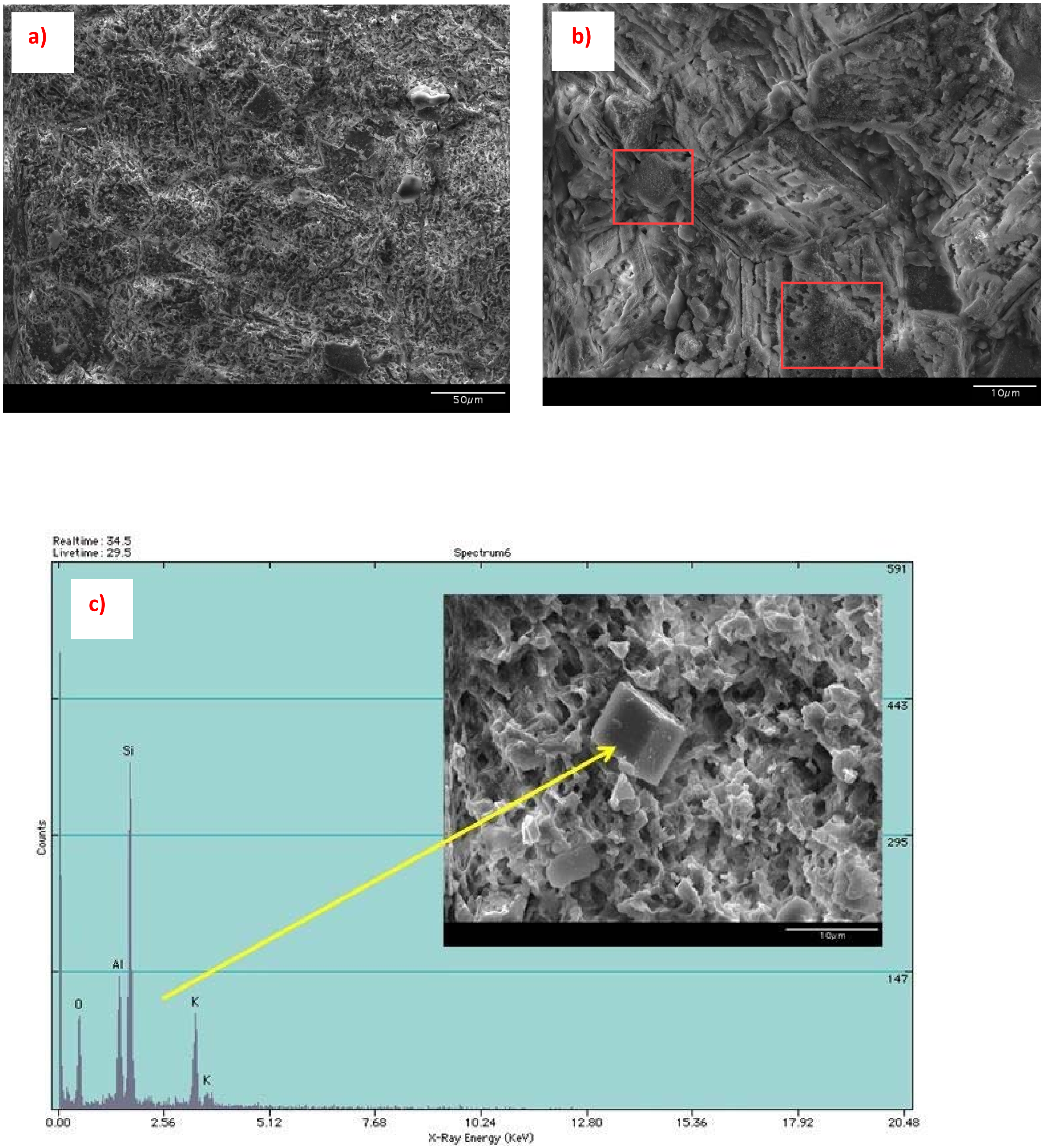
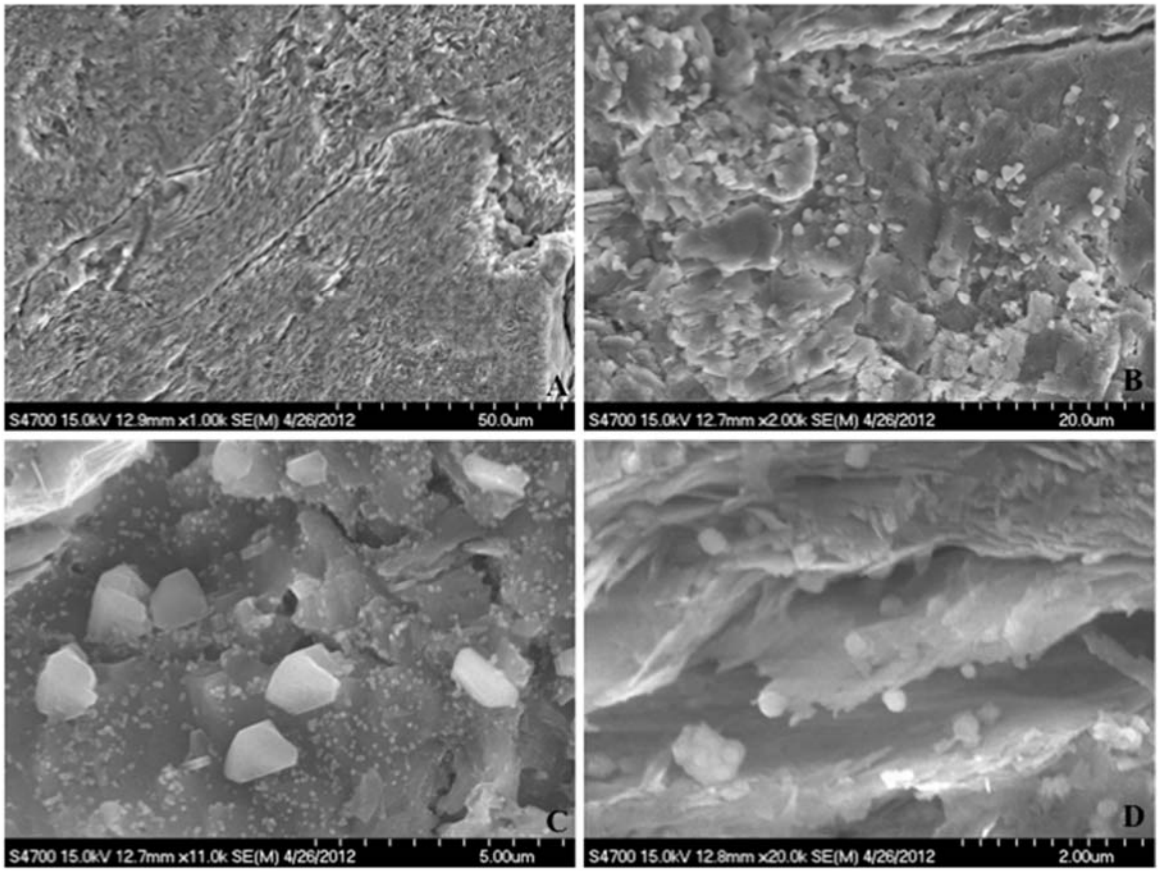


FIGURE 5.38. SCANNING ELECTRON MICROGRAPH IMAGES OF A CORE SAMPLE FROM THE LAMOTTE SANDSTONE AT THE JTEC SITE AT 1,956 FT AFTER 42 DAYS OF EXPOSURE IN THE HIGH-PRESSURE CO_2 + H_2O TEST AT 90^{O}C. A) PITTED SURFACE FOLLOWING ALTERATION, B) ALTERED SURFACE DISPLAYING PITTING AND PRECIPITATED ALTERATION PHASE(S), C) FORMATION OF SECONDARY PHASE WITH FLAKEY AND HEXAGONAL MORPHOLOGY BELIEVED TO BE KAOLINITE, AND D) FORMATION OF OVAL PHASE WITH A SIMILAR MORPHOLOGY AS DISPLAYED IN THE ALTERED 1,892 FT LAMOTTE SAMPLE.



X-RAY DIFFRACTION ANALYSIS OF THE CLAY-SIZED FRACTION OF SEDIMENTS FROM THE JTEC SITE

Fifteen samples were selected for XRD analysis from the core taken from the JTEC Site (Table 5.12). Samples were chosen based on the ICP-OES analysis of the solution after completion of the high-pressure tests. Samples that had elevated potassium, aluminum, or iron in solution were selected as rock units that may have dissolving feldspars and/or mafic phases. Glauconite and illite (and muscovite) are listed together when found on XRD because it is difficult to distinguish between the two due to similar peaks, although the peak at approximately 17.9 degrees 2-theta is weaker in glauconite as compared with illite. Most samples display illite as the predominant clay mineral phase.

TABLE 5.12A. RESULTS FROM XRD ANALYSIS OF SELECTED SECTIONS FROM CORES SAMPLES FROM THE JTEC SITE

Core Depth (ft)	Clay Mineral Types Found	Non-Clay Strong Peaks	Formation - Unit
1460	illite	dolomite	Eminence
1473	no identified clays	dolomite	Eminence
1528	no identified clays	quartz, dolomite	Derby-Doerun
1578	illite	dolomite	Davis/Derby-Doerun
1601	illite, glauconite?	calcite, dolomite	Davis
1637	illite		Davis
1669	illite, glauconite?	quartz, calcite, dolomite	Davis
1713	Na-smectite, illite	dolomite, quartz, mounting putty	Bonneterre
1799	no identified clays	quartz	Reagan
1840	no identified clays	quartz	Reagan
1892	glauconite/Illite	dolomite	Reagan
1989	no identified clays	quartz, calcite	Lamotte
2020	no identified clays	quartz	Lamotte
2088	illite	quartz	Lamotte
2144	no identified clays	quartz	Basal Lamotte

TABLE 5.12B. SEMI-QUANTITATIVE CLAY FRACTION PROPORTIONAL DETERMINATIONS FOR EACH SAMPLE ANALYZED AT THE JTEC SITE. CALCULATED PERCENTAGES ARE ESTIMATED TO BE ACCURATE TO WITHIN +/- 10%. "BD" = BELOW DETECTION.

Formation	Depth (ft)	% Illite	% Kaolinite	% Smectite	% Chlorite	% Glauconite
Eminence	1460	100	bd	bd	bd	bd
Eminence	1473		No	Clays	Detected	
Derby-Doerun	1528		No	Clays	Detected	
Davis/Derby-Doerun	1578	100	bd	bd	bd	bd
Davis	1601	100	bd	bd	bd	Trace?
Davis	1637	100	bd	bd	bd	bd
Davis	1669	100	bd	bd	bd	Trace?
Bonneterre	1713	90	bd	10	bd	bd
Reagan	1799		No	Clays	Detected	
Reagan	1840		No	Clays	Detected	
Reagan	1892	100	bd	bd	bd	bd
Lamotte	1989		No	Clays	Detected	
Lamotte	2020		No	Clays	Detected	
Lamotte	2088	100	bd	bd	bd	bd
Basal Lamotte	2144		No	Clays	Detected	

PORE VOLUME STORAGE CAPACITY

In summary, the JTEC borehole at the JTEC site encountered approximately 70 ft of the Reagan Sandstone at the top of the Lamotte Sandstone. The Reagan Sandstone had an average porosity of 10.78%, with a range 6% to 17%. The overall Lamotte Sandstone was approximately 120 ft thick, with an average porosity of 8.9% and a range from 4% to 17%.

Using a pressure gradient of about 0.45 psi/ft, an average depth of the Lamotte Sandstone of 2,000 ft, an average formation pressure of 915 psi, irreducible water saturation of 18.4%, and an average temperature of is 89^{o} F, the pore volume available for gas storage is calculated as:

$$PVgas = \frac{43560 * Porosity * (1 - Sw)}{\dfrac{Ps * (Tf + 460) * z}{Ts * Pi}}$$

where,

Bulk volume = 43,560 ft^2/acre*A*h

A = area in acres

h = formation thickness, ft

Pi = static reservoir pressure

Tf = reservoir temperature

z = gas factor

Sw = water saturation

Ts = surface temperature

Ps= surface pressure

$$PVgas = \frac{43560 * 0.089 * (1 - .184)}{\dfrac{14.7 * (89 + 460) * 0.79}{520 * 915}}$$

$$PVgas \approx 0.23 MMscf / acre - ft$$

Based on average porosity values and absolute pore volume, the total pore space for these formations is 0.23 million standard cubic feet (MMCF)/acre-ft, or 43.7 MMCF/acre given the 190 ft of Reagan and Lamotte Sandstones. This is an approximate volumetric estimate, which assumes displacement of all formation fluids to irreducible water saturation. This estimate does not reflect the actual CO_2 solubility, relative permeability effects, or injection characteristics modeled through the use of CMG simulation, and storage capacity defined by the CMG is preferred.

Since both the Reagan and Lamotte Sandstones are brine filled, CMG simulations indicated rapid pressure buildup in the confined model volume. Reservoir injection simulations were conducted with a wide range of assumptions and storage capacity is affected significantly by formation depth, thickness, and porosity. A model volume of 800 m x 800 m (2,624 ft x 2,624 ft) was found to be useful for simulating CO_2 injection. This model included 5-spot water withdrawal. The optimal injection rate for this reservoir configuration was found to be 60m^3/day (at reservoir conditions). Based on the optimum case studied 5.63×10^8 lbs of CO_2 were stored over 15.8 years with a stored relative efficiency of 2.5%pv/m^3. This is equivalent to storing 2.55×10^5 metric tons of CO_2.

Reservoir permeability for the Reagan Sandstone ranged from near 0 md to 900 md, with an average of 236 md over the interval. In the Lamotte Sandstone, the permeability ranged from 0 to 11.5 md, and the average permeability over the interval was 2.16 md, which is very low. A permeability of 20 md was used for the Lamotte Sandstone CMG modeling.

The Davis Formation evaluated at JTEC had low permeability (<0.001 md) and an average of 2.1% porosity. Only one zone (1,502-1,528 ft) demonstrated high porosity with a corresponding permeability of 0.15-0.19 md. It is suggested that cap rock has permeability in the nano-darcy range (one million times smaller than a millidarcy). Due to limitations in the equipment, it is not possible to directly measure the permeability below 0.001 md (1 millidarcy/1000 = 1 microdarcy). However, based on the measurements never reaching even 1 micordarcy, it appears the Davis Formation is a potential seal for CO_2 sequestration. Capillary pressure measurements were used on subsequent wells in an attempt to better understand CO_2 entry pressure for the Davis Formation.

Long term injection tests were not conducted at the site, but multiple intervals were tested for hydraulic conductivity. Average formation breakdown pressure for the Bonneterre was approximately 2,247 psi (bottom hole) and 1,851 psi for the Lamotte Sandstone. The lowest breakdown gradient seen in the Lamotte Sandstone was 1,443 psi/2,024 ft = 0.71 psi/ft. CMG simulations were limited to an even lower value, 0.61 psi/ft, as the simulations were completed prior to field pressure testing. Hence the maximum injection rate of 70 m^3/day (Figure 5.33) may be conservative.

The water drawn from both the Reagan and Lamotte Sandstones at the JTEC Site were Ca-Mg- bicarbonate dominated solutions with low total salinities. All three borehole water samples produced total dissolved solids (TDS) values from between 159 and 227 mg/L. The US EPA currently defines an Underground Source of Drinking Water (USDW) as an aquifer that contains <10,000 mg/L total dissolved solids and the JTEC salinities were a factor of approximately 45-fold below this level. It is thus recommended that this site be removed from further consideration as a CO_2 injection well.

2.THOMAS HILL ENERGY CENTER

Task 4.a. Determine the Permeability of Core Samples from the Confining Layer and Target Formation at the Four Missouri Power Plant Sites

Task 4.b. Determine Porosity, Permeability, Grain Size Distribution, Pore Throat Size and Shape, and Minerals Present in Representative Core Samples at the Four Missouri Power Plant Sites

POROSITY AND PERMEABILITY

Table 5.13 summarizes the porosity and permeability measurements of core samples taken from the Thomas Hill borehole. Based on the previously good agreement of Missouri S&T and Core lab results for the JTEC borehole, no further core samples were sent to Core Labs for evaluation.

Average porosity and permeability values are summarized in Tables 5.14 and 5.15. Figure 5.39 through 5.42 provide a graphic representation of the data.

TABLE 5.13. POROSITY AND PERMEABILITY RESULTS FOR CORE SAMPLES FROM THE THEC SITE

Formation	Sample ID	Depth	Porosity	Permeability	Grain Density
		ft	%	md	g/cc
Derby-Doerun (Formation top: 1,951 ft)	1V	1959	0.19	-	2.803
	1H	1959	-	-	-
Davis (Formation top: 1,985 ft)	8V	2024	7.20	0.057	2.696
	8H	2024	9.12	0.1069	2.696
	12V	2059	10.66	0.0255	2.658
	12H	2059	11.35	0.069	2.658
	13V	2071	6.44	0.00012	2.617
	13H	2071	5.08	0.001	2.626
	14V	2081	0.63	0.00096	2.697
	14H	2081	1.54	0.0923	2.723
Bonneterre (Formation top: 2,083 ft)	15V	2093	-	0.0015	-
	15H	2093	-	0.0008	-
	18V	2120	1.92	0.0065	2.781
	18H	2120	1.07	0.0062	2.767
	28V	2214	0.71	0.033	2.85
	28H	2214	1.44	0.0258	2.832
	35V	2282	14.16	0.04	2.767
	35H	2282	9.69	3.073	2.845
	40V	2327	11.20	0.3649	2.649
	40H	2327	14.53	3.3255	2.661
Lamotte (Formation top: 2,333 ft)	42T	2345	9.25	11.033	2.636
	42B	2345	7.89	11.033	2.636
	44V	2362	11.21	0.0341	2.642
	44H	2362	8.31	1.202	2.643
	48T	2403	9.93	2.1132	2.661
	48B	2403	8.74	2.177	2.637
	50T	2420	10.64	171.88	2.661
	50B	2420	13.09	28.377	2.647
	51T	2429	6.21	306.58	2.641
	51B	2429	17.34	7.021	2.732
	55V	2468	9.88	7.6489	2.638
	55H	2468	12.72	39.168	2.641
	58T	2496	13.22	93.743	2.645
	58B	2496	13.12	63.406	2.648
	63AT	2539	12.99	5.531	2.638
	63AB	2539	8.36	5.673	2.632

TABLE 5.14. POROSITY AND PERMEABILITY RESULTS FOR CORE SAMPLES FROM THE CONFINING LAYER FOR THE THOMAS HILL SITE

Depth	Average porosity	Vertical permeability	Horizontal permeability	Average grain density
ft	%	md	md	g/cc
1959	0.19	-	-	2.803
2024	8.16	0.057	0.1069	2.696
2059	11.01	0.0255	0.069	2.658
2071	5.76	0.00012	0.001	2.622
2081	1.09	0.00096	0.0923	2.710
2093	-	0.0015	0.0008	-
2120	1.49	0.0065	0.0062	2.774
2214	1.07	0.033	0.0258	2.841
2282	11.93	0.04	3.073	2.806
2327	12.86	0.3649	3.3255	2.655

FIGURE 5.39. DERBY-DOERUN, DAVIS FORMATION AND BONNETERRE FORMATION POROSITY

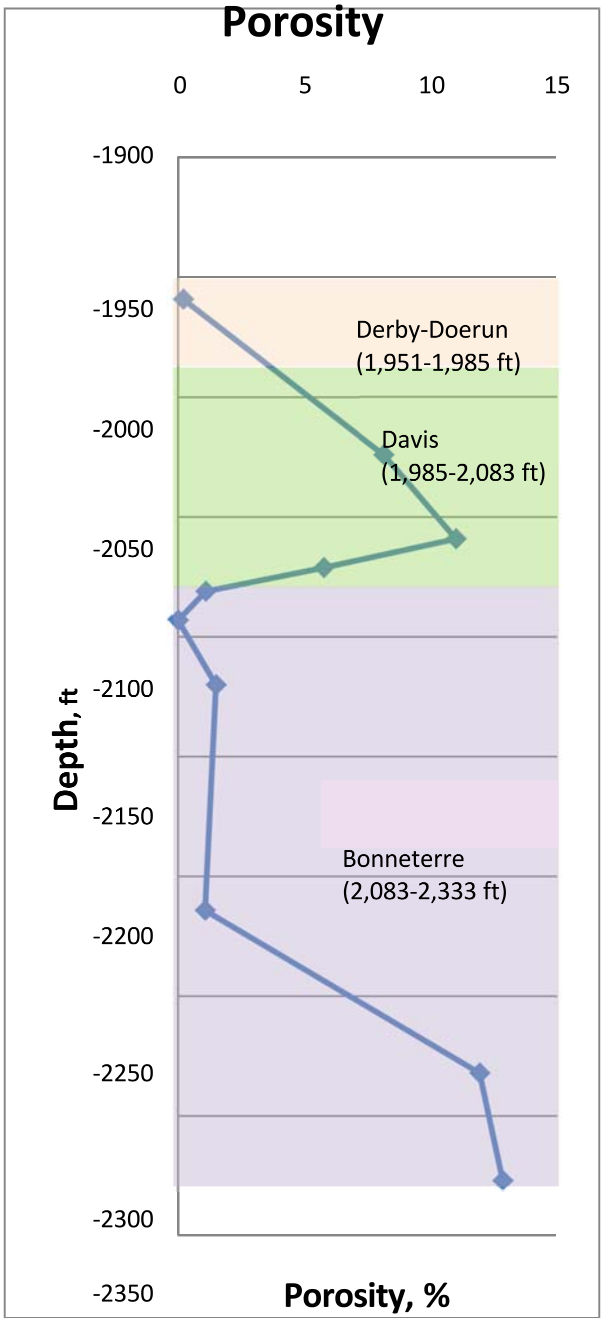


FIGURE 5.40. DERBY-DOERUN, DAVIS FORMATION AND BONNETERRE FORMATION VERTICAL

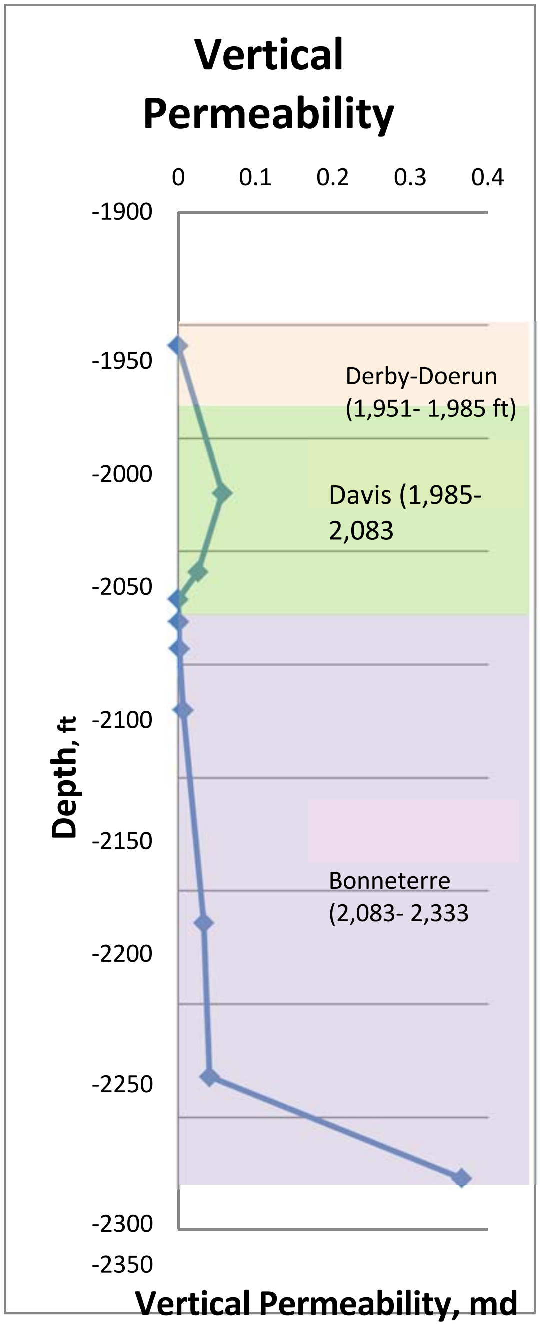


FIGURE 5.41. DERBY-DOERUN, DAVIS FORMATION AND BONNETERRE FORMATION POROSITY HORIZONTAL PERMEABILITY

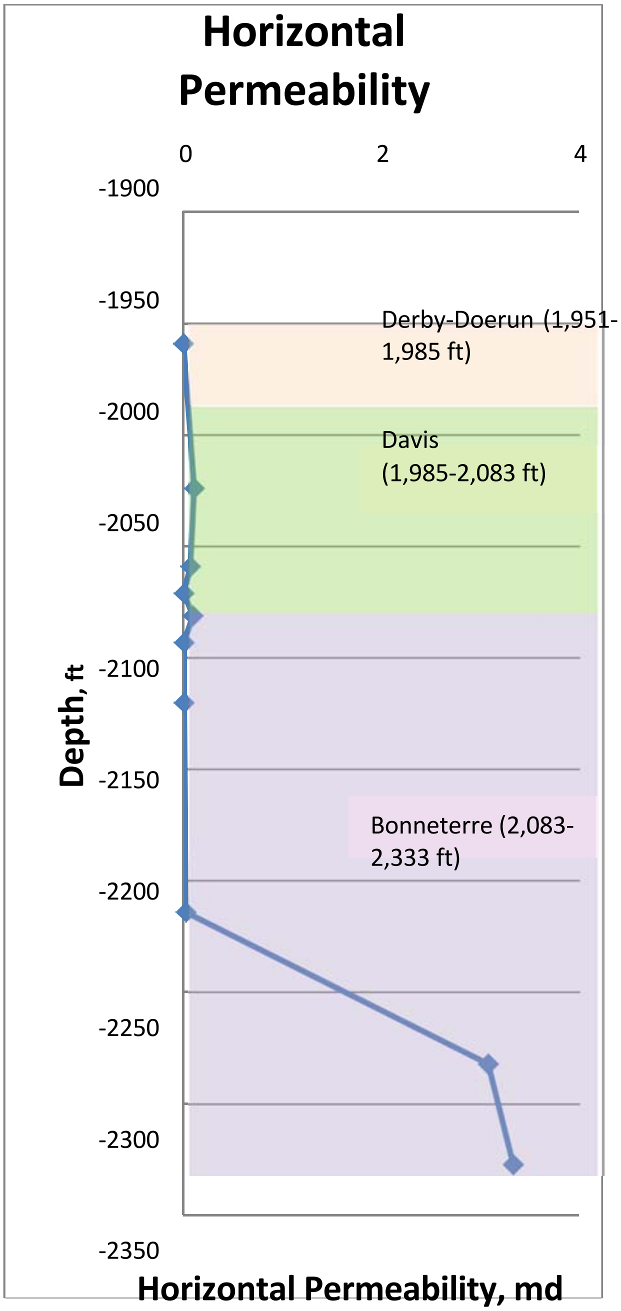
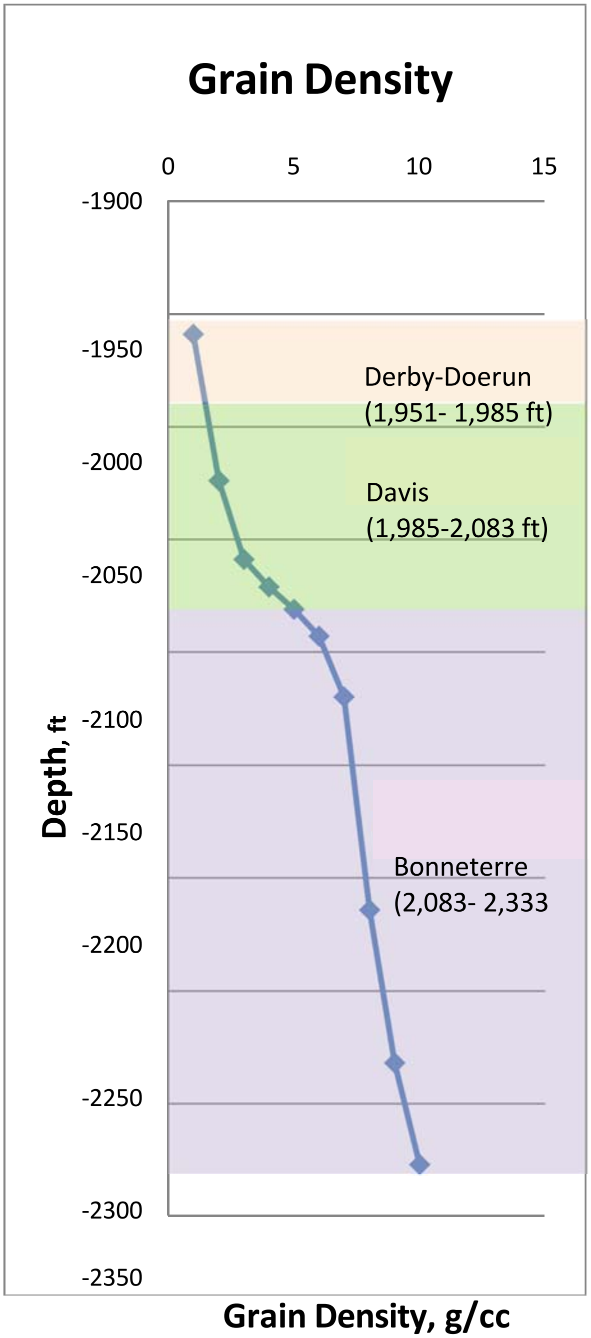


FIGURE 5.42. DERBY-DOERUN, DAVIS FORMATION AND BONNETERRE FORMATION GRAIN DENSITY



Core analysis of the confining layer indicates a range of permeability from less than one microdarcy to 3 millidarcies. Two samples, at 2,071 ft and 2,093 ft exhibited permeability of one microdarcy or less. The vertical permeability was measured by rotating core samples and indicated very low (<.001 md) vertical permeability from 2,071 ft to 2,120 ft. Average porosity for the confining later was approximately 6%, with a range of 0.2% to 12.9%.

Average core porosity for the target formation was 10.8% with a range of 8.6% to over 13%. The porosity was high throughout the target formation as shown in Table 15 and Figures 5.43 through 5.45. Average core permeability was 47 md with a range of 5.7 md to 307 md.

TABLE 5.15. AVERAGE POROSITY AND PERMEABILITY RESULTS FOR CORE SAMPLES FROM THE TARGET FORMATION FROM THE THEC SITE.

Depth	Average porosity	Average permeability	Average grain density
ft	%	md	g/cc
2345	8.57	11.033	2.636
2362	9.76	11.033	2.643
2403	9.33	2.1451	2.649
2420	11.87	100.129	2.654
2429	11.77	156.801	2.6865
2468	11.30	23.408	2.6395
2496	13.17	78.575	2.6465
2539	10.68	5.602	2.635

Figures 5.43 through 5.45 provide a graphical representation of the data.

FIGURE 5.43. LAMOTTE SANDSTONE POROSITY

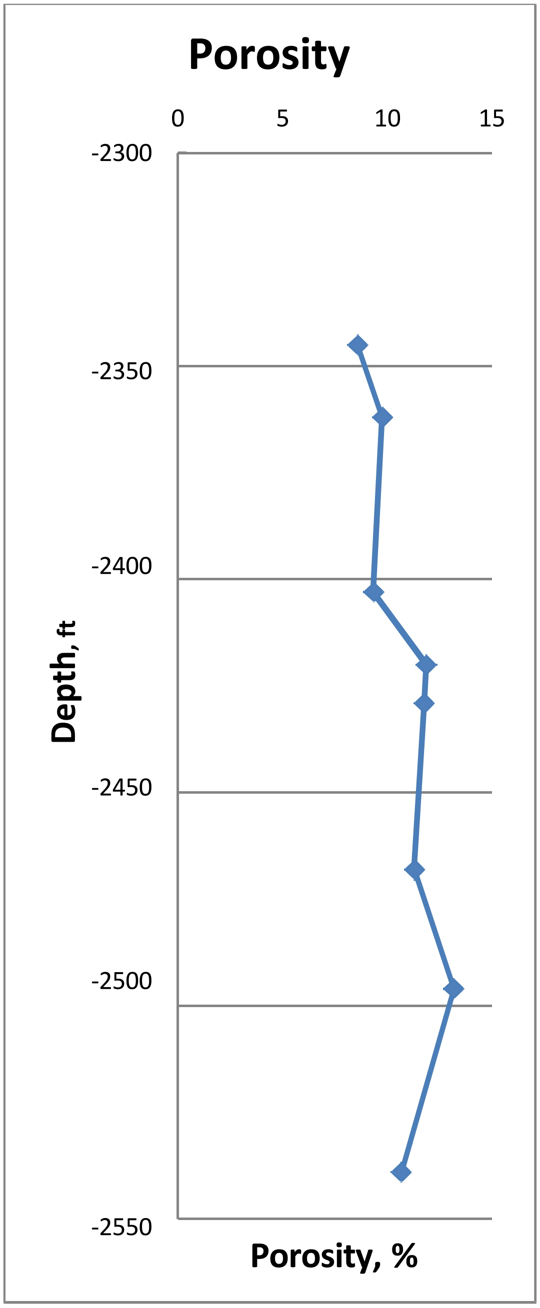


FIGURE 5.44. LAMOTTE SANDSTONE PERMEABILITY

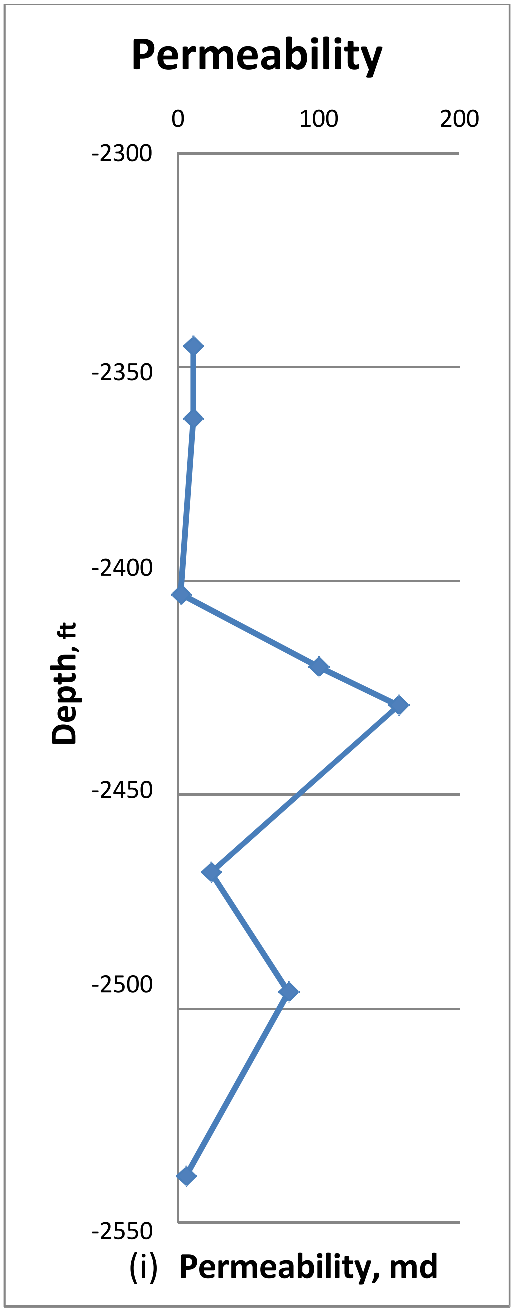
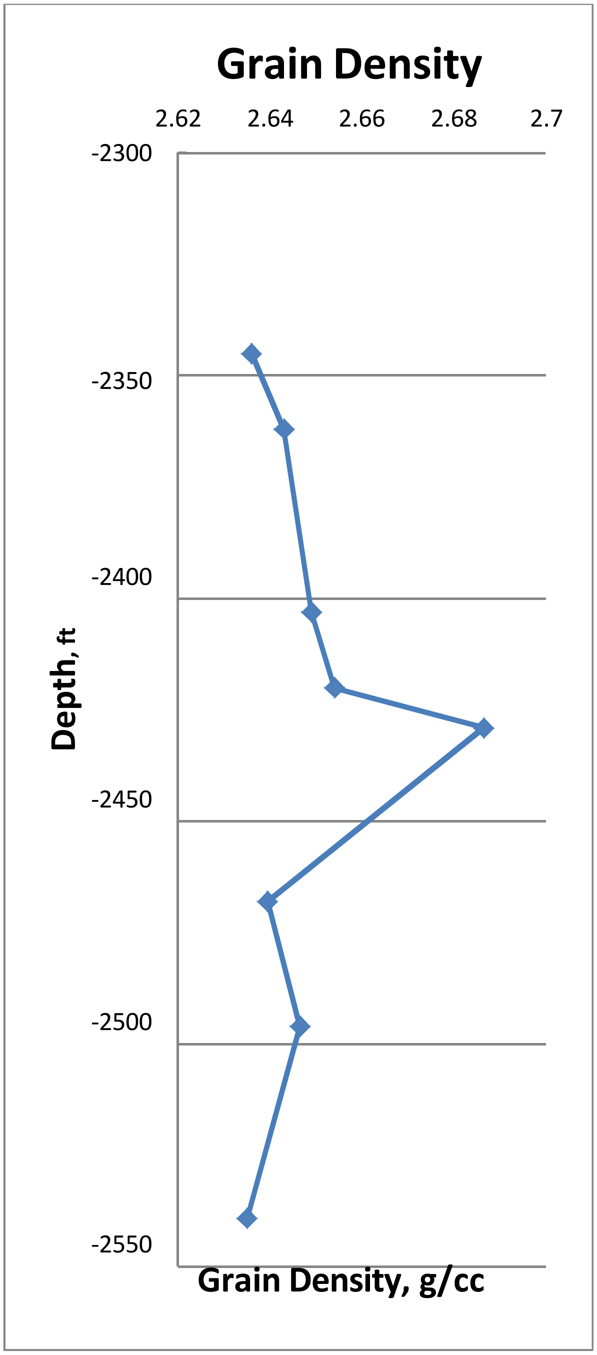


FIGURE 5.45. LAMOTTE SANDSTONE GRAIN DENSITY



Task 3.c. Determine permeability of the confining layer and target formation

Borehole Log Analysis

Open hole logs were run throughout the entire confining layer and target formation, ranging from approximately 1,930 ft to 2,500 ft. The open hole log suite included a Density Log, Gamma Ray Log, Resistivity Log, and Neutron Porosity Log. The data from these logs were analyzed to determine shale content of the formations as a percentage of total rock grain volume, and to calculate formation porosity.

The Gamma Ray Log run with the Density Log had a clean sand value of 0 American Petroleum Institute (API) units and a 100% shale value of 193.8 API units. The Gamma Ray Log run along with the Resistivity Log had a clean sand value of 9.2 API units and a 100% shale value of 203.3 API units. The Gamma Ray Log run with the Neutron Log had a clean sand value of 2 API units and a 100% shale value of 298.1 API.

All the well logs were plotted in Figure 5.46. Shale volumes for the borehole at the THEC site were plotted for individual well logs (Figures 5.47 through 5.52). A comparison plot of the shale volumes can be found in Figure 5.53.

FIGURE 5.46. COMBINED BOREHOLE LOGS FOR THE THEC BOREHOLE SITE CONFINING LAYERS

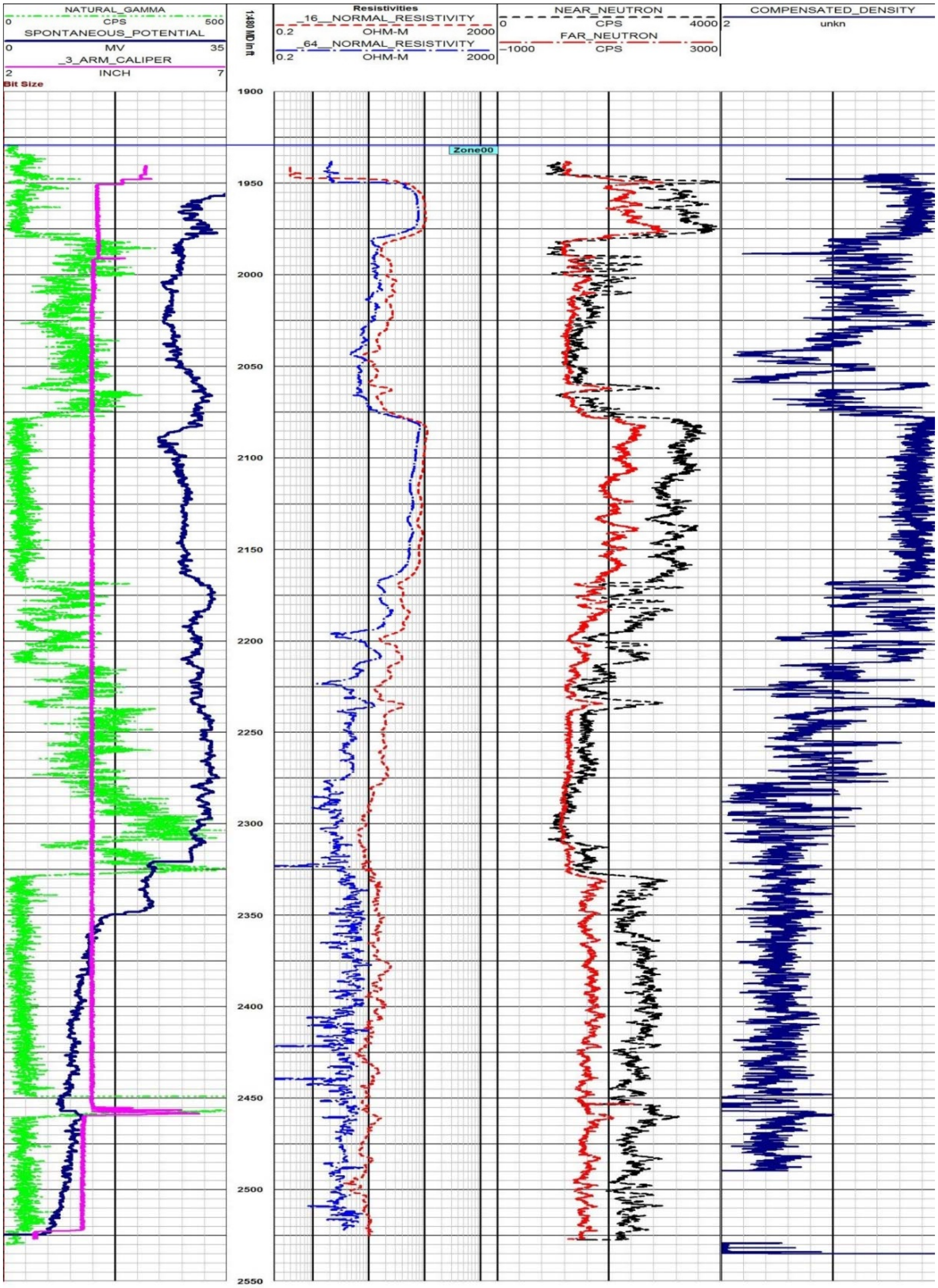


FIGURE 5.47. SHALE VOLUME (%) FROM THE GAMMA RAY LOG RUN ALONG WITH THE DENSITY LOG FOR THE THEC SITE.

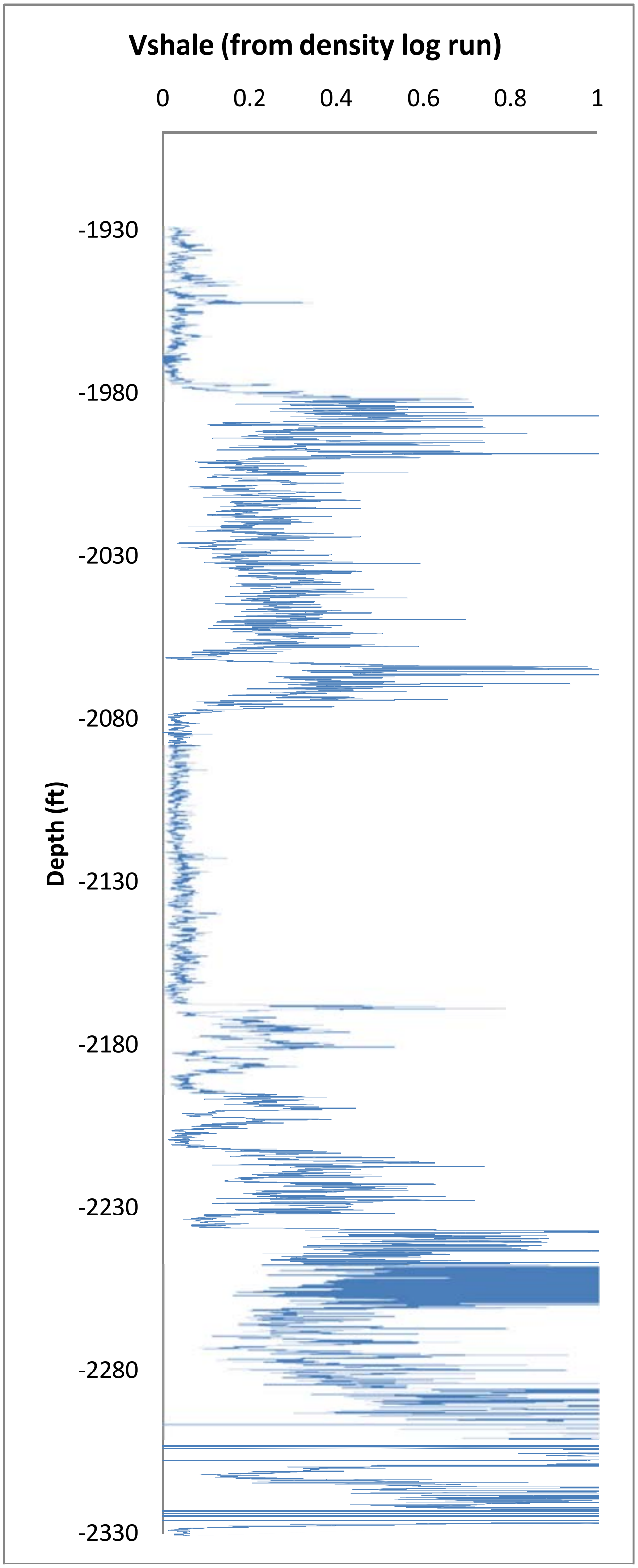


FIGURE 5.48. SHALE VOLUME (%) FROM THE GAMMA RAY LOG RUN ALONG WITH THE RESISTIVITY LOG FOR THE THEC SITE.

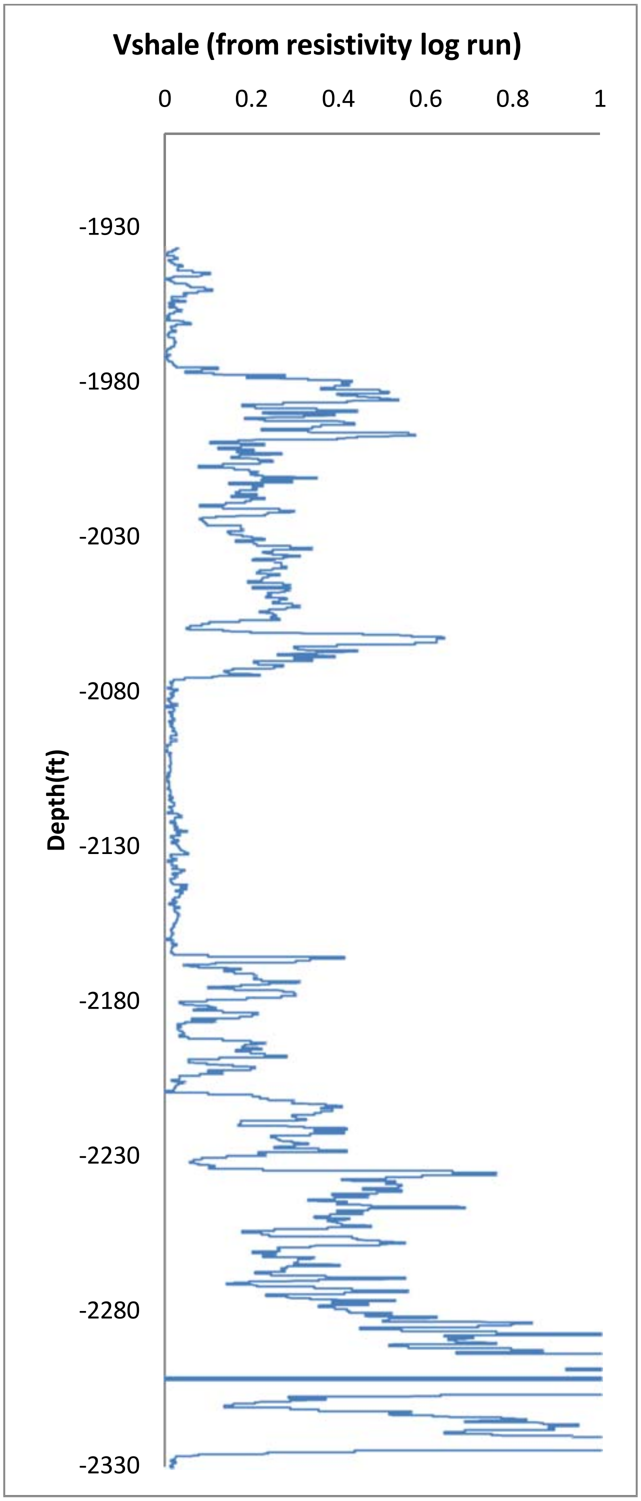
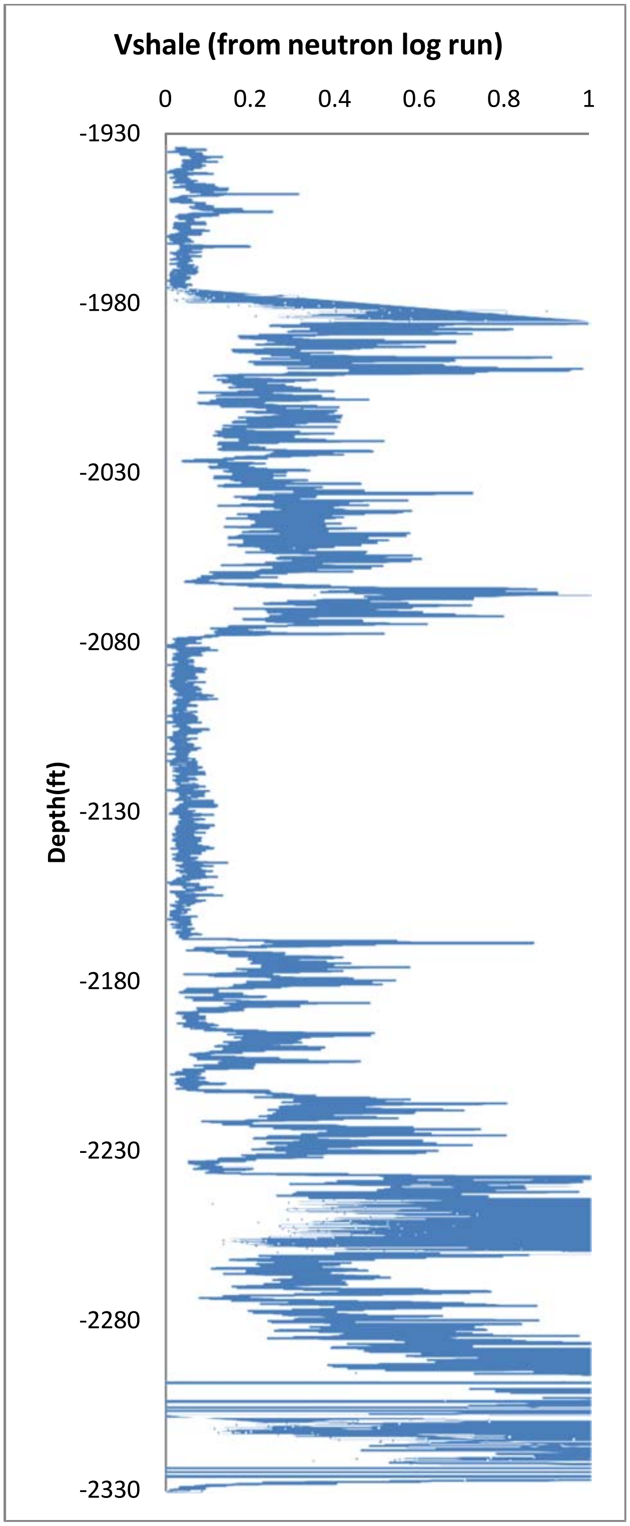


FIGURE 5.49. SHALE VOLUME (%) FROM THE GAMMA RAY LOG RUN ALONG WITH THE NEUTRON LOG FOR THE THEC SITE



TARGET FORMATION

The Gamma Ray Log run with the Density Log had a clean sand value of 0 API units and a 100% shale value of 193.8 API units. The Gamma Ray Log run along with the Resistivity Log had a clean sand value of 9.2 API units and a 100% shale value of 203.3 API units. The Gamma Ray Log run with the Neutron Log had a clean sand value of 2 API units and a 100% shale value of 298.1 API units.

Results from the shale volume calculation were then compared to the permeability results obtained from core samples in the Lamotte Sandstone. These plots can be found in Figure 5.54.

FIGURE 5.50. SHALE VOLUME (%) FROM THE GAMMA RAY LOG RUN ALONG WITH THE DENSITY LOG FOR THE THEC SITE

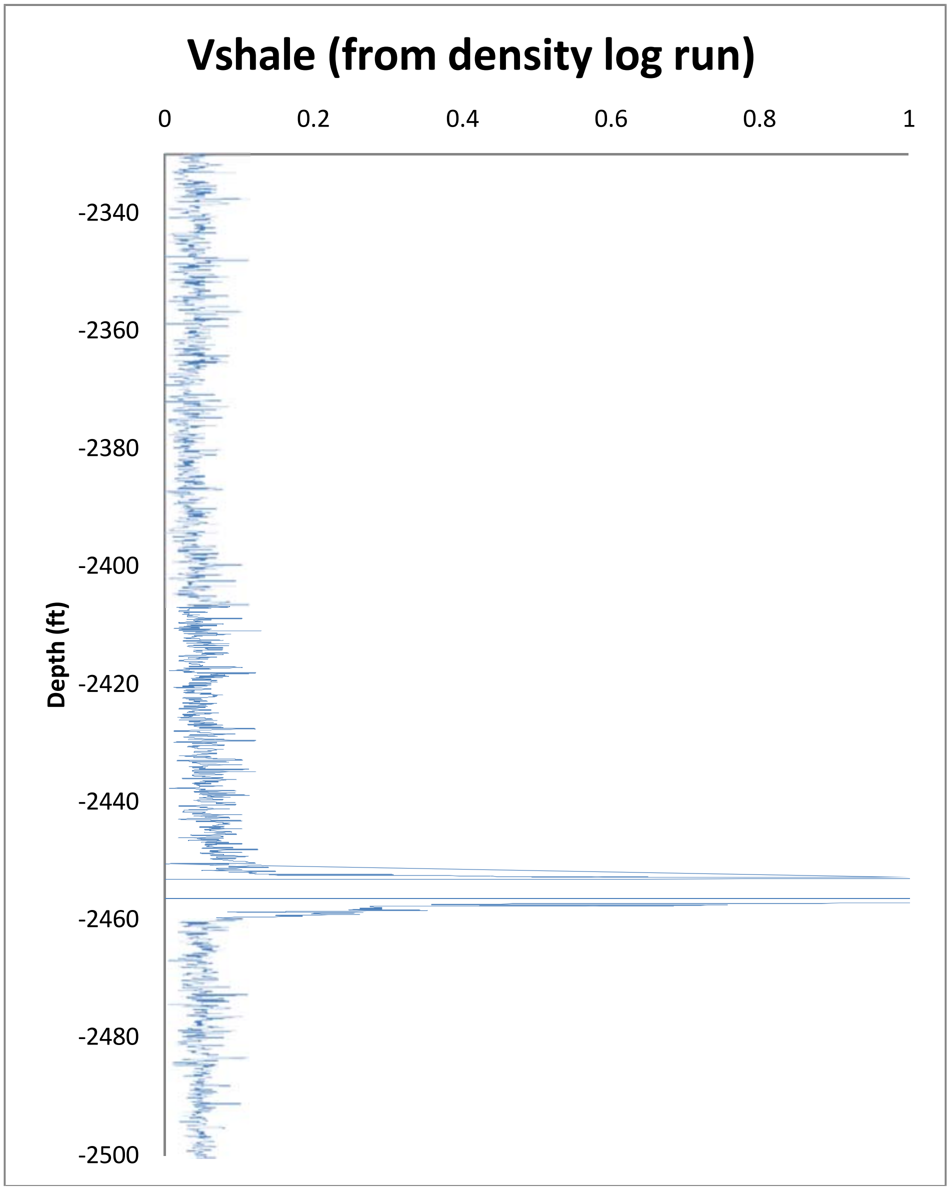


FIGURE 5.51. SHALE VOLUME (%) FROM THE GAMMA RAY LOG RUN ALONG WITH THE RESISTIVITY LOG FOR THE THEC SITE

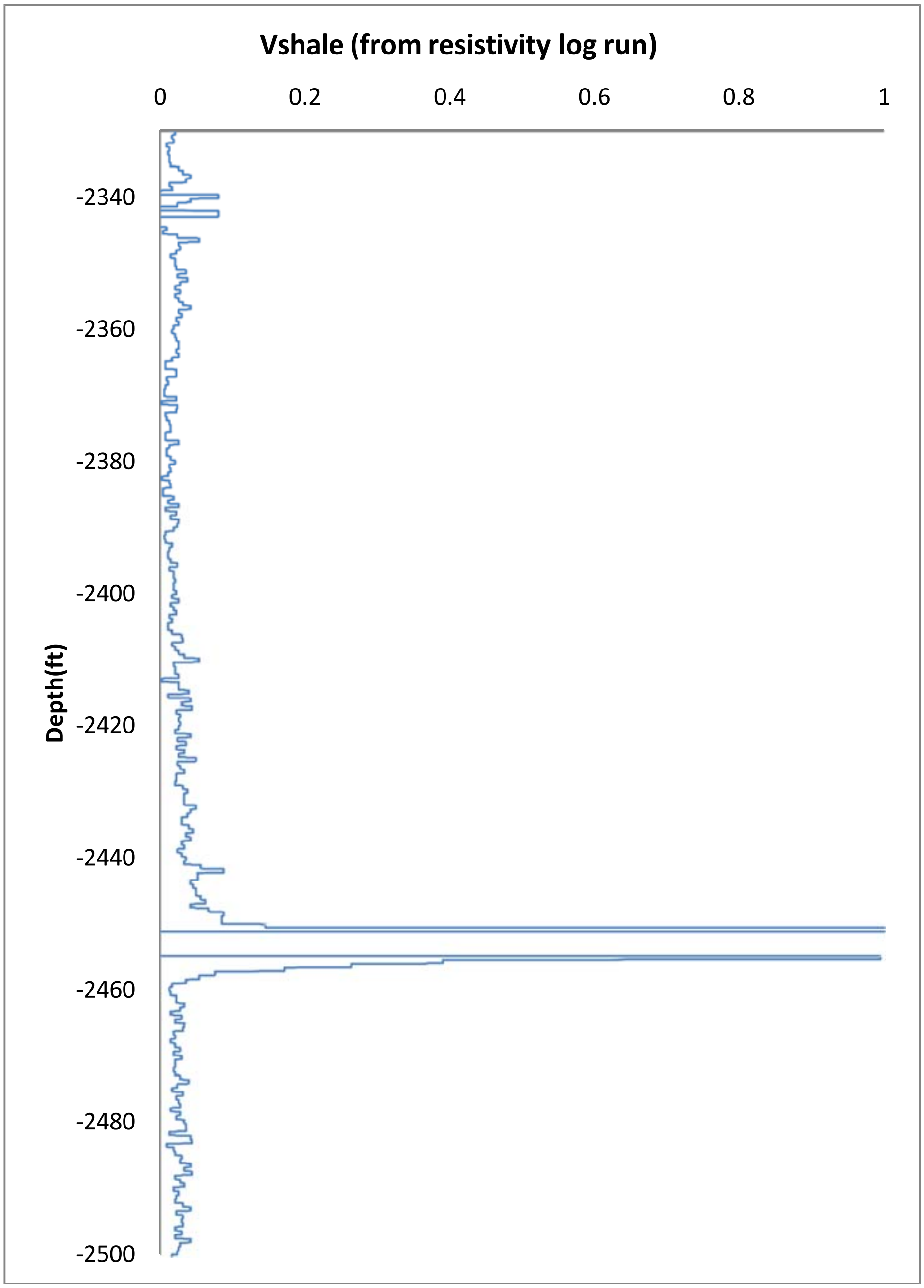


FIGURE 5.52. SHALE VOLUME (%) FROM THE GAMMA RAY LOG RUN ALONG WITH THE NEUTRON LOG FOR THE THOMAS HILL SITE

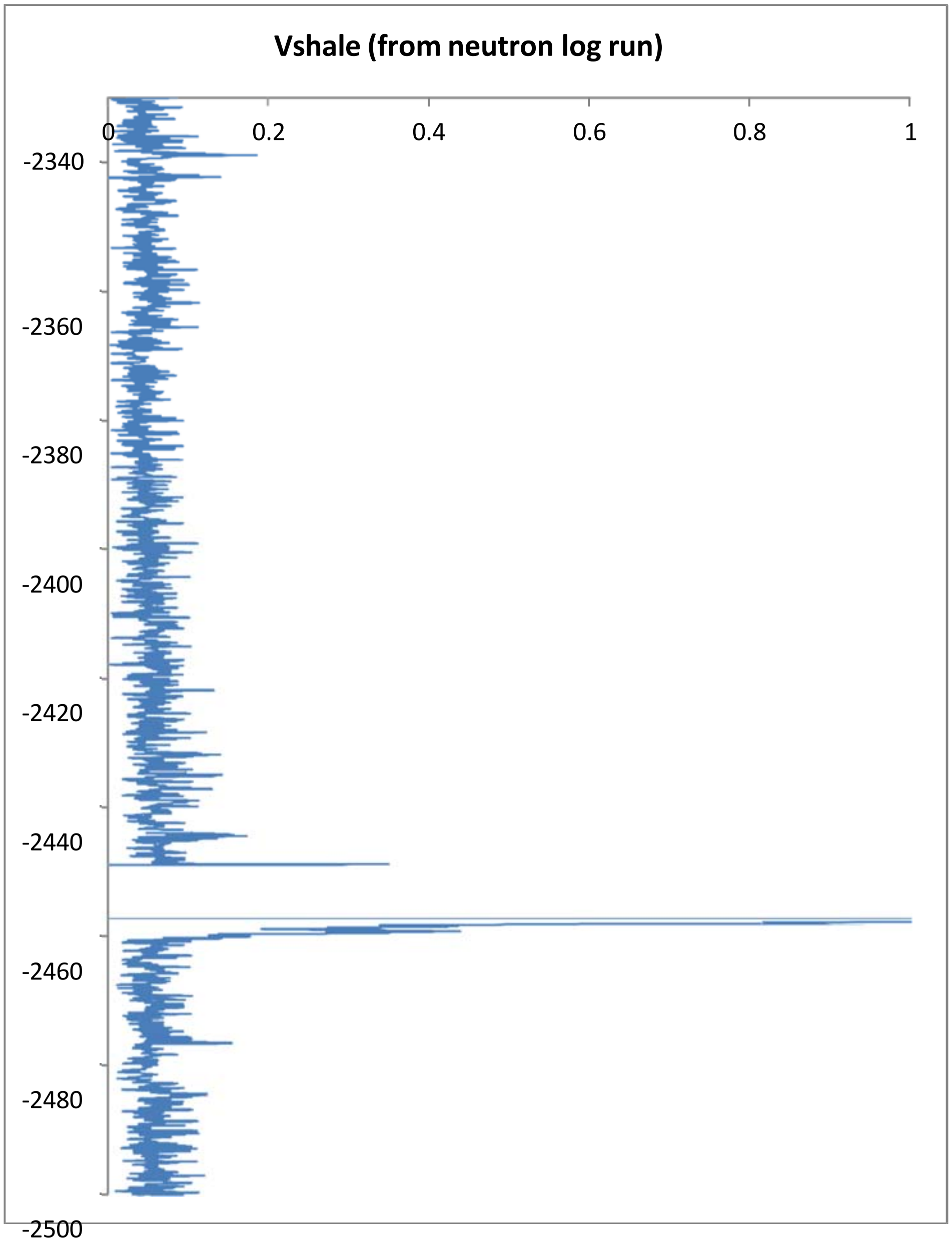
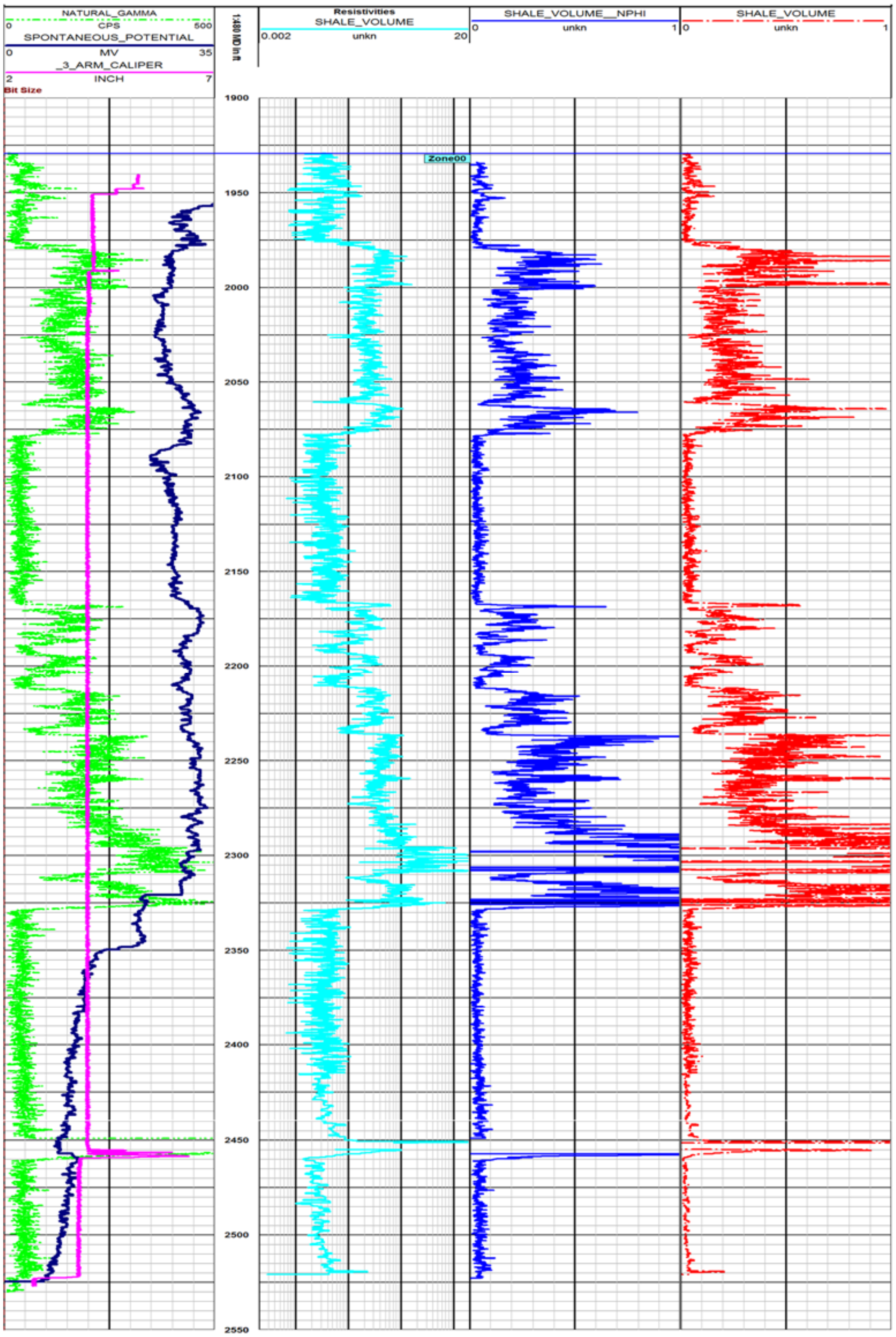
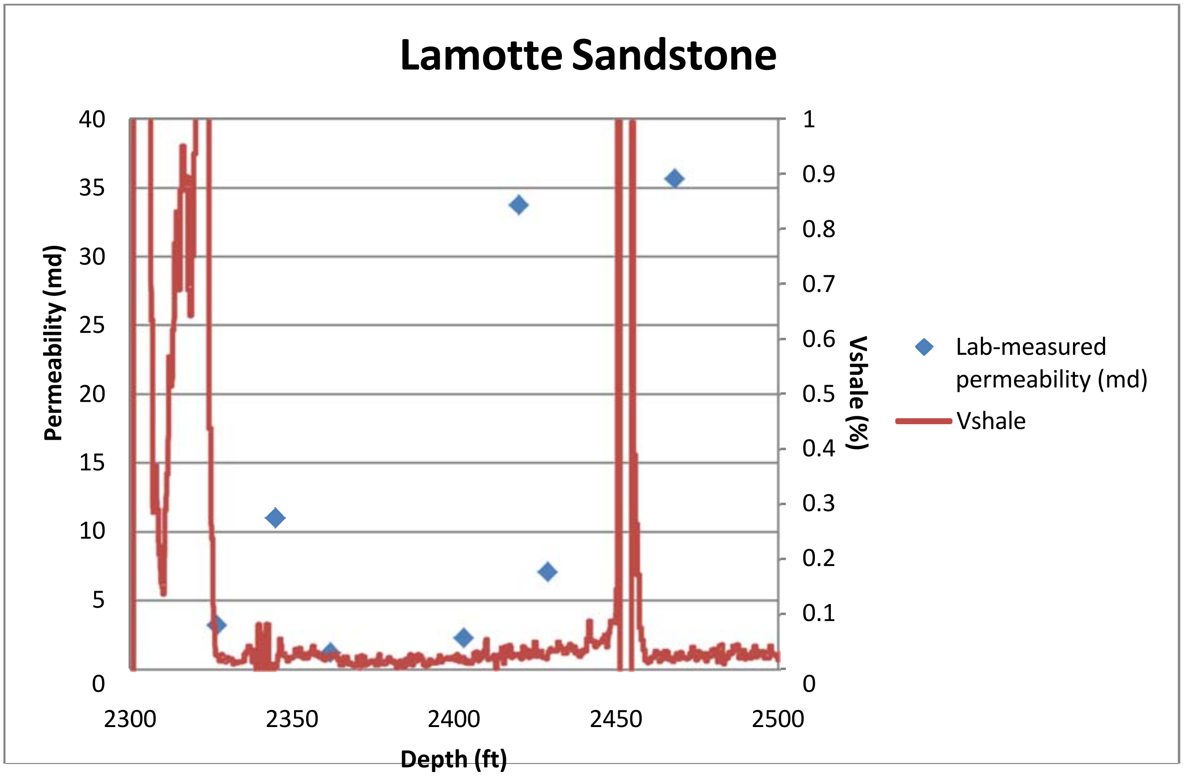


FIGURE 5.53. BOREHOLE LOGS AND SHALE VOLUMES COMPARISON FOR THE THEC SITE



As shown in Figure 5.53, shale volumes calculated from each of the three logs are similar for both the confining layer and target formation. The shale volumes are lower in the Derby-Doerun Formation, and are very high in the Davis Formation. Figure 5.54 provides a summary of permeability and shale volumes found in the THEC borehole.

FIGURE 5.54. PERMEABILITY AND SHALE VOLUME IN THE LAMOTTE SANDSTONE FOR THE THOMAS HILL SITE



POROSITY

The porosity measured during the core analysis was compared to results from each of the three methods used to estimate the porosity with well logs. These results are summarized in Tables 5.16 and 5.17 and illustrated graphically in Figures 5.55 and 5.56.

TABLE 5.16. SUMMARY COMPARISON OF POROSITY OF THE CONFINING LAYER FROM WELL LOGGING AND LABORATORY ANALYSIS OF CORE SAMPLES FROM THE THOMAS HILL SITE

Depth	Lab-measure porosity (%)	Well log-determined porosity (%)
ft		
1959	0.19	0.50
2024	8.16	8.33
2059	11.01	10.98
2071	5.76	5.56
2081	1.09	3.22
2093	-	9.423
2120	1.49	1.60
2214	1.07	3.94
2282	11.93	13.37
2327	12.86	11.11

FIGURE 5.55. COMPARISON OF POROSITY FROM BOREHOLE LOGGING AND LABORATORY ANALYSIS OF CORE SAMPLES FROM THE THEC SITE.

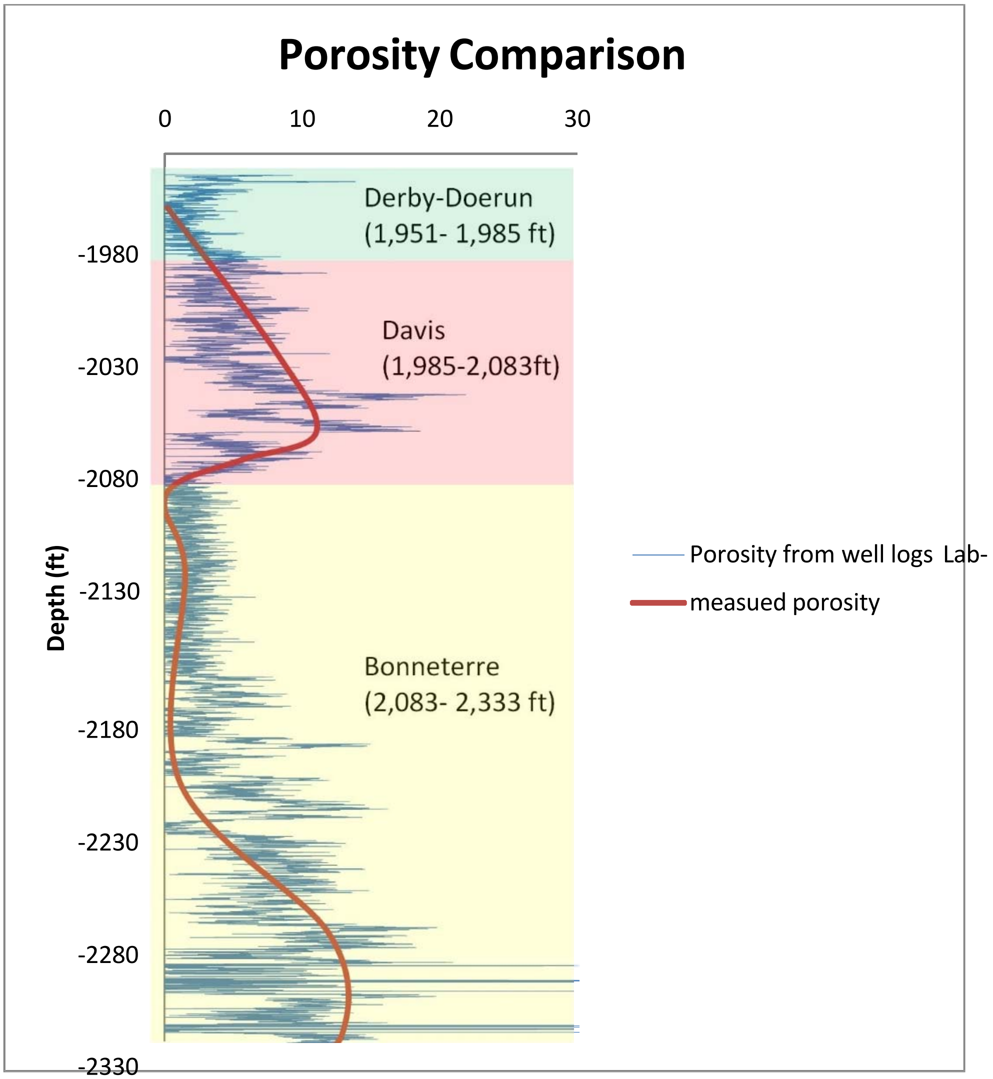


TABLE 5.17. SUMMARY COMPARISON OF LAMOTTE SANDSTONE POROSITY VALUES FROM WELL LOGGING AND LABORATORY ANALYSIS OR CORE SAMPLES FROM THE THOMAS HILL SITE

Depth (ft)	Lab-measure porosity (%)	Well logging-determined porosity (%)
2345	8.57	9.39
2362	9.76	9.50
2403	9.33	9.94
2420	11.87	10.44
2429	11.77	11.80
2468	11.30	10.09
2497	13.17	12.62

FIGURE 5.56. COMPARISON OF LAMOTTE SANDSTONE POROSITY FROM BOREHOLE LOGGING AND LABORATORY ANALYSIS OF CORE SAMPLES FROM THE THEC SITE

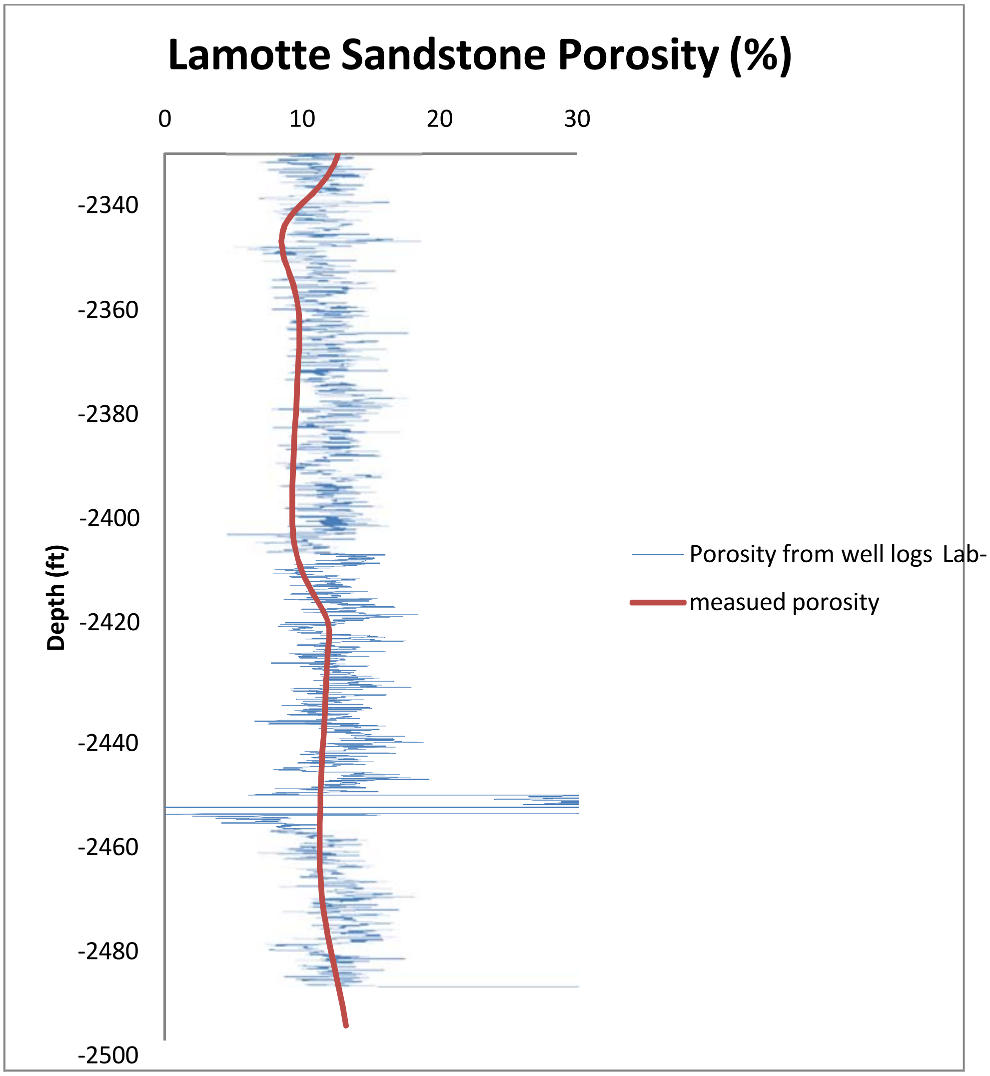
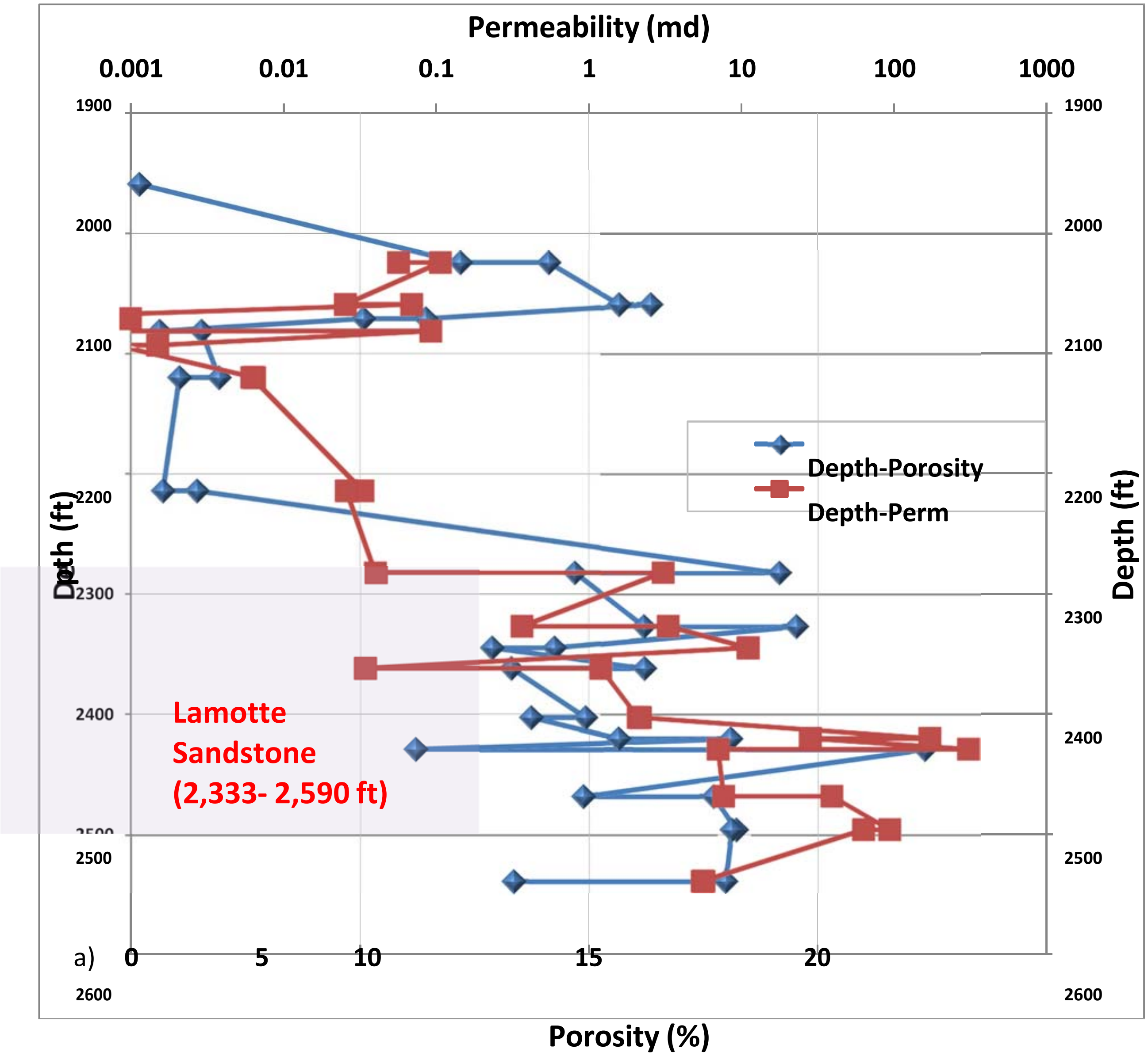


FIGURE5. 57. PERMEABILITY AND POROSITY VS. DEPTH FOR THE THOMAS HILL SITE



Well log calculated porosity and core laboratory measurements are in good agreement in the THEC borehole. Well logs confirm there is a low porosity zone in the Davis Formation from approximately 2,071 to 2,120 ft. This zone coincides with low permeability (<.001 md) as shown in Figure 5.57. The Davis Formation in the THEC borehole is similar to that found in the JTEC borehole, and appears to offer similar potential as a seal for CO_2 sequestration.

Figure 5.57 also shows that the Lamotte Sandstone in the THEC borehole has approximately a 120 foot section with average core porosity of 10.8%. There is no Reagan Sandstone present in the THEC borehole, but the porosity of the Lamotte is similar to that of the Reagan sandstone in the JTEC well. Permeability averages 47 md and ranges from 5.7 md to 307 md. From approximately 2,420 ft to 2,500 ft the Lamotte Sandstone has a permeability averaging 90 md. While the porosity in the Lamotte Sandstone is similar to what was found in the JTEC borehole, the permeability is significantly higher.

FRACTURE GRADIENT DETERMINATION

No fracture gradient test (diagnostic fracture injection test –DFIT or miniFrac) was carried out at the THEC site because of unforeseen borehole integrity issues, and as result, the fracture gradient was determined using standard fracture gradient calculation methods. Methods used to calculate the fracture gradient were the Eaton's method, Hubbert and Willis, and the Pennebaker correlation Method. The equations used in each method are given below.

EATON'S EQUATION:

$$\sigma_{H(\min)} = \frac{v}{(1-v)}\left(\sigma_{ob} - P_p\right) + P_p + \sigma_{tec}$$

$\sigma_{H(\min)}$ = Minumum Horizontal Stress (Least Principal Stress or Minimum Principal Stress)
v = Poisson's ratio
σ_{ob} = Overburden Stress or Major Principal Stress
P_p = Pore pressure or reservoir pressure
σ_{tec} = Tectonic stress
Overburden stress gradient was assumed to be 1.00 psi/ft

HUBBERT AND WILLIS EQUATION:

$$\sigma_{H(\min)} = \frac{\sigma_{ob}}{3} + P_p \qquad \sigma_{H(\min)} = \frac{\sigma_{ob} - P_p}{3} + P_p \qquad \sigma_{H(\min)} = \frac{\sigma_{ob} + 2P_p}{3}$$

$\sigma_{H(\min)}$ = Minumum Horizontal Stress (Least Principal Stress or Minimum Principal Stress)
σ_{ob} = Overburden Stress or Major Principal Stress
P_p = Pore pressure or reservoir pressure

PENNEBAKER CORRELATION:

$$\sigma_{H(\min}) = F_\sigma \sigma_{ma} \qquad \sigma_{H(\min}) = F_\sigma \sigma_{ob}$$

The Pennebaker Correlation F_σ, is also called effective (matrix) stress ratio and is a ratio that is correlated with depth. The two plots in Figure 5.58 and the Pennebaker correlation can be used to estimate the overburden stress if the depth of the borehole is known. The first plot gives the Pennebaker Correlation F_σ, while the second plot can be used to estimate the overburden stress gradient using the interval transit time of the Sonic (Acoustic) Log at the borehole depth.

FIGURE 5.58: OVERBURDEN GRADIENT DETERMINATION USING THE MATRIX STRESS RATIO AND ACOUSTIC OR SEISMIC LOG

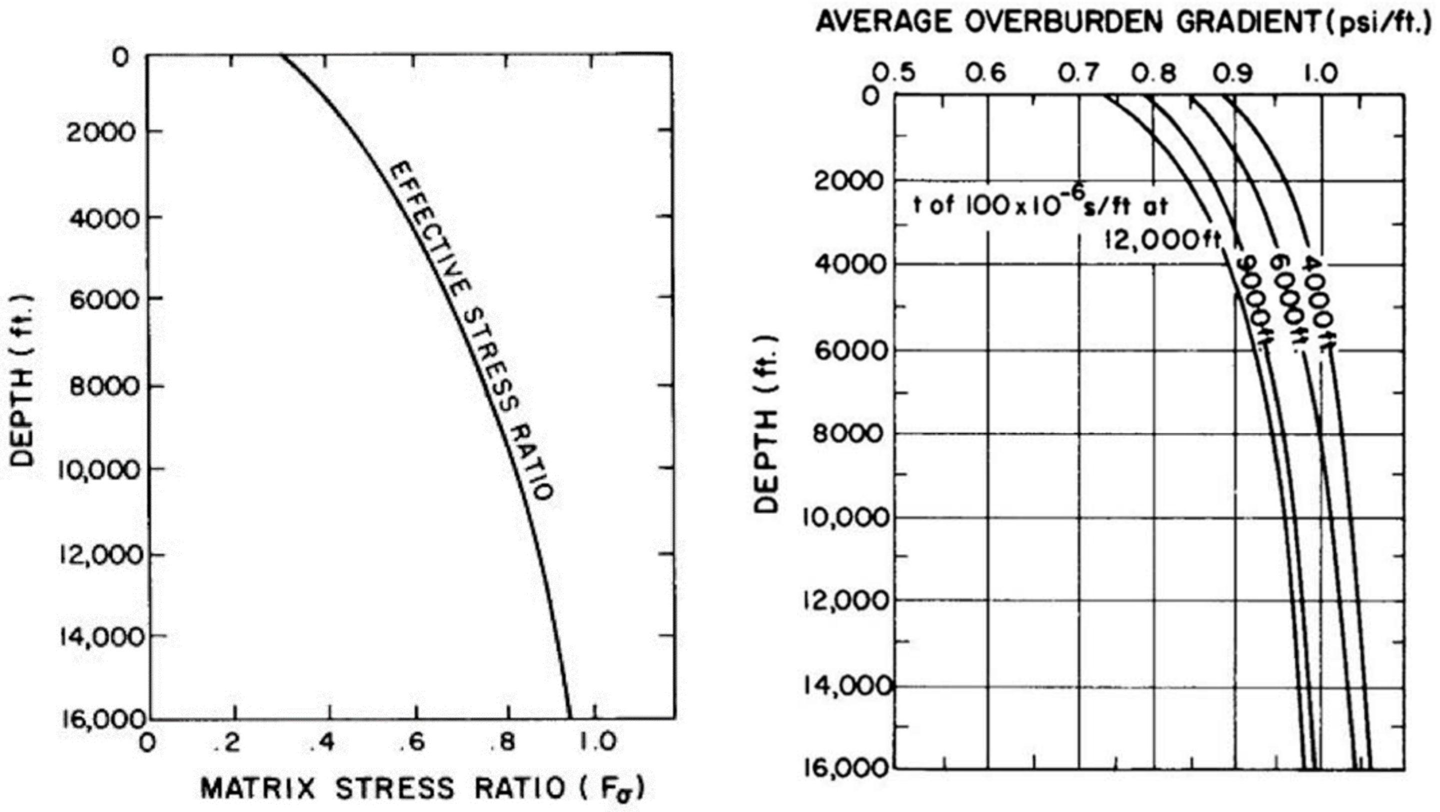


TABLE 5.18. FRACTURE GRADIENT CALCULATION METHODS USED FOR THE THEC SITE. ALL MEASURES OTHER THAN DEPTH ARE IN PSI.

Depth, ft	σ(OB) psi	Pore Press psi	Effective Vertical Stress	Effective Horizontal Stress	Eaton's Method	Hubbert - Wills	Pennebaker Correlation
100	100	44	56	20.71	64.71	62.67	61
200	200	88	112	41.42	129.42	125.33	122
300	300	132	168	62.14	194.14	188.00	183
400	400	176	224	82.85	258.85	250.67	244
500	500	220	280	103.56	323.56	313.33	305
600	600	264	336	124.27	388.27	376.00	366
700	700	308	392	144.99	452.99	438.67	427
800	800	352	448	165.70	517.70	501.33	488
900	900	396	504	186.41	582.41	564.00	549
1000	1000	440	560	207.12	647.12	626.67	610
1100	1100	484	616	227.84	711.84	689.33	671
1200	1200	528	672	248.55	776.55	752.00	732
1300	1300	572	728	269.26	841.26	814.67	793
1400	1400	616	784	289.97	905.97	877.33	854
1500	1500	660	840	310.68	970.68	940.00	915
1600	1600	704	896	331.40	1035.40	1002.67	976
1700	1700	748	952	352.11	1100.11	1065.33	1037
1800	1800	792	1008	372.82	1164.82	1128.00	1098

1900	1900	836	1064	393.53	1229.53	1190.67	1159
2000	2000	880	1120	414.25	1294.25	1253.33	1220
2100	2100	924	1176	434.96	1358.96	1316.00	1281
2200	2200	968	1232	455.67	1423.67	1378.67	1342
2300	2300	1012	1288	476.38	1488.38	1441.33	1403
2400	2400	1056	1344	497.10	1553.10	1504.00	1464
2500	2500	1100	1400	517.81	1617.81	1566.67	1525
2600	2600	1144	1456	538.52	1682.52	1629.33	1586
2700	2700	1188	1512	559.23	1747.23	1692.00	1647
2800	2800	1232	1568	579.95	1811.95	1754.67	1708
2900	2900	1276	1624	600.66	1876.66	1817.33	1769
3000	3000	1320	1680	621.37	1941.37	1880.00	1830
3100	3100	1364	1736	642.08	2006.08	1942.67	1891
3200	3200	1408	1792	662.79	2070.79	2005.33	1952
3300	3300	1452	1848	683.51	2135.51	2068.00	2013
3400	3400	1496	1904	704.22	2200.22	2130.67	2074
3500	3500	1540	1960	724.93	2264.93	2193.33	2135
3600	3600	1584	2016	745.64	2329.64	2256.00	2196
3700	3700	1628	2072	766.36	2394.36	2318.67	2257
3800	3800	1672	2128	787.07	2459.07	2381.33	2318

FIGURE 5.59. FRACTURE GRADIENT CALCULATION RESULTS FOR THE THEC SITE

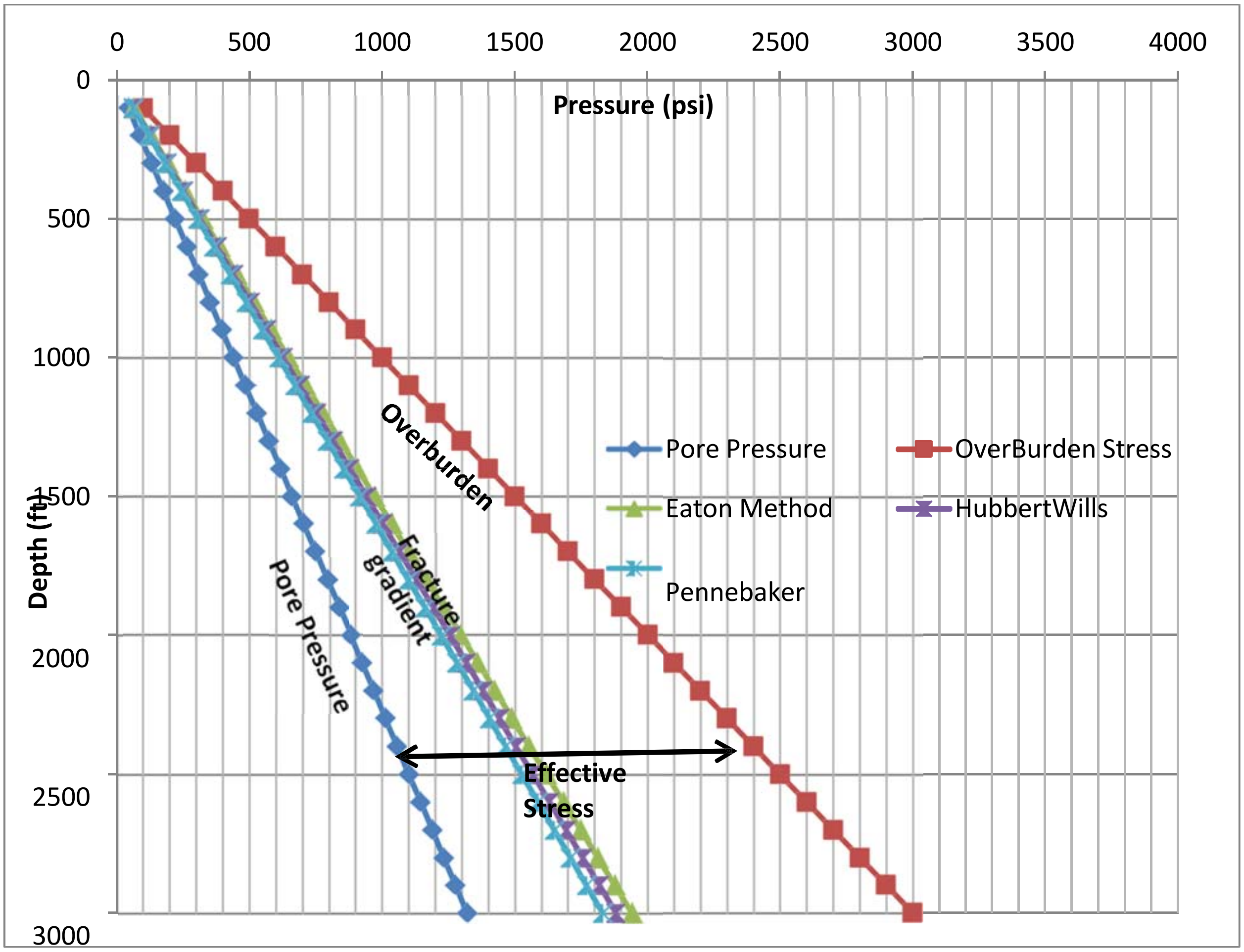


Table 5.19 provides a summary of the interval depths, and calculation of average porosity and permeability calculated for the Davis Formation, Bonneterre Formation and Lamotte Sandstone. The Davis Formation has a higher permeability zone at the top, which has been included in the calculation. However, as noted previously, there is a 50 foot section with very low permeability.

TABLE 5.19: PETROPHYSICAL PROPERTIES OF THE ROCK FORMATION IN THE THEC BOREHOLE FROM CORE DATA

Formation	Gross Pay Depth (ft)	Payzone Gross (ft)	NetPay Depth (ft)	Payzone Net (ft)	Perm, k (Avg)md	Porosity Ø(Avg)
Davis	1,930-2,081	151	2,282-2,327	45	0.044	8.3%
Bonneterre	2,093-2,327	234	2,093-2,193	100	1.4	12.4%
Lamotte	2,333-2,539	206	2,333-2,539	206	47.3	10.4%

Davis Formation:

$\sum h_i k_i = 1.98$ md.ft $\bar{k} = 0.044$ md

$\sum h_i \varnothing_i = 3.74$ ft $\bar{\varnothing} = 8.3\%$

Bonneterre Formation:

$\sum h_i k_i = 140$ md.ft $\bar{k} = 1.40$ md

$\sum h_i \varnothing_i = 12.4$ ft $\bar{\varnothing} = 12.4\%$

Lamotte Sandstone:

$\sum h_i k_i = 9{,}744$ md.ft $\bar{k} = 47.3$ md

$\sum h_i \varnothing_i = 21.7$ ft $\bar{\varnothing} = 10.4\%$

Task 4.b. Determine Porosity, Permeability, Grain size Distribution, Pore Throat Size and Shape, and Minerals Present in Representative Core Samples at the four Missouri Power Plant Sites

CAPILLARY PRESSURES

Figures 5.61 through 5.68 provide the results of mercury injection for the THEC site. The S_{Hg} vs. P_{c-Hg} curves are obtained by collecting the mercury injection capillary pressure (MICP) data. From the equations given in Task 4.a. of the methodology section, the S_W vs. P_{c-co2} curves can be derived.

The threshold pressure and the irreducible water saturation can be determined from these figures. All results are summarized in Table 5.20.

FIGURE 5.61. MERCURY CAPILLARY PRESSURE OF DERBY-DOERUN TOP ROCK FROM THE THEC SITE (SAMPLE #1V)

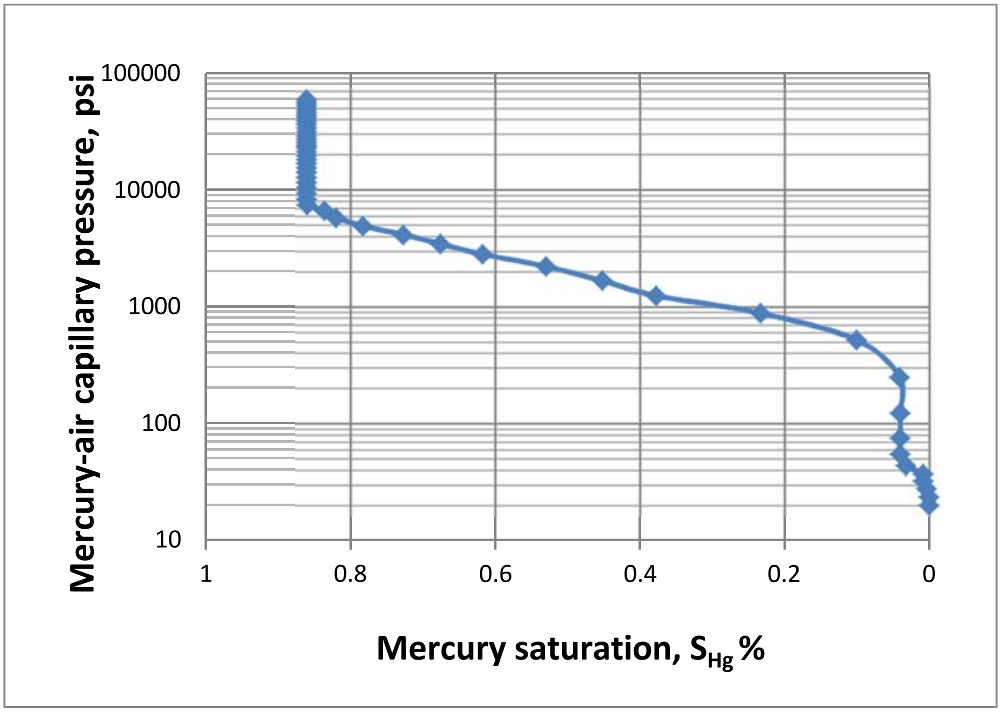


FIGURE 5.62. CO_2 CAPILLARY PRESSURE OF DERBY-DOERUN TOP ROCK FROM THE THEC SITE (SAMPLE #1V)

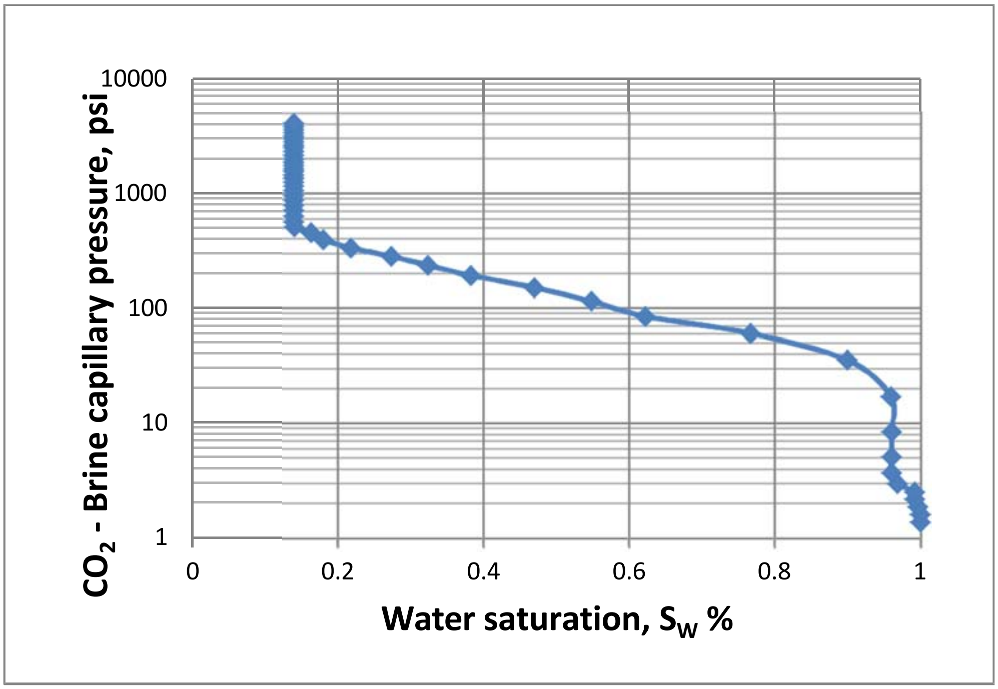


FIGURE 5.63. MERCURY CAPILLARY PRESSURE OF DAVIS FORMATION FROM THE THEC SITE (SAMPLE #12V)

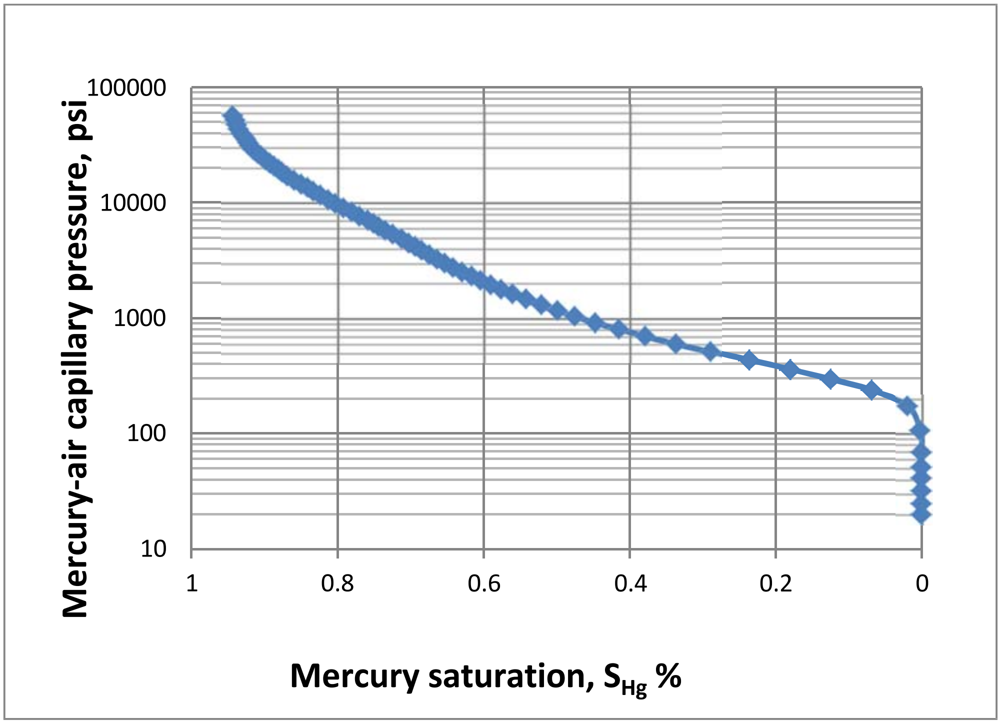


FIGURE 5.64. CO_2 CAPILLARY PRESSURE OF DAVIS FORMATION FROM THE THEC SITE (SAMPLE #12V)

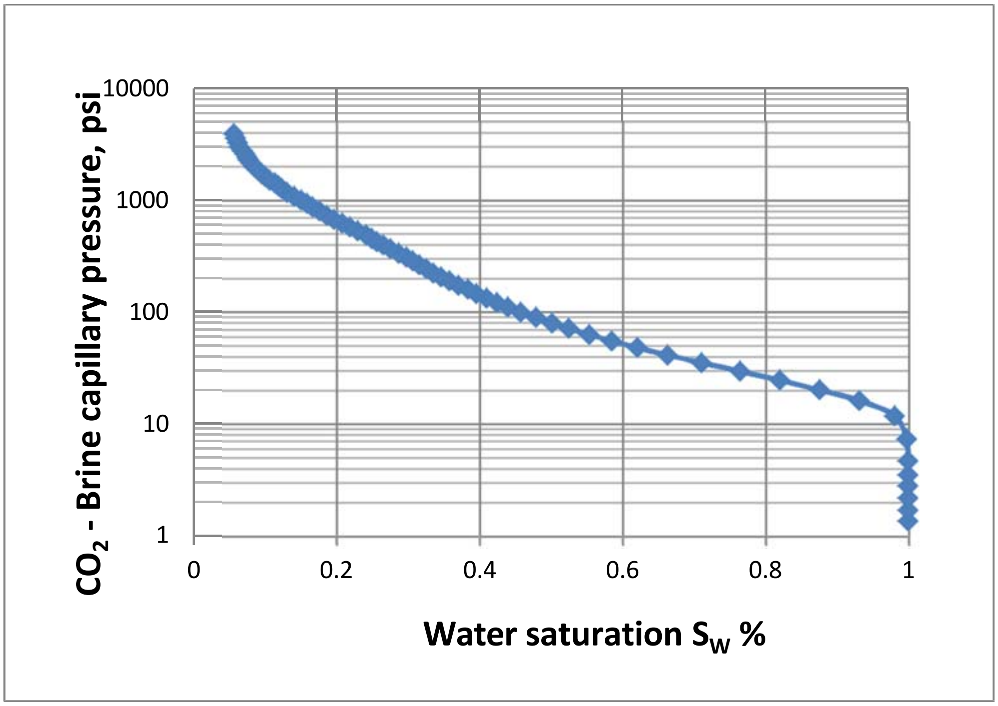


FIGURE 5.65. MERCURY CAPILLARY PRESSURE OF THE BONNETERRE FROM THE THEC SITE (SAMPLE #40V)

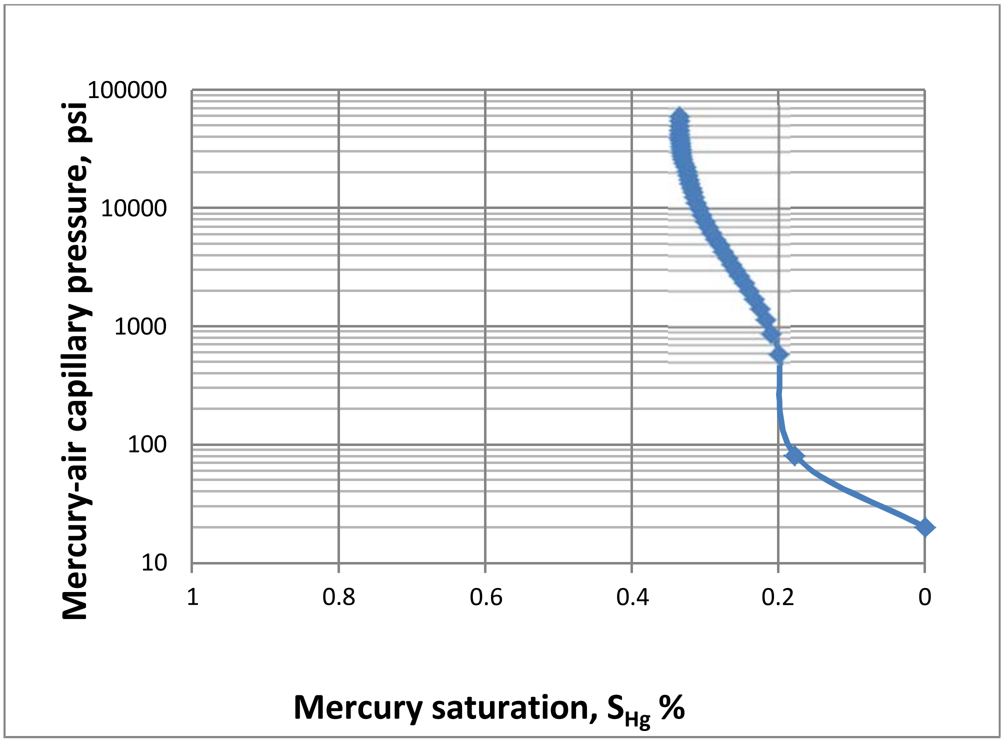


FIGURE 5.66. CO_2 CAPILLARY PRESSURE OF THE BONNETERRE FROM THE THEC SITE (SAMPLE #40V)

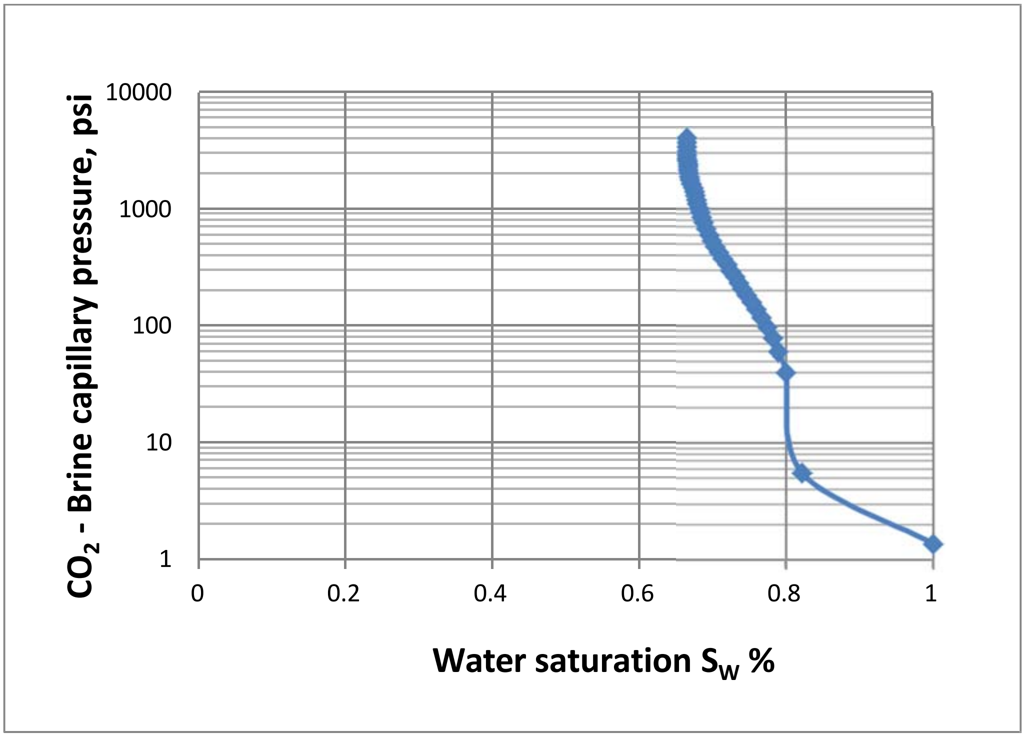


FIGURE 5.67. MERCURY CAPILLARY PRESSURE OF LAMOTTE SANDSTONE FROM THE THEC SITE (SAMPLE #48B)

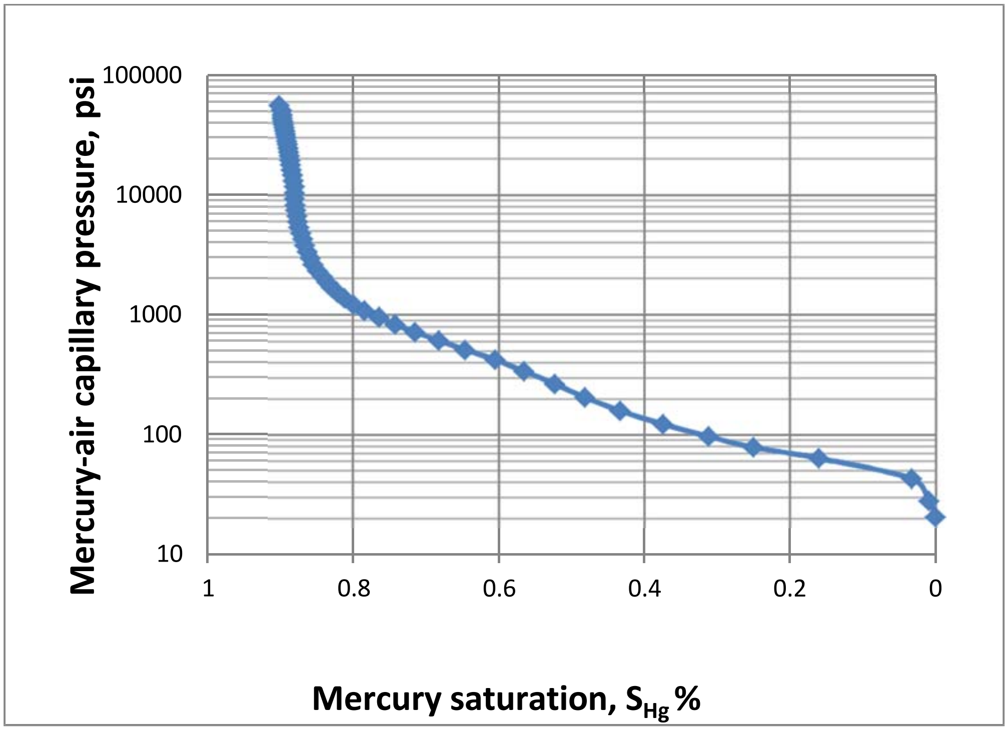


FIGURE 5.68. CO_2 CAPILLARY PRESSURE OF LAMOTTE SANDSTONE FROM THE THEC SITE (SAMPLE #48B)

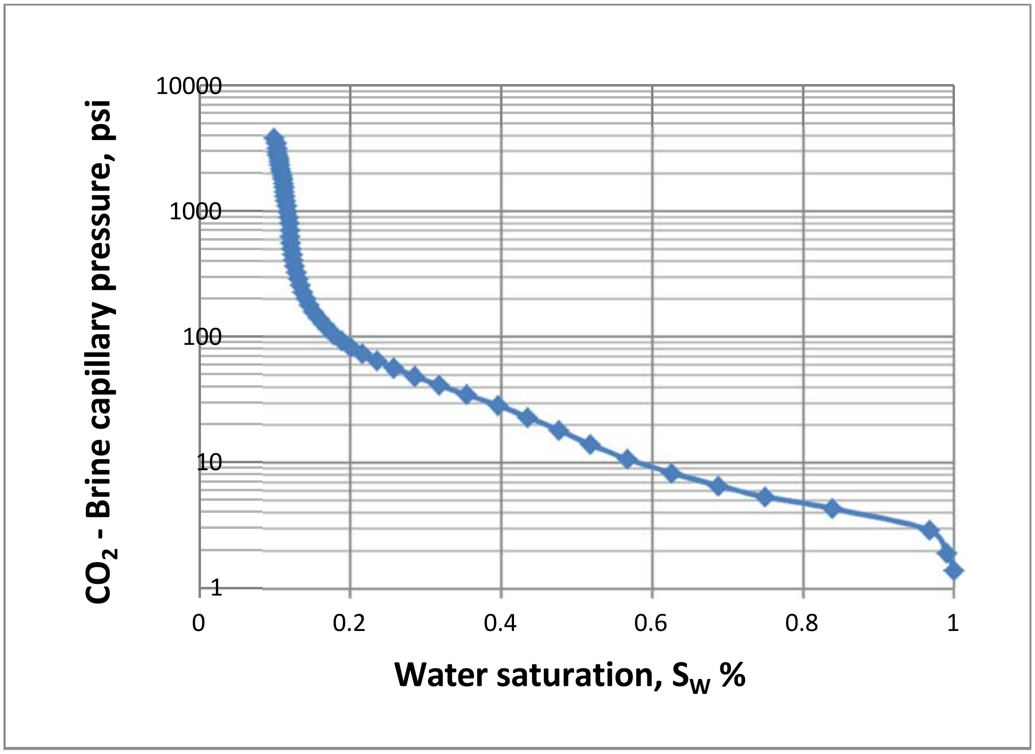


TABLE 5.20. PRIMARY AND DERIVED DATA FROM CORE SAMPLES FROM THE THEC SITE

Formation	Depth of sample	Pressure at sample depth	Temperature at sample depth	Threshold Entry Pressure (air- Hg system)	Threshold Entry Pressure (brine-CO_2) system)	Irreducible Water Saturation
	ft	psi	^{0}F	psi	psi	
Derby- Doerun	1959	896.25	99.18	251.215	17.08	0.14
Davis	2059	941.25	101.18	107.822	7.3308	0.056
Bonneterre	2327	1061.85	106.54	20	1.361	0.666
Lamotte	2362	1077.6	107.24	20	1.361	0.099

CO_2 entry pressure for the Davis Formation is low (7 psi) at the lower end of entry pressures reported in the literature for other potential aquifer sequestration sites. Daniel (2005) found the threshold pressure of the caprocks of Vlaming Sub-basin, Perth Basin, Western Australia is 53-607 psi. Iverson et al. (1992) found that the threshold pressure of Power River Basin is almost 2000 psi. Fleury et al. (2008) measured entry pressure of St Martin de Bossenay depleted oil field, Paris basin and found it from 5.88-323.4 psi. The quite low capillary entry pressure suggests that a migration might occur in some part of this formation. Comparing these values, the CO_2 entry pressure for the Davis is pretty low. However, the diffusion of CO_2 into caprock is not completely understood, and the Davis Formation may be an adequate barrier because the permeability is low.

Task 3.d. Determine the Injection Rate Profile for the Target Formation

GEOMECHANICAL TESTING OF THE DERBY-DOERUN, DAVIS, AND BONNETERRE FORMATIONS, AND THE LAMOTTE SANDSTONE

Nine core samples from the THEC borehole were sent to Britt Rock Mechanics Laboratory for analysis. One sample was not sufficient for analysis. Eight tri-axial compression tests were conducted with one test conducted on core from the Davis Formation, three tests conducted on the Bonneterre Formation, and four tests conducted on the Lamotte Sandstone. These geomechanical tests were conducted as described in Task 3.d. of the methodology section.

Table 22 presents the results from the tri-axial compression tests for the THEC site. As shown in this table is the Poisson's ratio for the tests from each of the core sample tested. The average Poisson's ratio for Davis, and Bonneterre Formations, and Lamotte Sandstone at THEC site was 0.22, 0.25, and 0.16, respectively.

The results of the tests indicate the Young's modulus in the Davis Formation at Thomas Hill site was 4.56 x 106 psi. Young's modulus for the Bonneterre Formation tests at Thomas Hill site ranges from 3.17 to 9.43 x 106 psi. Similarly, Young's modulus for the Lamotte Sandstone ranged from 3.48 to 6.61 x 106 psi.

Figure 5.69 shows a plot of stress versus strain for the core plug from the Lamotte Sandstone in the THEC borehole (Sample ID: 51T, Depth 2,429.00 ft) under a confining pressure of 2,300 psi. As shown, a distinct linear stress-strain behavior (Axial Strain) was seen during the loading cycle of the test. Also note that this was a non-failure tri-axial compression test and that the unloading cycle showed little hysteresis and returned to the origin of the plot indicating linear elastic behavior of the core plug sample. From the slope of the loading cycle, a Young's modulus of 3.48 x 106 psi was determined. The Poisson's ratio for the sample was determined to be 0.206. Figure 5.70 shows a plot of the interpreted stress versus strain data for the Lamotte Sandstone core plug from the THEC borehole (Sample ID: 51T, Depth 2,429.00 ft) under a confining pressure of 2,300 psi. As shown, a linear fit of the early stress strain relationship gave an R2 of 0.9994 indicating linear elastic behavior.

It should be noted that about half of the total samples tested exhibited hysteresis whereby the unloading cycle failed to return to the origin of the stress-strain plot. Such hysteresis is often seen in soft, ductile, and/or heterogeneous samples but is not generally seen in high modulus carbonate samples such as these. To minimize the effect of the heterogeneity great care was taken in the placement of the transducers. In addition, the equipment was calibrated on several occasions with aluminum plugs to ensure that the measurements were accurate. Appendix B provides the stress-strain data from each of the tri- axial compression tests on the Derby-Doerun, Davis, Bonneterre, Bonneterre/Lamotte Transition Zone, and Lamotte Sandstone, respectively.

FIGURE5.69. STRESS-STRAIN CURVE LAMOTTE SANDSTONE (ID 51T 2,429.00 FT)

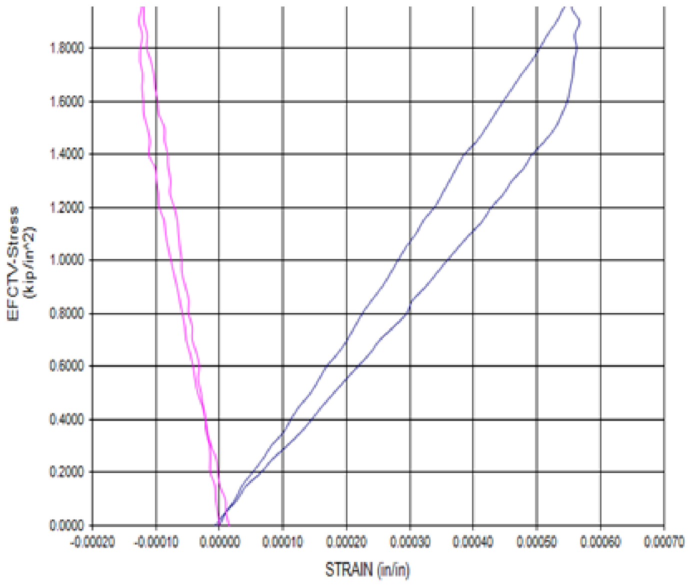


FIGURE 5.70. LINEAR ELASTIC BEHAVIOR OF THE LAMOTTE SANDSTONE (ID 51T 2,429.00 FT)

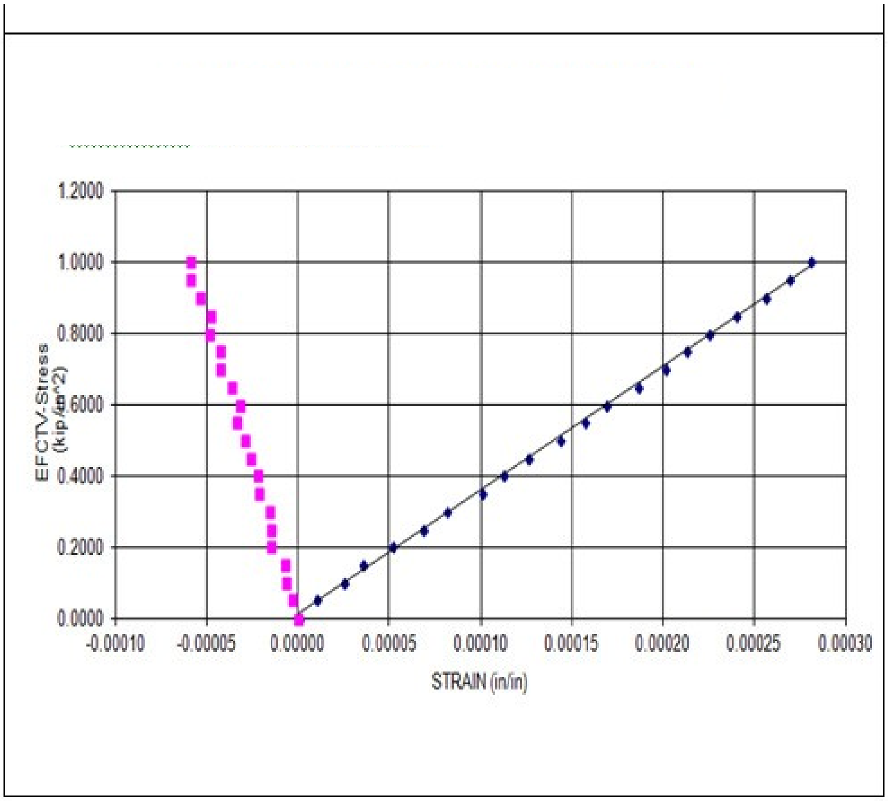


Table 5.22 presents geomechanical results for core samples from the Thomas Hill site.

TABLE 5.22. GEOMECHANICAL DATA FOR THE THEC SITE.

Thomas Hill Site							
Date/ID	Depth (Feet)	Formation Name	Sample ID	Bulk Modulus 1E+06	Young's Modulus 1E+06	Poisson’s Ratio	Confining Pressure (kip/in^2)
13071501	2024	Davis	8V	0.85	4.56	0.22	2.30
13071701	2120	Bonneterre	18V	1.20	9.43	0.31	2.30
13100301	2282	Bonneterre	35V	0.91	5.28	0.24	2.30
13101001	2327	Bonneterre	40V	0.61	3.17	0.21	2.30
13100201	2362	Lamotte	44V	0.93	3.94	0.15	2.30
13100401	2429	Lamotte	51T	0.68	3.48	0.21	2.30
13071101	2468	Lamotte	55V	1.34	5.77	0.15	2.30
13071001	2539	Lamotte	63A	1.69	6.61	0.12	2.30
Sample Orientation : Native State Sample Storage: Horz							

In general, rock properties for the Lamotte Sandstone in the THEC borehole were found to be similar to those found in the JTEC borehole. The one Davis Formation sample analyzed was significantly lower modulus than the average modulus found at JTEC (10.33 x 10^6 psi) and cannot be compared directly, as a single sample is not a statistical representation of the formation. The Bonneterre modulus was also lower in the THEC borehole, averaging 5.96 x 10^6 psi, compared to 14.39 x 10^6 for the JTEC borehole.

Task 3.e. Retrieve and Analyze Fluid Samples from the Target Formation

FORMATION WATER SAMPLES FROM THE THEC SITE

Formation water samples were collected from the THEC Site on July 7, 2012. In-situ measurements were made for conductivity, pH, Eh, dissolved oxygen and temperature. Ex-situ measurements of the water alkalinity, calcium hardness, and total hardness were conducted on site as soon as possible after removal from the borehole, with the alkalinity measurements being made first to minimize the effect from CO2 loss from the water samples. Additional aliquots of the water were collected and taken back to the Missouri S&T lab for cation, anion, total suspended solids (TSS), and total dissolved solids (TDS) analysis.

In situ water measurements in the THEC borehole site revealed an average pH of 6.62 +/- 0.01, Eh +11 +/- 2 millivolts, dissolved oxygen 0.52 mg/kg, and water temperature of 22.2 +/- 0.2oC (Table 5.23a). The water conductivity was nearly constant at 70.6 +/- 0.1 milliSiemens/cm and this corresponded with the high salinity of the water as noticed by its salty taste. All of these values were averaged for four readings collected over an 87 minute time period. Researchers from the Missouri Geological Survey (MGS) also conducted the same analyses (except Eh) using their portable field instruments and obtained essentially identical results. Alkalinity values averaged 200 +/- 12 mg/L.

Turbidity values were very low at 1.27 +/-0.44 NTU (nephelometric turbidity unit) indicating a clear water system with minimal particulate matter (Table 5.23a). The water did, however, become notably cloudy with reddish-orange particulate material after approximately 30 minutes. All samples displayed an abundance of these particles after being returned to the Missouri S&T lab five to six hours later (Figure 5.71a). The addition of approximately 2% by volume of high purity HNO3 rapidly re-dissolved the particles and restored the fluid to a completely clear state within one hour. This acidification step was planned for the samples prior to ICP-OES cation analysis. The particles were likely to be a ferric iron (Fe3+) oxide bearing solid phase(s) that formed when the more soluble ferrous iron (Fe2+) from the well was exposed to the oxygenated atmosphere.

Filtered water samples for cation (UF-unfiltered; -5.0 µm, -0.45µm, and -0.02 µm) and anion (- 0.45µm) analysis also were collected, with all filtering and sample splits performed on site immediately after the primary water sample was collected from the borehole. Cation analytical results indicated that the differences between unfiltered and various filtered size fractions were not statistically significant within one standard deviation determined between the various filtrate sizes (Table 5.23b). The waters are Na-Cl dominated, but also contain significant amounts of Ca, Mg, K, and SO42-. The presence of these components was also confirmed by the examination of the TDS evaporation residue solids where gypsum, anhydrite, and halite were detected (CaSO4.2H2O, CaSO4, and NaCl, respectively; Figure 5.71b).

The THEC samples averaged a density of 1.0360 g/cm3, with a standard deviation of 0.0014 g/cm3 for three measurements. The precipitated iron oxide particles were included in these density determinations as the iron was originally dissolved in the brine when the samples were collected from the borehole. For reference, the density of seawater at 25oC is approximately 1.0260 g/cm3. Seawater has a salinity of approximately 35 parts per thousand (ppt), compared to the Lamotte Sandstone water samples from the THEC site which had a salinity of approximately 46 ppt.

Three parallel analytical procedures were used to evaluate the TDS or salinity content of water samples from the Lamotte Sandstone at the THEC Site.

1. <u>Total Dissolved Solids (TDS) by Evaporation to Dryness:</u> The most direct method by which to measure salinity was to filter out any particles greater than 0.45 microns (TSS fraction), collect the filtrate in a pre-weighed beaker, evaporate to dryness (first at 95°C, followed by evaporation at 180°C after the liquid fraction had evaporated), and weigh the beaker to determine the accumulated residue (TDS fraction). The precipitation of iron oxide phases in the water samples from the THEC site within an hour after collection precluded the application of the TSS analysis procedure, as solids had formed in the solution before they could be processed for TSS analysis (Figure 5.71). The TSS step was thus omitted. This is not considered to be a significant sampling omission because the original amount of particulate material in the water drawn from the borehole was negligible as indicated by the very low turbidity values (Table 5.23a). The TDS determinations for the water samples thus included the soluble fraction, the precipitated iron oxides (these were originally present as a dissolved specie when the water samples were collected), and any trace amount of solid phases that would have been present in the water when it was drawn from the borehole. The TDS values averaged 46,287 +/- 11 mg/kg for three separate samples collected within an 80 minute period. This measured value was slightly lower than the MGS value of 50,800 mg/L (49,035 mg/kg for brine density of 1.0360 kg/L).

   Crystals that formed during evaporation were examined under an optical microscope and found to contain white cubic halite crystals, white flakey salts, white acicular gypsum crystals, and iron oxides (Figure 5.71b). After weighing, the evaporative solids we re- dissolved by rinsing in deionized water. The residual white acicular phase and the iron oxides remained as insoluble residues while the white crust and cubes were easily dissolved. The acicular phase was noted to have a hexagonal or pseudo-hexagonal morphology when viewed under the optical microscope and also was un-reactive when immersed in a dilute 5% hydrochloric acid solution. The crystals also were analyzed by XRD and found to be a mixture of the sulfate minerals gypsum and anhydrite ($CaSO_4.2H_2O$ and $CaSO_4$, respectively (Figure 5.72). Further examination of isolated particles using SEM- EDS analysis revealed Ca- and S-dominated hexagonal-shaped grains and elongate, acicular Ca-S crystals with a radiating-stellated habit (Figure 5.73). The SEM-EDS analysis also revealed the occurrence of the acicular crystals growing within dissolution pits of the hexagonal phase, suggesting that the former grains are deriving their atoms from the hexagonal crystals as they were dissolving. The detection of gypsum as a crystal residue from the TDS evaporative procedure also indicates that a small amount of residual water bound within the gypsum crystals was never fully removed from the system. A rounded carbon-rich phase, and platy-hexagonal grains were also detected by SEM-EDS analysis, but both of these latter two phases were relatively minor in abundance.

2. <u>Tabulating cation and anion analytical determinations:</u> A second method is to tabulate the ppm (mg/kg) content of all species detected in solution (Table 5.23). This tabulation would include the major and minor cations Na, Ca, Mg, K, Si, Fe, and Mn (ICP-OES), alkalinity ions (predominantly HCO_3^-), and anions SO_4^{2-}, Cl, F, NO_3^- (Ion Chromatography). Anion analyses were performed by VHG Labs in Manchester, New Hampshire.

These tabulation results indicate the following:

a)	Major and minor cation analysis (0.45 micron filtered)	= 18,233 mg/kg
b)	HCO_3^- (alkalinity)	= 200 mg/kg
c)	Anion analysis (0.45 micron filtered)	= 27,390 mg/kg
	Measured – Calculated Total	= 45,823 mg/kg

3. Conductivity Measurements: The third method uses the conductivity value and a multiplication factor of 0.667 to convert conductivity to TDS. The multiplication factor is required because conductivity is a measure of the conductance of ions dissolved in a fluid over a specified distance of one centimeter, and thus depends on the concentration of the ions and their respective charges (e.g., Na^+ versus Ca^{2+}). Salinity, however, is a determination of the concentration of all the ions (and neutral charged species), and their respective atomic weights. Converting conductivity values to salinity involves the application of an empirically derived multiplication factor, with that multiplication factor being dependent on the types of ions present in solution. For the “One-Shot” brand KCl standard solution a multiplication factor of 0.667 is recommended. Multiplying the Lamotte Sandstone water sample conductivity of 70,600 microSiemens/cm (Table 5.23a or 70.6 milliSiemens/cm) by the recommended 0.667 multiplication factor gives a salinity of 47,090 mg/kg.

FIGURE 5.71. WATER SAMPLES COLLECTED FROM THE THEC SITE. A) LEFT - THEY DISPLAY A REDDISH- ORANGE DISCOLORATION CAUSED BY IRON PRECIPITATES. BOTTLES AT THE FAR RIGHT IN THE PHOTO CONTAIN DEIONIZED WATER FIELD BLANKS AND DO NOT DISPLAY ANY IRON DISCOLORATION. B) RIGHT - EVAPORITE CRYSTALS APPEAR IN THE BOTTOM OF 200 ML PYREX BEAKER FOLLOWING EVAPORATION OF WATER SAMPLE. THESE CRYSTALS INCLUDE IRON PRECIPITATES, WATER SOLUBLE CUBIC SALT, A WHITE ACICULAR PHASE, AND THE WATER SOLUBLE WHITE CRUST ON THE VESSEL SIDES.

FIGURE 5.72. X-RAY DIFFRACTION ANALYSIS OF THE WATER AND HYDROCHLORIC ACID INSOLUBLE EVAPORATE CRYSTAL FROM THE THEC SITE. THE XRD SPECTRA INDICATE A MIXTURE OF ANHYDRITE AND GYPSUM. THE BOTTOM THREE BAR IMAGES DISPLAY THE DETECTED PEAK POSITIONS AND RELATIVE INTENSITIES (FROM TOP TO BOTTOM) OF THE EVAPORITE SAMPLE, THE CATALOG PEAK POSITIONS FOR ANHYDRITE, AND THE CATALOG PEAK POSITIONS FOR GYPSUM.

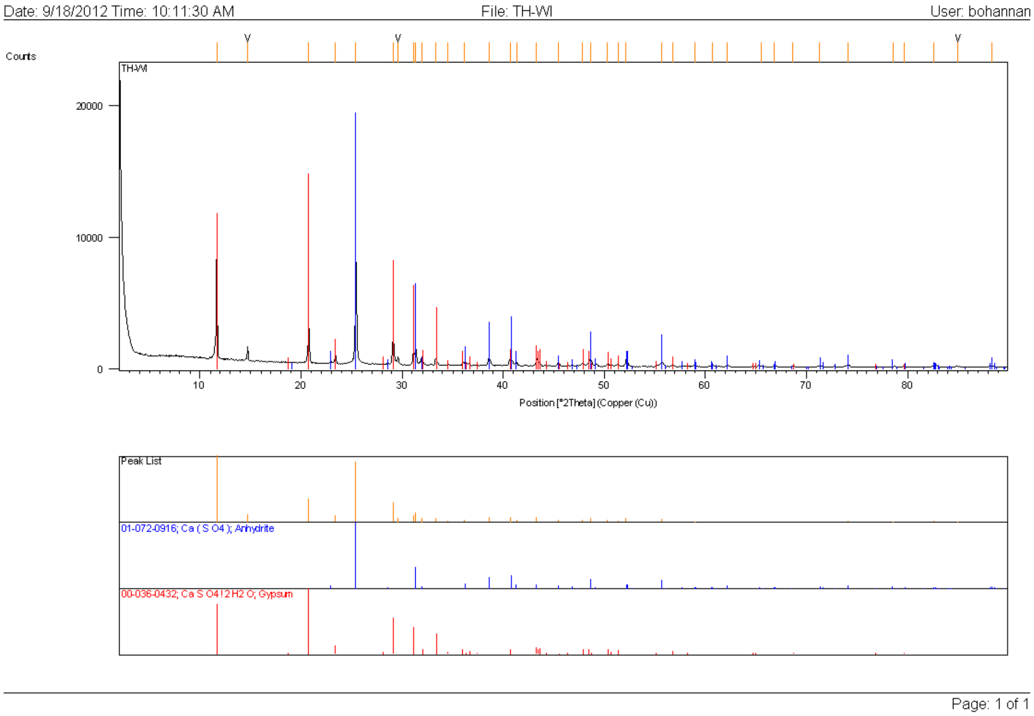
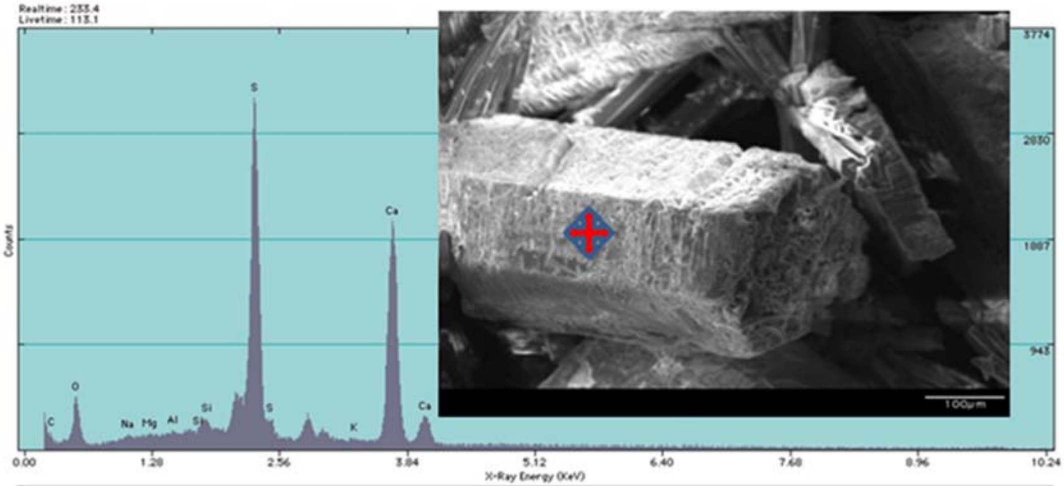
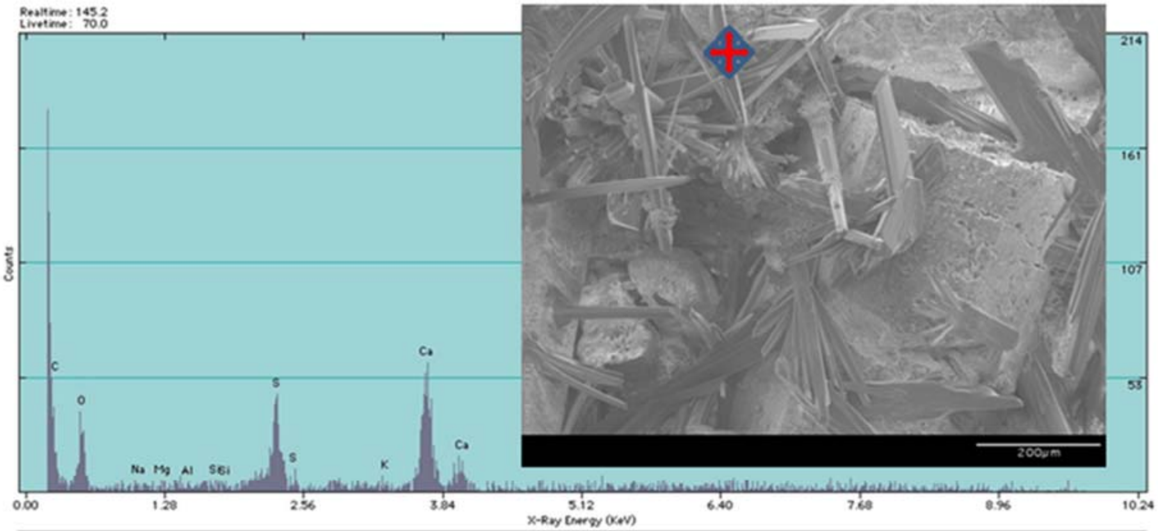


FIGURE 5.73. SCANNING ELECTRON MICROSCOPY – ENERGY DISPERSIVE SPECTROSCOPY (SEM-EDS) ANALYSIS OF CRYSTALS PRODUCED DURING THE EVAPORATION OF THE WATER SAMPLES FROM THE THOMAS HILL SITE FOR THE TOTAL DISSOLVED SOLIDS (TDS) TEST. EDS ANALYTICAL RESULTS INDICATE A CA-SULFATE DOMINATED COMPOSITION FOR BOTH CRYSTAL MORPHOLOGIES. CROSSES INDICATE POSITION ON CRYSTALS WHERE THE EDS ANALYSIS WAS PERFORMED. A) TOP IMAGE OF ACICULAR ANHYDRITE (CASO4). ANHYDRITE IS IN THE ORTHORHOMBIC CRYSTAL SYSTEM, BUT PSEUDO-HEXAGONAL FORMS ARE SOMETIMES OBSERVED. B) BOTTOM IMAGE OF BLADED ROSETTES OF GYPSUM (CASO4.2H2O) FORMING ON A CORRODED ANHYDRITE CRYSTAL.



Quantitative Results for Probe 1
Analysis : Bulk Method : Standardless
Acquired 11-Oct-2012, 15.0 KeV @10 eV/channel

Element	Weight %	Atomic %	Oxide %	
C	2.53	4.83	2.53	
O	42.29	60.60	0.00	
Na	0.52	0.52	0.71	(Na20)
Mg	0.26	0.25	0.43	(MgO)
Al	0.12	0.10	0.22	(Al203)
Si	0.07	0.06	0.16	(SiO2)
S	18.35	13.12	45.83	(S03)
K	0.22	0.13	0.26	(K20)
Ca	35.63	20.38	49.86	(Ca0)
Total	100.00		100.00	



Quantitative Results for Probe 1
Analysis : Bulk Method : Standardless
Acquired 11-Oct-2012, 15.0 KeV @10 eV/channel

Element	Weight %	Atomic %	Oxide %	
C	27.46	42.82	27.46	
O	30.78	36.03	0.00	
Na	0.18	0.15	0.24	(Na20)
Mg	0.05	0.04	0.08	(MgO)
Al	0.24	0.16	0.45	(Al203)
Si	0.01	0.00	0.01	(SiO2)
S	12.78	7.47	31.92	(S03)
K	0.29	0.14	0.35	(K20)
Ca	28.22	13.19	39.48	(Ca0)
Total	100.00		100.00	

TABLE 5.23A. WATER QUALITY DATA FROM THE LAMOTTE SANDSTONE AT THE THEC SITE. N/A = NOT ANALYZED. NTU = NEPHELOMETRIC TURBIDITY UNIT.

	7/10/2012		Eh	Temp	Conduct.	Alkalinity	Ca Hardness	Mg Hardness	Turb
Sample Number	**Time**	**pH**	**mV**	**ºC**	**milliS/cm**	**mg/L**	**mg/L**	**mg/L**	**NTU**
Thomas Hill A UF	10:22 am	6.60	+13	22.2	70.5	195	6600	3700	1.07
Thomas Hill B UF	11:02 am	6.63	+10	21.9	70.6	201	6400	3300	1.88
Thomas Hill C UF	11:41 am	6.62	+10	22.4	70.7	203	6300	3700	0.87
Thomas Hill D UF	11:49 am	6.64	+9	22.4	70.6	n/a	n/a	n/a	n/a
Thomas Hill Ave.		6.62	+11	22.2	70.6	200	6433	3567	1.27
Thomas Hill Standard Deviation		0.01	2	0.2	0.1	3	125	189	0.44
# of readings		4	4	4	4	3	3	3	3

TABLE 5.23B. MAJOR ELEMENT CATION ANALYSIS FOR THE WATER SAMPLES COLLECTED FROM THE LAMOTTE SANDSTONE AT THE THEC SITE ON 7/10/2012. ALL VALUES IN MG/KG (PPM). UF=UNFILTERED; - 5.0 = -5.0 MICROMETER FILTERED; -0.45=0.45 MICROMETER FILTERED; -0.02=0.02 MICROMETER FILTERED; N/A = NOT ANALYZED.

Sample Name	Si	Fe	Ca	Mg	K	Na	Mn	Cl	SO_4^{2-}
TH a 7/10/2012 UF	n/a	n/a	2349	838	195	14,146	n/a	n/a	n/a
TH a 7/10/2012 -5.0	n/a	n/a	2529	850	207	14,721	n/a	n/a	n/a
TH a 7/10/2012 -0.45	4.2	10.2	2514	870	206	14,727	0.4	25,200	1300
TH a 7/10/2012 -0.02	n/a	n/a	2526	868	206	14,763	n/a	n/a	n/a
TH b 7/10/2012 UF	n/a	n/a	2450	863	202	14,548	n/a	n/a	n/a
TH b 7/10/2012 -5.0	n/a	n/a	2468	853	203	14,560	n/a	n/a	n/a
TH b 7/10/2012 -0.45	4.1	10.3	2482	850	207	14,585	0.4	26,700	1380
TH b 7/10/2012 -0.02	n/a	n/a	2483	865	205	14,590	n/a	n/a	n/a
TH c 7/10/2012 UF	n/a	n/a	2486	852	200	14,546	n/a	n/a	n/a
TH c 7/10/2012 -5.0	4.1	10.3	2466	865	202	14,581	n/a	n/a	n/a
TH c 7/10/2012 -0.45	n/a	n/a	2477	861	205	14,673	0.4	n/a	n/a
TH c 7/10/2012 -0.02	n/a	n/a	2511	869	207	14,708	n/a	n/a	n/a
Thomas Hill Average -0.45	4.1	10.3	2491	860	206	14,662	0.4	25,950	1340
Thomas Hill Std. Dev.	0.0	0.1	20	11	1	434	0.0	750	40
Number of readings	3	3	3	3	3	3	3	2	2

HIGH PRESSURE AND TEMPERATURE CO_2 + H_2O TESTS FOR CORE SAMPLES FROM THE THEC SITE

Seven samples from the THEC site were reacted in the 90ºC high pressure CO_2 + H_2O tests. These included four samples of the Davis Formation confining layer (including selected samples of carbonate and non-carbonate shale), a glauconitic sandy lens of the Bonneterre Formation, and two samples of the Lamotte Sandstone (Table 5.25). All samples were sectioned into multiple polished disks to provide material for duplicate sample experiments of the same time period as well as experiments over multiple time periods (Table 5.26). Some sample disks also were broken into segments that were then assigned a letter (A, B, C, and D) with two pieces of the same sample being reacted in the same vessel to allow for different analyses to be performed on duplicate reacted samples from the same vessel.

The rock samples reacted in the 90°C high pressure CO_2 + H_2O tests may lose mass due to corrosion processes that release rock constituents into the test leachant solution. Alternatively, samples may gain mass through the hydration of solid phases and/or precipitation of alteration phases that have incorporated dissolved elements from the rock sample as well as components derived from the CO_2 and H_2O rich environment of the reaction vessels. Most samples lost between 0.5 – 1.5% of their starting weight during the testing period (Table 5.26). Several samples had recorded excessive weight losses (>5 wt. %) due to disaggregation of clay-rich portions. The Davis Formation samples were most often affected by this process. Meaningful weight change measurements thus could not be obtained from these disaggregated samples.

TABLE 5.25. SAMPLES WITH THEIR RESPECTIVE DEPTHS AND BRIEF DESCRIPTION OF LITHOLOGY.

Sample	Depth (ft)	Formation	Lithology
TH-CS	1988.3	Davis	Carbonate shale
TH-6	2006.3	Davis	Carbonate shale
TH-10	2045.5	Davis	Silty carbonate with small layers of interbedded shale and sandstone with dolomite crystals detected by SEM-EDS analysis.
TH-NCS	2071.5	Davis	Non-carbonate shale with glauconite inclusions
TH-GS	2206.7	Bonneterre	Dolomitic sandstone with glauconite; small iron oxides and pyrites present
TH-QA	2468.7	Lamotte	Quartz arenite sandstone
TH-BS	2539.1	Lamotte	Quartz arenite sandstone

TABLE 5.26. THEC WATER AND CORE SAMPLE MEASUREMENTS TAKEN AFTER HIGH-PRESSURE CORROSION TESTING WAS COMPLETED. ALL SAMPLES WITH WEIGHT LOSS >5% WERE SHALE SAMPLES THAT HAD PARTIALLY DISINTEGRATED INTO FRAGMENTS DURING THE EXPERIMENTS.

Sample ID	Depth (ft)	Formation	Test time (d)	Rock Wt	Final Wt (g)	Wt Loss (g)	% loss	% gain	pH	Eh (mV)
CS1	1988.3	Davis	19	2.1365	2.0210	0.1155	5.41%		6.07	+49.8
CS2	1988.3		19	2.3404	Disintegrated	-	-		Unstable	Unstable
TH 6 C	2006.3		28	1.9193	1.8954	-0.0239	1.25%		6.07	+55
TH 6 A			36	Samples disintegrated into small pieces						
TH 6 B			36							
TH 10 A	2045.5		28	0.8176	0.8041	-0.0135	1.65%		5.96	+57
TH 10 B			28	1.9171	1.8888	-0.0283	1.48%			
NCS1	2071.5		19	2.1225	1.8217	0.3008	14.17%		5.61	+76
NCS2			19	1.9326	1.9251	0.0075	0.39%		5.67	+73
NCS4			19	2.3910	2.3856	0.0054	0.23%		5.66	+74
NCS5			36	1.1628	1.1528	-0.0100	0.86%		5.65	+75
NCS6			36	1.0587	1.0498	-0.0089	0.84%			
GS3	2206.7	Bonneterre	1	2.3927	2.3759	0.0168	0.70%		6.00	+48
GS1			10	2.3244	2.3094	0.0150	0.65%		5.89	+60
GS4			10	2.3404	2.3198	0.0206	0.88%		5.96	+54
GS2			25	2.3791	2.3448	0.0343	1.44%		5.93	+62
GS5			36	1.9394	1.9075	-0.0319	1.64%		5.86	+62
GS6			36	1.3442	1.337	-0.0072	0.54%			
QA2	2468.7	Lamotte	1	2.0477	2.0396	0.0081	0.40%		5.81	+59
QA3			1	2.2390	2.2271	0.0119	0.53%		5.75	+63
QA4			5	2.2197	1.8029	0.4168	18.78%		5.74	+68
QA1			25	2.4269	2.4099	0.0170	0.70%		5.99	+58
BS1	2539.1		19	1.7615	1.7479	0.0136	0.77%		5.95	+58
BS2			19	2.3124	2.2934	0.0190	0.82%		5.93	+58
TH 63 (BS) A			28	0.6102	0.603	-0.0072	1.18%		5.73	+74
TH 63 (BS) B			28	0.7398	0.7278	-0.0120	1.62%		5.73	+74
BS4			77	1.9444	1.9299	0.0145	0.75%		6.18	+46
Blank	-		77	-	-	-	-	-	3.55	+199
Blank	-		77	-	-	-	-	-	4.00	+175
Blank	-		77	-	-	-	-	-	4.03	+175

The pH values for the blank tests run with just CO_2 dry ice and deionized water ranged from approximately 3.5 to 4.0 values. This records the acidification process where $H_2CO_{3(aq)}$ is produced by the reaction $CO_2 + H_2O \rightarrow H_2CO_{3(aq)}$. The pH of the post-test leachate solutions following the reaction of the THEC samples had increased to between 5.61 and 6.18 (Table 5.26). The increase reflects the neutralization process where the elemental rock constituents dissolve into the water and consume or buffer against the $H_2CO_{3(aq)}$ and associated species in solution. There was little notable difference between the pH changes resulting from tests between the Davis Formation, Bonneterre Formation, and Lamotte Sandstones samples. This was an unexpected result as the carbonate-rich rock samples (Davis and Bonneterre Formations) were expected to be more efficient at neutralizing the acid species in the water. The effective pH buffering capacity of the samples from the Lamotte Sandstone may be a result of the presence of small amounts of reactive carbonate cement, clays, and/or feldspar grains. The presence of carbonate minerals was confirmed in two un-reacted samples of the Lamotte Sandstone from core at 2,468.7 ft and 2,539.1 ft as these reacted to released CO_2 bubbles when exposed to a dilute HCl solution. The buffering of the acids and an associated increase in solution pH may have played a role in promoting carbonate mineralization reactions because the solubility of the carbonate ion (CO_3^{2-}), alkaline earths (e.g., Ca^{2+}, Mg^{2+}), and some transition metals (Fe^{2+}) will decrease with respect to carbonate mineral formation as the pH rises.

SOLUTION ANALYSIS OF CORE SAMPLES FROM THE THEC SITE FROM HIGH PRESSURE AND TEMPERATURE CO_2 + H_2O TESTS

Leachate solutions generated by reacting the sample solids in the CO_2 + H_2O experimental environment were analyzed by ICP-OES for core samples from the Davis, and Bonneterre Formations, and Lamotte Sandstone (Table 5.27). Deionized water was used to initiate the tests to evaluate the effect of the host-rock formation in influencing water composition. Two carbonate- rich shale horizons from the Davis Formation were reacted in these tests, the 19-day 1,988.3 ft and 28- and 36-day 2,006.3 ft samples. For both these samples, Ca was released in significantly higher concentrations than all other elements indicating that dissolution of calcite ($CaCO_3$) was dominating the reactions. For the 1,988.3 ft sample, the release concentrations of elements from highest to lowest were Ca, Na, K, Mg, Si, and Mn (1.13E-02, 2.20E-03, 1.34E-03, 1.27-03, 8.00 E-04, and 1.61E-05 molal, respectively). For the 2,006.3 ft Davis Formation sample reacted for 28 days, concentration trends in decreasing order were Ca, Mg, Na, K, Si, and Mn (1.29E-03. 7.45E-04, 6.94E-04, 6.89E-04, 3.16E-04, and 1.67E-04, respectively). Concentrations also increased universally for all elements between the 28- and 36-day reactions (samples TH 6 C, D to TH 6 A, C; Table 5.27). The moderately high concentrations of Na and K in the leachate solutions may reflect residual ions adsorbed the mineral surfaces due to rocks being contacted by the brine solutions in the subsurface (Table 5.23). The elevated K/Na ratios in the leachant relative to the formation water brine, plus the presence of illite ($KAl_2(AlSi_3O_{10})(OH)_2$) as detected in the XRD analyses (Table 5.28), suggests that some of the dissolved K may have been released as a result of the alteration of illite minerals. Potassium also could be released from feldspar minerals; however, these were not detected in the XRD analyses.

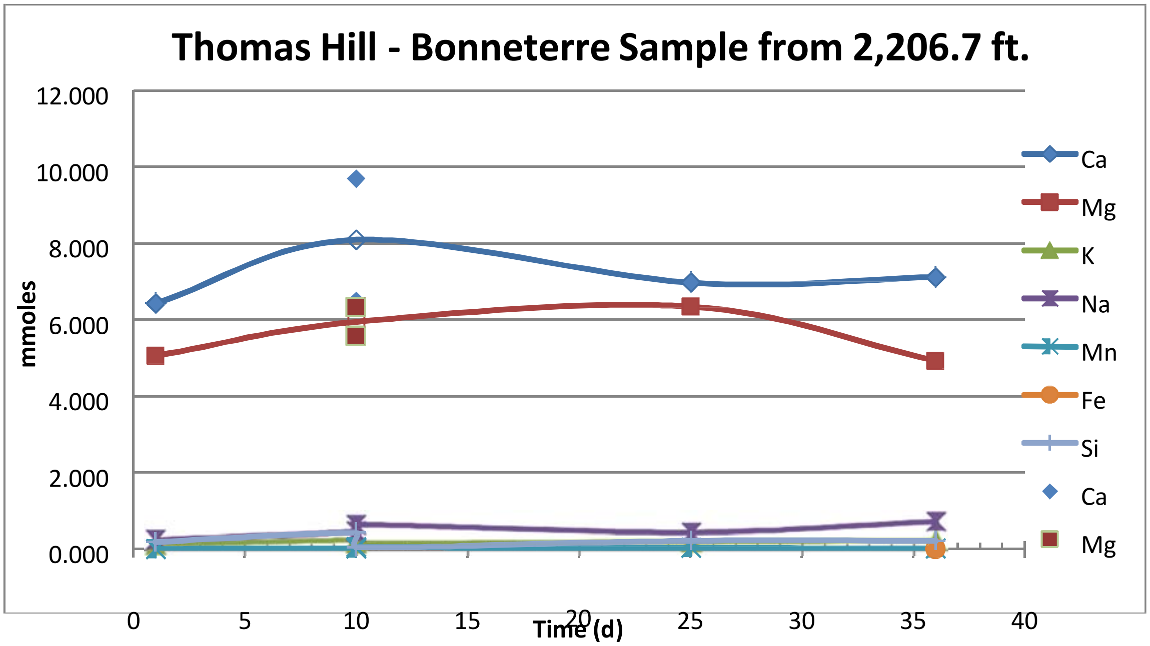
The 2,045.5 ft Davis Formation sample was a silty carbonate-rich shale. This sample was reacted for 28 days with reaction release trends being lower in Ca, higher in Mg, and similar with respect to all other elements when compared to the previously discussed 1,988.3 ft and 2,006.3 ft samples (Table 5.27). The lower Ca and higher Mg release suggests that dolomite was being dissolved in 2,045.5 ft sample during the corrosion tests.

The 2,071.5 ft Davis Formation sample appeared to contain only a minor amount of carbonate mineral as an extremely small amount of CO_2 effervescence was noted when a dilute hydrochloric acid solution was applied to its surface. Multiple horizons of the non-carbonate shale from the Davis and Derby-Doerun Formations represent a possible cap-rock for the St. Francois Aquifer, and thus would be the primary horizons responsible for preventing leakage of injected CO_2 back to the surface. Three samples of the Davis Formation 2,071.5 ft horizon were reacted for 19 days (Thomas Hill NCS-1, -2, and -4) and a fourth was reacted for 36 days (Table 5.27; Thomas Hill NCS 5, 6). The elemental concentrations for Ca, Mg, and K displayed a moderate increase from the 19- to 36-day reactions, while Na and Mn concentrations were relatively constant, and Si and Fe displayed a decrease. When compared to the carbonate-rich 1,988.3 ft and 2,006.3 ft samples, the 2,071.5 ft sample displayed a noticeable decrease in Ca release, reflecting what is likely to be a decrease in the amount of calcite being dissolved. Silicon release was relatively high in the 19-day sample, but then decreased for the 36-day reactions suggesting the initial dissolution of silicate phases was eventually being followed by the precipitation of silicates as alteration phases. The high release of Mg and K in conjunction with silicon may indicate that the silica was released from some clay minerals (though Mg is also a common constituent in dolomite as well).

The glauconitic sandstone from the Bonneterre Formation at 2,206.7 ft depth was reacted for time periods up to 1, 10, 25, and 36 days and displayed a congruent release between Ca and Mg throughout the testing period (Tables 5.27a and b, Figure 5.74a). The release of these elements in a 1:1 molar ratio suggests that dolomite (Ca, Mg(CO_3)$_2$) was the predominant mineral being dissolved. The XRD analytical results also indicate that dolomite is an abundant mineral in these samples (Table 5.28b). The release of K, Na, Mn, Fe, Si, and Al were all at low concentrations.

The two samples from the Lamotte Sandstone at 2,468.7 ft and 2,539.1 ft displayed an increase in concentration of Ca up to 26 days of reaction time, followed by a decrease up to the final 77-day experiment (Tables 5.27 a and b; Figure 5.74b). The elements Si, K, and Mn also followed a similar trend, albeit at a much lower concentrations, with Si displaying the most dramatic decrease in the long term tests. By contrast, Na and Mg increased gradually throughout the testing interval up to the final test at 77 days. The magnitude of and rapid nature of Ca release from these Lamotte Sandstone samples was unexpectedly very high given their quartz rich nature. The source for the excess Ca was determined to be calcite cement between the quartz as determined by observing effervescence of CO_2 bubbles after a 5% HCl solution was applied to the un-reacted samples.

FIGURE 5.74. ELEMENTAL RELEASE FROM THE THEC SITE CORE SAMPLES AFTER COMPLETION OF THE HIGH-PRESSURE CO2 + H2O TESTS AT 90OC. CALCULATED AVERAGE VALUES ARE SHOWN IN OPEN SYMBOLS. CONCENTRATION VALUES ARE IN MILLIMOLAL. A) ELEMENTAL RELEASE FROM GLAUCONITIC SANDSTONE OF THE BONNETERRE FORMATION FROM 2,207.7 FT. THE NEAR EQUIVALENT RELEASE RATES OF CA AND MG LIKELY REFLECT THE DISSOLUTION OF DOLOMITE. B) LAMOTTE SANDSTONE SAMPLE FROM 2,539.1 FT SHOWING RELATIVELY HIGH CA AND SI RELEASE AT 19 DAYS, FOLLOWED BY A GRADUAL DECREASE TO 77 DAYS. ALUMINUM WAS ANALYZED FOR BOTH SAMPLES BUT WAS FOUND TO BE BELOW THE DETECTION LIMIT (APPROXIMATELY 4 X 10-3 M MOLAL).



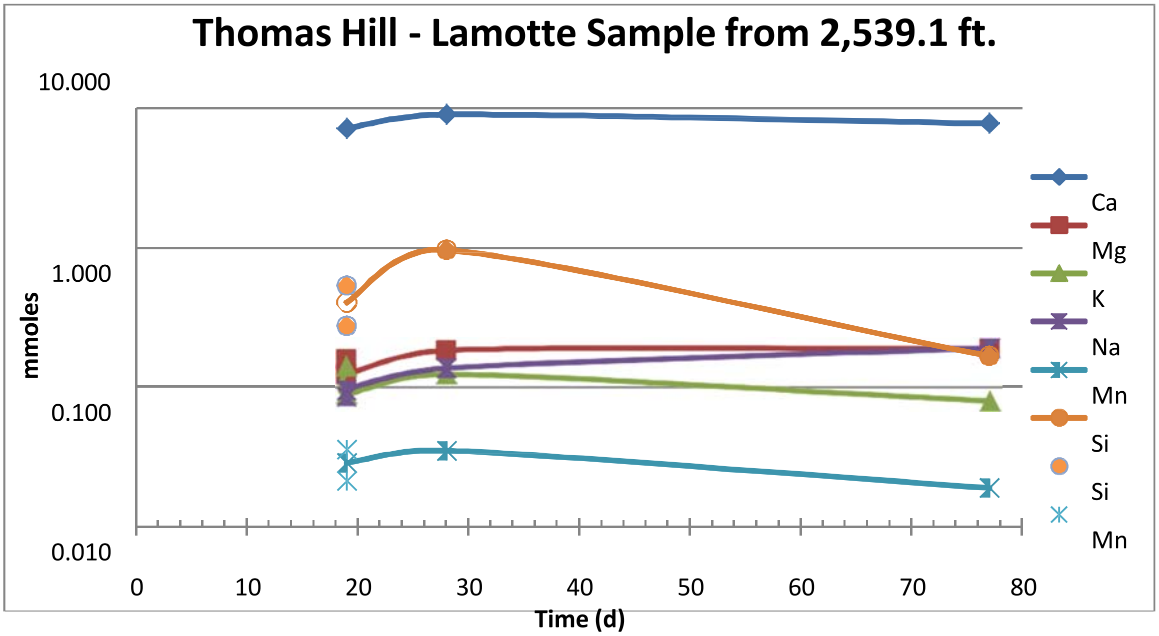


TABLE 5.27A. MAJOR ELEMENT CONCENTRATIONS FROM HIGH PRESSURE CO_2 + H_2O TESTS AT 90^0C WITH THEC CORE SAMPLES (VALUES IN PPM, MG/KG). ALUMINUM WAS BELOW DETECTION (<0.1 PPM) FOR ALL SAMPLES.

Sample # and test length in days	Depth (ft)	Ca	Mg	K	Na	Mn	Fe	Si
Thomas Hill CS-1; 19d	1988.3	453	30.9	52.5	50.5	0.9	<0.1	22.5
Thomas Hill 6 A,B; 36d	2006.3	519	32.0	49.7	52.7	0.3	<0.1	9.5
Thomas Hill 6 C,D: 36d	2006.3	518	18.1	26.9	16.0	0.1	<0.1	8.9
Thomas Hill 10 A,B; 28d	2045.5	357	111	32.6	68.8	0.9	<0.1	10.1
Thomas Hill NCS-1; 19d	2071.5	164	37.2	37.0	25.9	1.0	0.3	28.3
Thomas HillNCS-2; 19d	2071.5	161	37.6	35.5	40.6	0.8	0.4	30.3
Thomas Hill NCS-4; 19d	2071.5	205	45.6	36.5	38.3	0.9	0.5	23.7
Thomas Hill NCS-5,6; 36d	2071.5	239	46.9	42.4	39.7	0.9	<0.1	15.7
Thomas Hill GS-1; 10d	2206.7	263	123	5.7	6.0	0.7	<0.1	5.5
Thomas Hill GS-2; 25d	2206.7	396	154	10.1	10.9	1.5	1.8	12.2
Thomas Hill GS-3; 1d	2206.7	265	136	6.9	14.9	2.7	1.1	1.5
Thomas Hill GS-4; 10d	2206.7	285	155	8.3	10.3	2.0	<0.1	6.3
Thomas Hill GS-5,6; 36d	2206.7	291	120	9.6	16.9	1.2	<0.1	6.3
Thomas Hill QA-1; 25d	2468.7	487	5.6	4.3	2.5	1.0	<0.1	12.8
Thomas Hill QA-2; 1d	2468.7	264	4.1	3.9	0.9	0.5	0.1	6.3
Thomas Hill QA-3; 1d	2468.7	393	5.7	3.9	2.3	0.7	<0.1	3.9
Thomas Hill QA-4; 5d	2468.7	561	19.2	5.6	3.9	0.5	<0.1	12.6
Thomas Hill BS-1; 19d	2539.1	368	3.8	5.5	2.0	2.0	<0.1	15.1
Thomas Hill BS-2; 19d*	2539.1	222	3.0	3.5	2.2	1.2	<0.1	7.7
Thomas Hill BS-4; 77d	2539.1	369	4.5	4.9	3.2	1.9	<0.1	27.1

Thomas Hill BS-5,6	2539.1	319	4.6	3.1	4.4	1.0	<0.1	4.7
Blank #1; 77d		0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Blank #2; 77d		<0.1	<0.1	0.4	<0.1	<0.1	<0.1	<0.1

TABLE 5.27B. MAJOR ELEMENT CONCENTRATIONS FROM HIGH PRESSURE CO2 + H2O TESTS AT 90OC WITH THOMAS HILL CORE SAMPLES (VALUES IN MOLAL, MOLES/KG). N/A – NOT APPLICABLE BECAUSE ANALYSES WERE BELOW DETECTION LIMITS. ALUMINUM WAS BELOW DETECTION (<0.1 PPM) FOR ALL SAMPLES.

Sample Number	**Depth (ft)**	**Ca**	**Mg**	**K**	**Na**	**Mn**	**Fe**	**Si**
Thomas Hill CS-1	1988.3	1.13E-02	1.27E-03	1.34E-03	2.20E-03	1.61E-05	N/A	8.00E-04
Thomas Hill 6 A,B	2006.3	1.29E-02	1.32E-03	1.27E-03	2.29E-03	5.55E-06	N/A	3.40E-04
Thomas Hill 6 C,D	2006.3	1.29E-02	7.45E-04	6.89E-04	6.94E-04	1.67E-06	N/A	3.16E-04
Thomas Hill 10 A,B	2045.5	8.91E-03	4.57E-03	8.34E-04	2.99E-03	N/A	N/A	3.59E-04
Thomas Hill NCS-1	2071.5	4.09E-03	1.53E-03	9.45E-04	1.13E-03	1.74E-05	5.00E-06	1.01E-03
Thomas HillNCS-2	2071.5	4.02E-03	1.54E-03	9.09E-04	1.76E-03	1.55E-05	6.76E-06	1.08E-03
Thomas Hill NCS-4	2071.5	5.11E-03	1.88E-03	9.34E-04	1.67E-03	1.69E-05	9.06E-06	8.43E-04
Thomas Hill NCS-5,6	2071.5	5.96E-03	1.93E-03	1.08E-03	1.73E-03	1.59E-05	N/A	5.57E-04
Thomas Hill GS-1	2206.7	6.56E-03	5.06E-03	1.45E-04	2.59E-04	1.21E-05	N/A	1.97E-04
Thomas Hill GS-2	2206.7	9.88E-03	6.33E-03	2.58E-04	4.73E-04	2.76E-05	3.21E-05	4.35E-04
Thomas Hill GS-3	2206.7	6.61E-03	5.59E-03	1.77E-04	6.49E-04	4.93E-05	1.96E-05	5.47E-05
Thomas Hill GS-4	2206.7	7.11E-03	6.38E-03	2.12E-04	4.46E-04	3.72E-05	N/A	2.25E-04
Thomas Hill GS-5,6	2206.7	7.26E-03	4.94E-03	2.46E-04	7.34E-04	2.15E-05	N/A	2.25E-04
Thomas Hill QA-1	2468.7	1.22E-02	2.30E-04	1.10E-04	1.07E-04	1.77E-05	N/A	4.55E-04
Thomas Hill QA-2	2468.7	6.57E-03	1.69E-04	1.00E-04	3.97E-05	8.20E-06	1.79E-06	2.23E-04
Thomas Hill QA-3	2468.7	9.81E-03	2.34E-04	1.00E-04	9.95E-05	1.22E-05	N/A	1.38E-04
Thomas Hill QA-4	2468.7	1.40E-02	7.90E-04	1.43E-04	1.69E-04	9.77E-06	N/A	4.49E-04
Thomas Hill BS-1	2539.1	9.18E-03	1.56E-04	1.41E-04	8.67E-05	3.60E-05	N/A	5.37E-04
Thomas Hill BS-2*	2539.1	5.54E-03	1.23E-04	8.95E-05	9.63E-05	2.14E-05	N/A	2.75E-04
Thomas Hill BS-4	2539.1	9.21E-03	1.85E-04	1.24E-04	1.37E-04	3.52E-05	N/A	9.65E-04
Thomas Hill BS-5,6	2539.1	7.96E-03	1.89E-04	7.99E-05	1.91E-04	1.89E-05	N/A	1.67E-04
Blank #1		3.6E-06	N/A	N/A	N/A	N/A	N/A	N/A
Blank #2		N/A	N/A	9.75E-06	N/A	N/A	N/A	N/A

SEM-EDS analysis was carried out on three of the reacted core samples from the THEC site that had been subjected to the high pressure CO_2 corrosion testing environment. These tests were conducted to find possible physical alteration features such as dissolution pits or secondary mineral phases that may have precipitated during the experimental reactions. A carbonate-rich shale and siltstone sample of the Davis Formation from a depth of 2045.5 ft after 28 days of reaction displayed the formation of a reddish iron oxide coating and microsphere shaped grains. For comparison, both the un-reacted and altered samples from this sample are shown in Figure

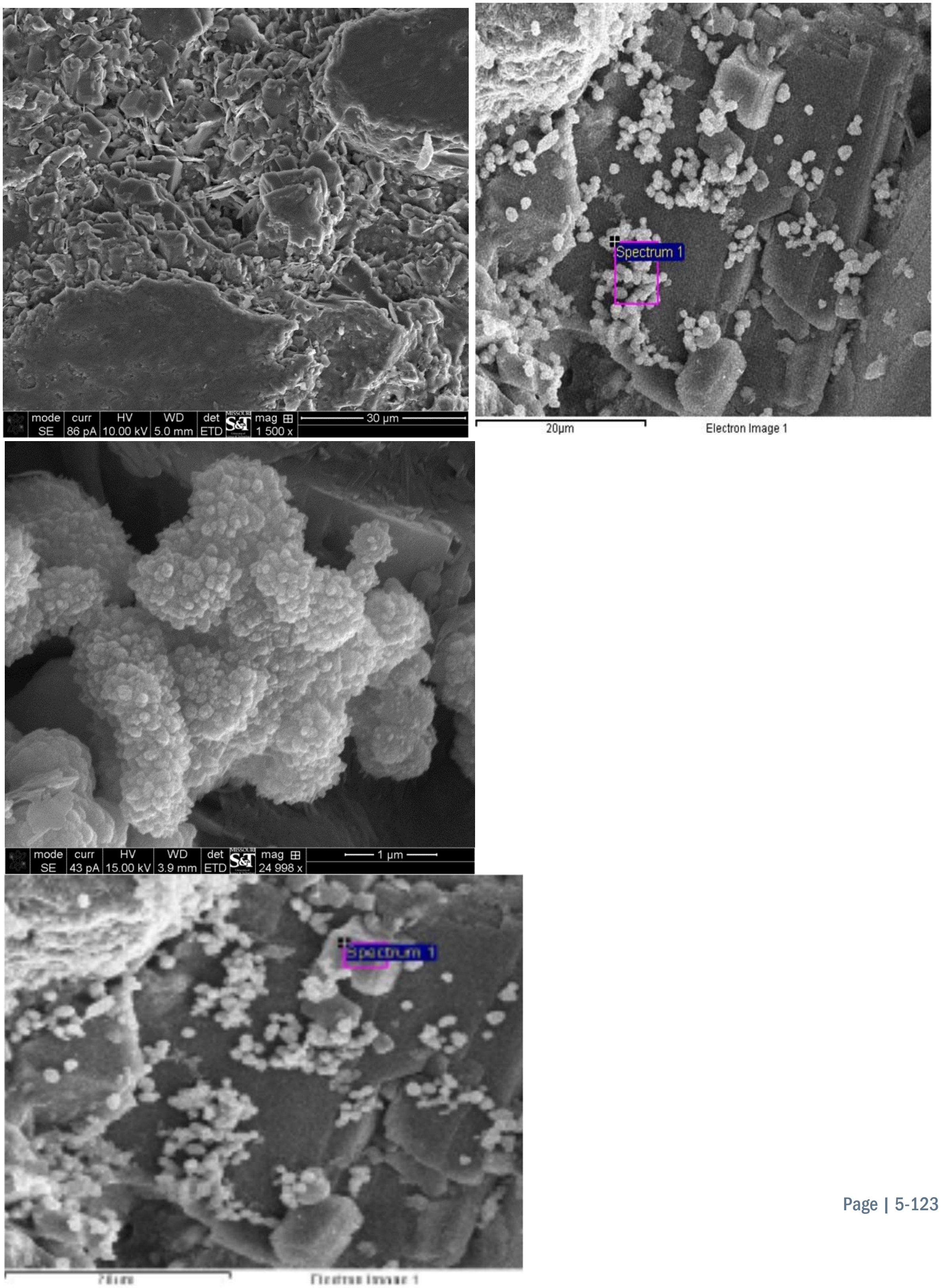
5.75. In the corroded sample image, the spheres appear scattered in clusters on the surface whereas in the non-corroded sample they are absent. A closer inspection of the microspheres revealed they were agglomerations of yet smaller nanosphere grains (Figure 5.75c). Because this sample was carbonate-rich shale to begin with, an acid test could not reveal if the spheres were carbonate minerals. An EDS scan was performed on the microspheres, but the SEM beam penetrated through the spheres and returned a composition that was indistinguishable from the substrate underneath.

The dolomite- and glauconite-rich sandstone (depth 2206.7 ft) from the Bonneterre Formation was examined with four different samples being reacted for 1, 10, 25, and 36 days. An un-reacted sample was also examined and revealed the presence of dolomite and platy-clay grains that were present in the original sample matrix (Figure 5.76). This sample was visibly altered by the corrosion testing, as it had been partially encrusted by an orange iron oxide layer that formed during testing (Figure 5.77a). Long, acicular needles with attached botryoidal grains also were found within pores in this sample (Figure 5.77b and c). The EDS analysis on the needles revealed the presence of S, C, and Cu (Figure 5.77d and e), however, the electron beam was wider than the needles, so EDS results may be picking up background compositions from either side of the needles and thus may not be entirely representative of the needles. While it is likely that these crystals are not derived as secondary mineral deposits as a result of corrosion testing, their exact origin is unknown. It is postulated they may be biogenic microfossils that occurred in the original rock as a localized region of sulfide mineralization. The EDS spectra did indicate the presence of abundant carbon as would be expected for a biogenic material.

Botryoidal grains also were found on the surface of the 2,206.7 ft Bonneterre Formation sample, as small (<5μm) agglomerated grains with a flakey internal habit (Figure 5.78). The botryoids appeared to have formed as an alteration phase that precipitated during the corrosion testing. This second type of botryoid was analyzed by SEM-EDS and found to be composed largely of iron and oxygen and may thus be hematite (Fe_2O_3), goethite ($FeO(OH)$), ferric hydroxide ($Fe(OH)_3$)), or another phase of a similar composition. The molar ratios of Fe:O that were detected by EDS analysis suggest the presence of goethite when the ratio was 1:2, and ferric hydroxide when the ratio was 1:3, respectively (Figure 5.78 and 5.79).

The final THEC sample analyzed (2,539.1 ft) was reacted for 19, 28, and 77 days. The Lamotte Sandstone was primarily a quartz arenite, and SEM-EDS analysis showed silica as the predominant component present (Figure 5.80). No dissolution pits or alteration minerals were found on or between grains following the experiments, though clays may be present as pore filling cements. Most samples showed little, if any, visible change in color or other physical appearance following corrosion testing.

FIGURE 5.75. INTERBEDDED SHALE/SILTSTONE SAMPLE FROM THE DAVIS FORMATION AT A DEPTH 2,045.5 FT. BOXED AREAS SHOW REGIONS WHERE EDS ANALYSIS WAS TAKEN. A) UN-REACTED SAMPLE SURFACE PRIOR TO CORROSION TESTING, B) REACTED SURFACE AFTER 28 DAYS OF EXPOSURE SHOWING THE FORMATION OF MICROSPHERES AND BLOCKY-RHOMBOHEDRAL CRYSTALS ACROSS THE SAMPLE SURFACE. SAMPLE WAS REACTED AT 90OC UNDER A PRESSURIZED CO2 + H2O ENVIRONMENT. C) HIGH MAGNIFICATION IMAGE OF THE MICROSPHERES SHOWING THEIR COMPOSITION OF AGGLOMERATED NANOSPHERE PARTICLES, AND D) LOCATION OF EDS ANALYSIS OF BLOCKY-RHOMBOHEDRAL PHASE. THE LINKED TABLE BELOW DISPLAYS EDS ANALYTICAL COMPOSITIONS OF THE MICROSPHERE AND BLOCKY GRAINS OUTLINED IN BOX FROM FIGURE 5.75B AND D, RESPECTIVELY.



Microsphere composition	Elemental Weight%	Atomic %		Blocky phase composition	Elemental Weight%	Atomic %
O	40.18	63.20		O	57.47	71.57
Al	5.63	5.25		Al	8.05	5.95
Si	14.07	12.61		Si	24.58	17.44
K	4.46	2.87		K	9.90	5.04
Fe	35.66	16.07				

FIGURE 5.76. SCANNING ELECTRON MICROGRAPH IMAGE OF UN-REACTED GLAUCONITIC SANDSTONE FROM 2,206.7 FT DEPTH IN THE BONNETERRE FORMATION. IT SHOWS RHOMBOHEDRAL-SHAPED DOLOMITE GRAINS AS WELL AS A FLAKEY PHASE BELIEVED TO BE A CLAY MINERAL.

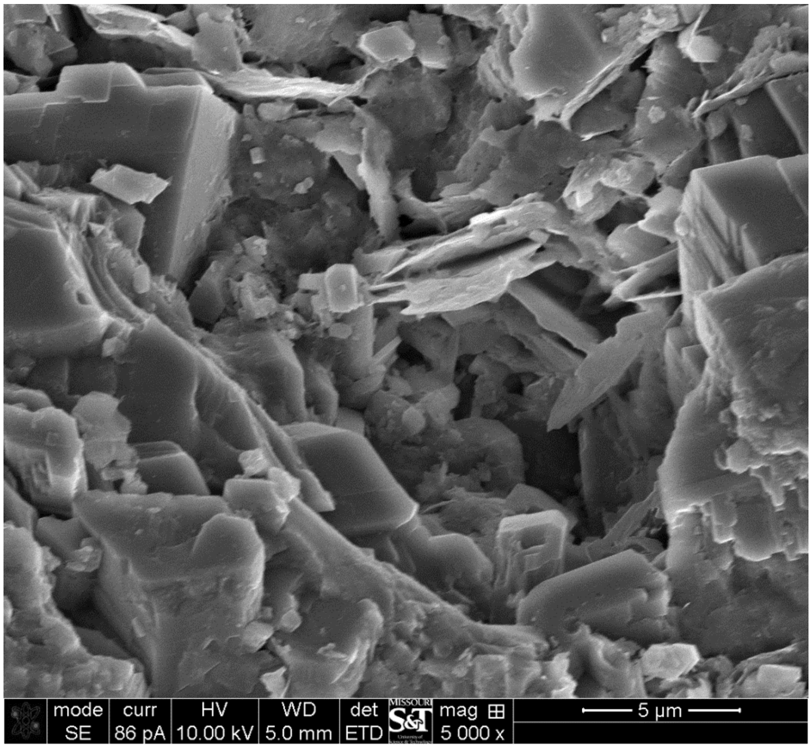
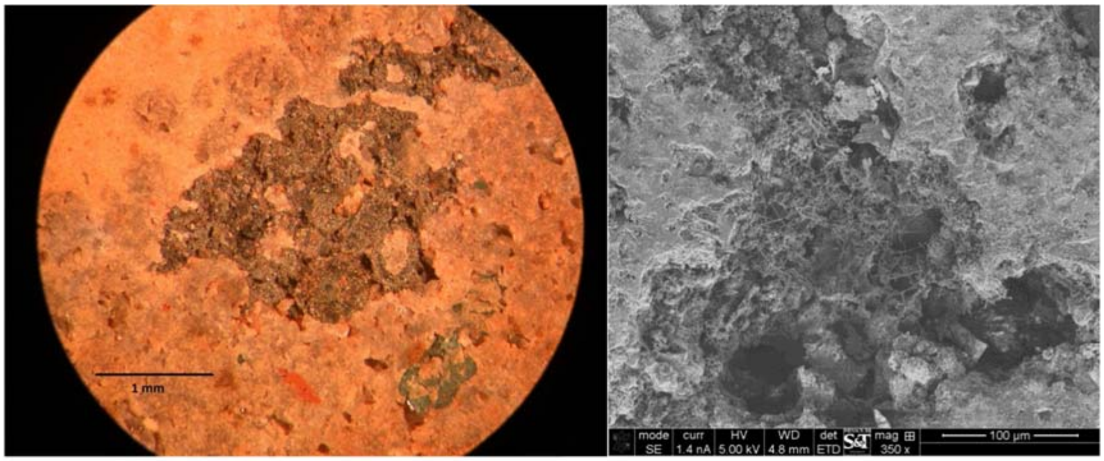
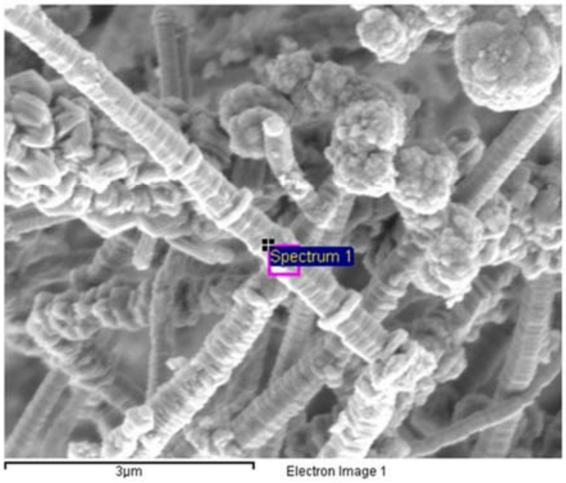
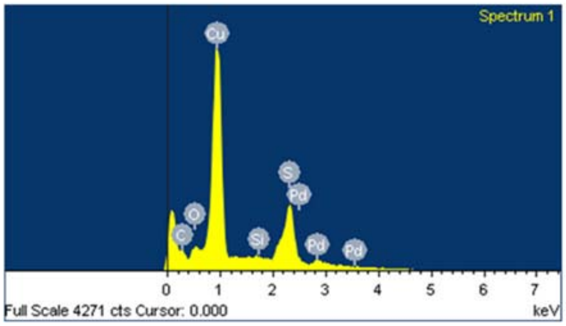


FIGURE 5.77. MICROGRAPHS AND EDS ANALYSIS OF CORE SAMPLES FROM THE BONNETERRE FORMATION AT THE THEC SITE AT A DEPTH OF 2,206.7 FT. A) SAMPLE WAS REACTED AT 90^{O}C UNDER A PRESSURIZED CO_2 + H_2O ENVIRONMENT FOR 25 DAYS. A) UPPER LEFT, OPTICAL MICROSCOPY IMAGE SHOWING MASS OF PRECIPITATED HEMATITE AND RESIDUAL PYRITE (CENTER OF IMAGE) AND LARGE GREEN GLAUCONITE GRAINS (BOTTOM RIGHT OF IMAGE), B) UPPER RIGHT, SCANNING ELECTRON MICROSCOPY (SEM) IMAGE OF SURFACE TAKEN BETWEEN TWO OF THE CIRCULAR IRON PHASE INCLUSIONS SHOWS A PRESENCE OF NEEDLE-LIKE STRUCTURES, C) MIDDLE LEFT, HIGHER MAGNIFICATION IMAGE SHOWING DETAILS OF NEEDLES AND BOTRYOIDAL GROWTHS ON AND BETWEEN THE NEEDLES THAT OCCURRED IN PORES, AND BOXED AREA THAT WAS TARGETED BY ELECTRON BEAM FOR EDS ANALYSIS, D) EDS SPECTRUM (BOTTOM LEFT) DISPLAYING S, C, CU DOMINATED COMPOSITION, AND E) BOTTOM RIGHT, SEMI-QUANTITATIVE EDS COMPOSITION TABLE.

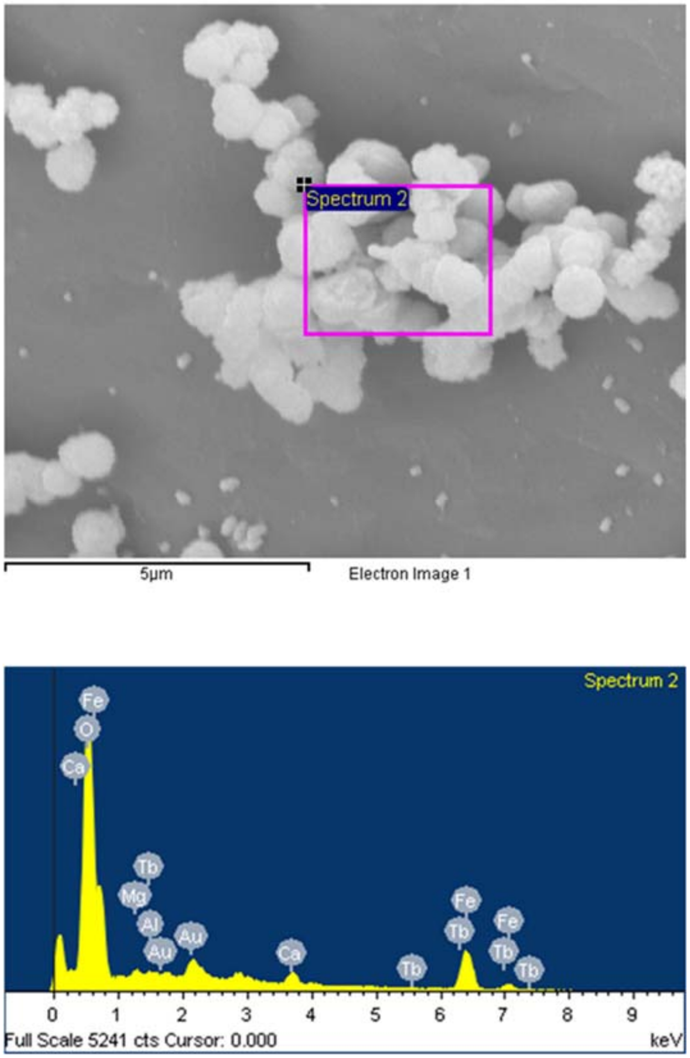






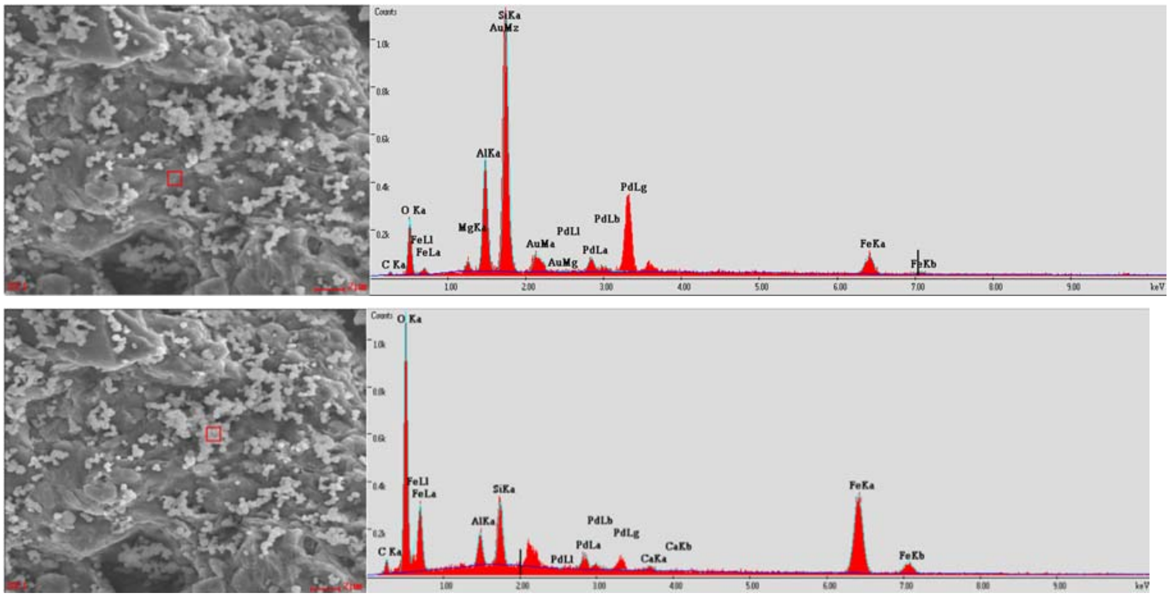
Element	Weight%	Atomic%
C K	7.36	25.58
O K	1.84	4.81
Si K	0.60	0.89
S K	19.72	25.66
Cu L	58.34	38.31
Pd L	12.13	4.76
Totals	100.00	

FIGURE 5.78. MICROGRAPH, EDS SPECTRA AND ELEMENT DATA FOR A CORE SAMPLE FROM THE BONNETERRE FORMATION AT THE THEC SITE AT A DEPTH OF 2,206.7 FT. A) IRON-RICH FLAKES THAT HAVE INTER-GROWN TO PRODUCE BOTRYOIDAL MICROSPHERES ON THE SURFACE OF THE ALTERED CORE SAMPLE THAT WAS REACTED AT 90OC UNDER A PRESSURIZED CO2 + H2O ENVIRONMENT FOR 25 DAYS. B) IMAGE TO LOWER LEFT SHOWS EDS SPECTRA OBTAINED FROM BOXED AREA IN PHOTO, AND C) IMAGE TO RIGHT DISPLAYS EDS RESULTS INDICATING THE PRESENCE OF A FE-O DOMINATED COMPOSITION. REMAINING ELEMENTS MAY BE A RESULT OF THE SIGNAL BEING DERIVED FROM THE SUBSTRATE OR AU-PD COATING USED FOR SEM ANALYSIS.



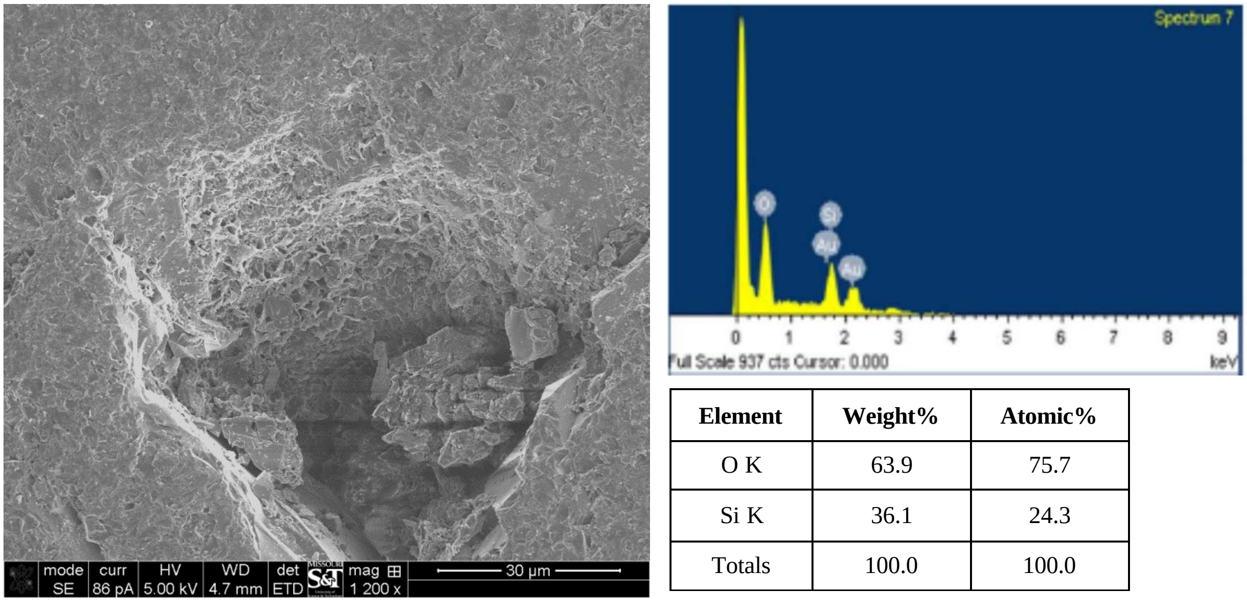
Element	Weight%	Atomic%
O K	29.83	63.76
Mg K	0.18	0.25
Al K	0.33	0.42
Ca K	2.53	2.16
Fe L	48.25	29.54
Tb L	14.40	3.10
Au M	4.48	0.78
Totals	100.00	

FIGURE 5.79. BOTRYOIDAL IRON OXIDE MICROSPHERES DEVELOPED ON THE ALTERED SURFACE OF THE CORE SAMPLE OF THE BONNETERRE FORMATION FROM THE THEC SITE AT 2,206.7 FT. THE SAMPLE WAS REACTED AT 90^{O}C UNDER A PRESSURIZED CO_2 + H_2O ENVIRONMENT FOR 25 DAYS. BOXES IN PHOTOGRAPHS SHOW LOCATIONS FOR ENERGY DISPERSIVE SPECTROSCOPY (EDS) DATA FOR BACKGROUND SUBSTRATE (UPPER PHOTO) AND CLUSTER OF MICROSPHERES (LOWER PHOTO) WITH SPECTRAL RESULTS SHOWN TO RIGHT. ELEMENTAL COMPOSITIONS OBTAINED BY THE EDS ANALYSES OF BOTH AREAS ARE SHOWN IN THE LINKED TABLE BELOW.



	Background	Substrate		Microspheres	
Element	**Element Wt.%**	**Atomic %**		**Elemental Wt. %**	**Atomic %**
C	3.8	9.2		5.9	12.8
O	15.5	28.5		33.0	54.2
Fe	14.8	7.8		45.5	21.4
Mg	1.2	1.5		none detected	none detected
Ca	none detected	none detected		0.8	0.6
Al	13.2	14.4		3.8	3.7
Si	33.4	35.0		6.7	6.2
Au	11.4	1.7		none detected	none detected
Pd	6.7	1.9		4.4	1.1

FIGURE 5.80. SCANNING ELECTRON MICROSCOPY IMAGE, EDS SPECTRUM AND ELEMENT DATA FROM A BONNETERRE FORMATION CORE SAMPLE FROM THE THEC SITE AT A DEPTH OF 2,539.1 FT. A) LEFT, THE CORE SAMPLE HAS BEEN REACTED AT 90^{O}C UNDER A PRESSURIZED CO_2 + H_2O ENVIRONMENT FOR 28 DAYS. NO DEFINITIVE ALTERATION PHASES WERE NOTED ON THE SAMPLE SURFACE OR WITHIN PORES; HOWEVER, CORRUGATED MATERIAL ON THE UPPER PORE SURFACE IN CENTER OF PHOTO DISPLAYS THE TEXTURE TYPICAL FOR CLAY MINERALS. B) EDS SPECTRUM OF THE ANALYZED AREA SHOWING SI AND O COMPOSITION (AU AND PD PEAKS RESULT FROM CONDUCTIVE COATING ADDED TO SAMPLE PRIOR TO ANALYSIS), AND C) ELEMENTS PRESENT AND THEIR RESPECTIVE ABUNDANCES IN ARE SHOWN IN TABLE AT BOTTOM RIGHT.



Element	Weight%	Atomic%
O K	63.9	75.7
Si K	36.1	24.3
Totals	100.0	100.0

X-RAY DIFFRACTION (XRD) ANALYSIS FOR CORE SAMPLES FROM THE THEC SITE

The clay-sized particle fraction of all of the core samples from the Davis Formation and Lamotte Sandstone at the THEC site contained illite or muscovite as the predominant mineral constituent (Tables 5.28a and b). The XRD spectra for the Davis Formation sample from the THEC Site (1,988.3 ft depth) displayed prominent peaks at approximately 8.8 degrees 2-theta (Figure 5.81a). This peak correlates to both Illite and muscovite, which are virtually indistinguishable by XRD analysis due to having similar c-axis d-spacings (9.97-9.98 Å for illite, 10.01 Å for muscovite). The 8.8 degree 2-theta peak will subsequently be referred to as illite as this phase is the more likely of the two to be found in sedimentary rocks.

Glauconite and dolomite were both detected in the Bonneterre Formation sample (Figure 5.81b). The glauconite is tentatively identified based upon a broad diffuse peak between approximately 4 – 10 degrees 2-theta. The peak broadening is believed to result from a poorly oriented clay particle slide, which in turn results from glauconite's common habit of curling into pellets. The peak at 30.9 degrees correlates with the presence of dolomite. This peak unexpectedly shifted to a lower angle following glycolation and heat treatment, but was still within the range expected for dolomite and/or high-Mg calcite.

Minor amounts of chlorite (14.2 Å) were detected in the 2071.5 ft Davis Formation sample, while kaolinite (7.16 Å) was detected in both of the Davis Formation samples (Tables 5.28b). Quartz was the dominant non-clay mineral component in the Davis Formation and Lamotte Sandstone samples (Table5.28a). Halite was detected in several samples and likely precipitated upon drying of the samples.

The XRD instrument generally does not detect minor phases that are present in concentrations < 5-10% by weight.

TABLE 5.28A. CLAY-SIZED FRACTION MINERALS DETECTED BY X-RAY DIFFRACTION ANALYSIS OF CORE SAMPLES FROM THE THEC SITE.

Core Depth (ft)	Clay Mineral Types Found	Major Non-Clay Peaks	Formation
1988.2	Illite, minor Kaolinite	Calcite, quartz	Davis
2071.5	Illite, minor Kaolinite, minor chlorite	Quartz	Davis
2206.7	Glauconite	Dolomite	Bonneterre
2468.7	Dominantly illite	Quartz	Lamotte
2539.1	Dominantly illite	Quartz	Lamotte

TABLE 5.28B. SEMI-QUANTITATIVE CLAY FRACTION DETERMINATIONS FOR EACH CORE SAMPLE ANALYZED FROM THE THEC SITE. NOTE THAT SOME CHLORITE MAY HAVE BEEN PRESENT IN MINOR QUANTITIES TOO SMALL TO INCLUDE IN THE CALCULATIONS. "BD" – BELOW DETECTION.

Sample ID	Depth (ft)	Formation	% Illite	% Kaolinite	% Chlorite	% Glauconite
TH-CS	1988.3	Davis	75	25	bd	bd
TH-NCS	2071.5	Davis	85	15	Trace	bd
TH-GS	2206.7	Bonneterre	bd	bd	bd	100
TH-QA	2468.7	Lamotte	100	bd	bd	bd
TH-BS	2539.1	Lamotte	100	bd	bd	bd

FIGURE 5.81A. X-RAY DIFFRACTION SPECTRA FOR CORE SAMPLE OF THE DAVIS FORMATION FROM THE THEC SITE AT A DEPTH OF THE 1,988.3 FT. PEAKS AT 8.8, 17.8, AND 26.8 DEGREES 2-THETA INDICATE THE PRESENCE OF ILLITE, THE PEAK 12.5 INDICATES KAOLINITE, THE 20.8 AND 26.6 REFLECT THE PRESENCE OF QUARTZ, AND 29.5 IS THE PEAK FOR CALCITE.

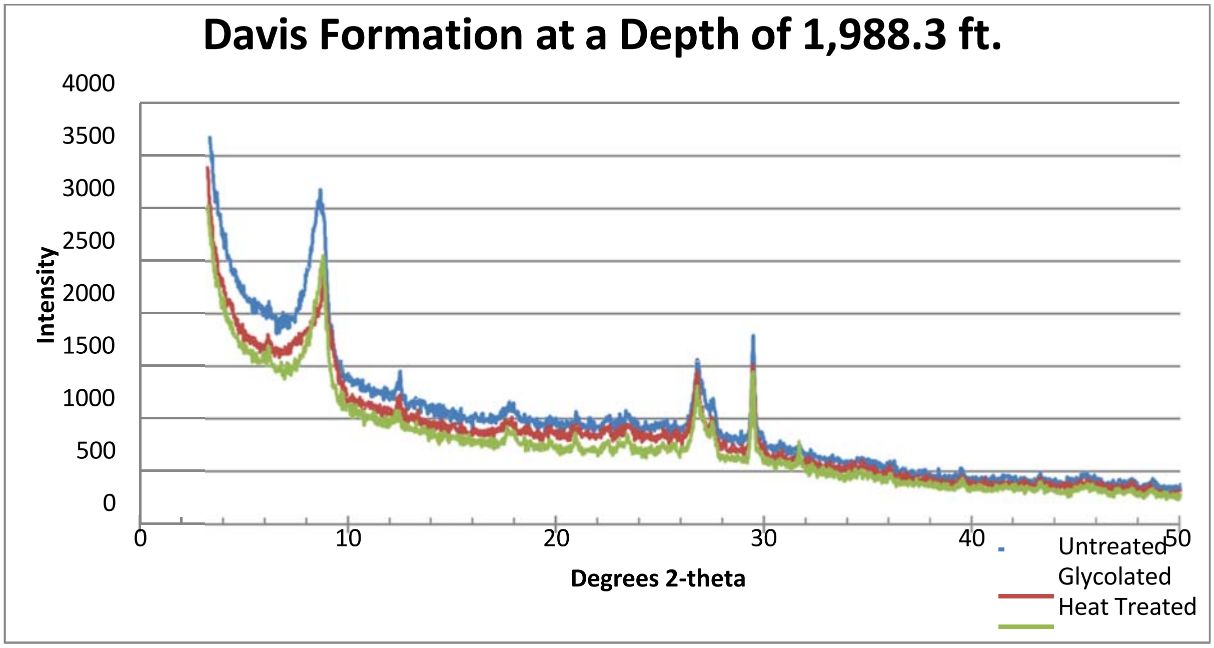
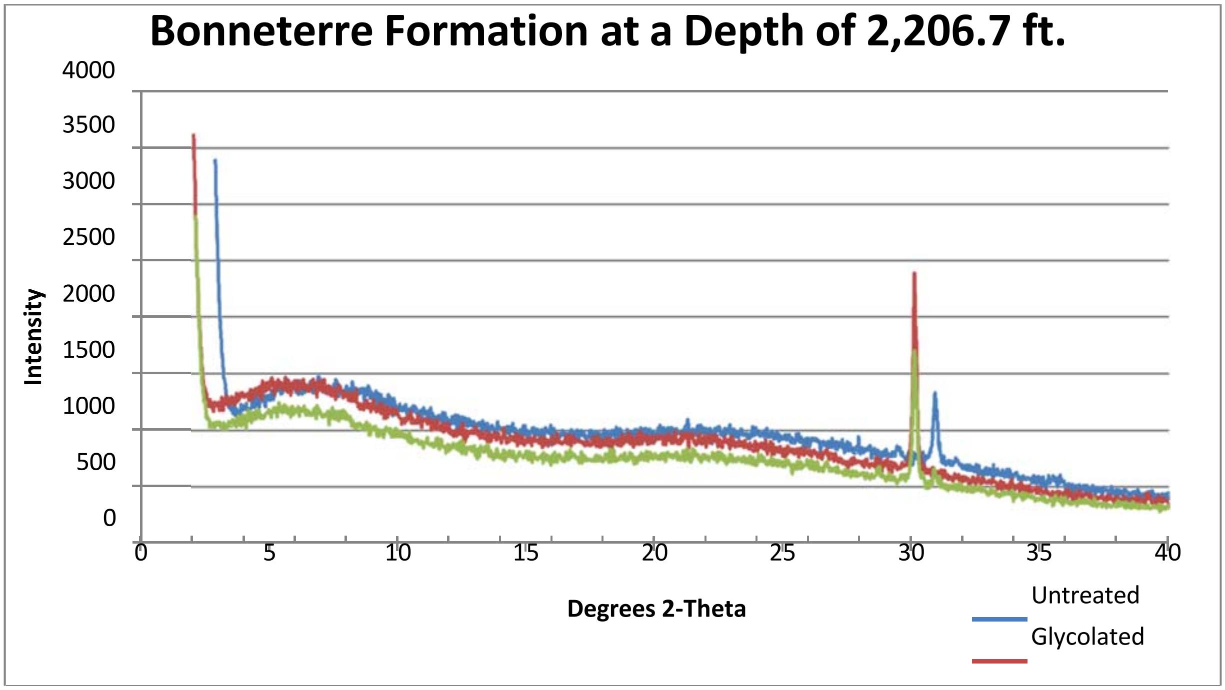


FIGURE 5.81B. X-RAY DIFFRACTION SPECTRA FOR THE CORE SAMPLE OF THE BONNETERRE FORMATION FROM THE THEC SITE AT A DEPTH OF 2,206.7 FT. THERE IS A BROAD DIFFUSE PEAK BETWEEN ~ 4 – 10 DEGREES 2-THETA, WHICH IS BELIEVED TO REPRESENT GLAUCONITE WITH A POOR ORIENTATION. THE PEAK AT 30.9 DEGREES INDICATES THE PRESENCE OF DOLOMITE.



In summary, the THEC borehole had an excellent section of Lamotte from approximately 2,345 ft to 2,500 ft. The Lamotte Sandstone had porosity similar to the JTEC borehole, with average of 10.8% (cores) and a range of 8% to 13%. Average formation permeability was 47 md, with a range of 11 md to 157 md. From 2,420 ft to 2,500 ft the Lamotte Sandstone has the highest permeability, averaging approximately 90 md through this zone. Core porosity and log porosity were in good agreement.

The Davis Formation was encountered from 1,985-2,083 ft, and the Bonneterre Formation from 2,083-2,333 ft. There are two zones with porosity and elevated permeability in the Davis Formation. These are 11% porosity and .11 md at 2,059 ft, and 12% porosity with vertical permeability of 0.3 md at 2,327 ft. The Davis Formation is best between 2,071 ft. and 2,120 ft. Capillary pressure for the Davis Formation was somewhat low, and further examination of the Davis is recommended prior to any sustained injection.

Geomechanical testing of core samples from the THEC borehole indicated that the Lamotte modulus is approximately 7×10^6 and the Davis Formation is 3×10^6. No pump-in tests were conducted to measure breakdown pressure directly. The fracture gradient was determined using standard fracture gradient calculation methods including Eaton's method, Hubbert and Willis, and the Pennebaker Correlation Method. These calculations indicate a fracture gradient of 0.61 to 0.64 psi/ft in the Lamotte Sandstone.

No reservoir simulation was conducted for the THEC site, and CMG reservoir simulation is required to adequately model CO_2 injection and storage. However, some general observations can be drawn by comparing the THEC reservoir characteristics to those found at JTEC, which was modeled and simulated extensively. Reservoir porosity was similar in both boreholes, but the THEC site has significantly better permeability compared to JTEC (47 md to 2 md on average). The THEC borehole also has nearly 50 ft of formation with an average permeability of 90 md. Assuming a linear scale, one could expect up to 4 times the injectivity modeled for the JTEC site. Although porosity is similar, the Lamotte Sandstone is thicker and slightly deeper at the THEC site, which would provide an increase in storage capacity.

The water drawn from the Lamotte Sandstone unit at the THEC site was a NaCl dominated brine with proportionally minor Ca, and very minor Mg-bicarbonate-sulfate fractions (Figure 5.82). The iron concentration was also high enough to produce a visible amount of precipitated iron oxide and/or hydroxide particles (Fe_2O_3, $FeO(OH)$, or $Fe(OH)_3$) after conversion of Fe^{2+} that was present in the subsurface, into Fe^{3+} upon exposure to the oxygenated atmosphere. The three methods used to determine salinity of the water samples from the Lamotte Sandstone were in close agreement, varying by <3%. The TDS evaporation method for determining salinity produced a value of 46,287 ± 11 mg/kg, the cation + bicarbonate + anion tabulation method resulted in a value of 45,723 mg/kg, while the conductivity value calculation produced a salinity value of 47,090 ± 67 mg/kg. The THEC site thus had a dissolved salt concentration that was well above the 10,000 mg/kg EPA limit for classification as a Class VI injection facility.

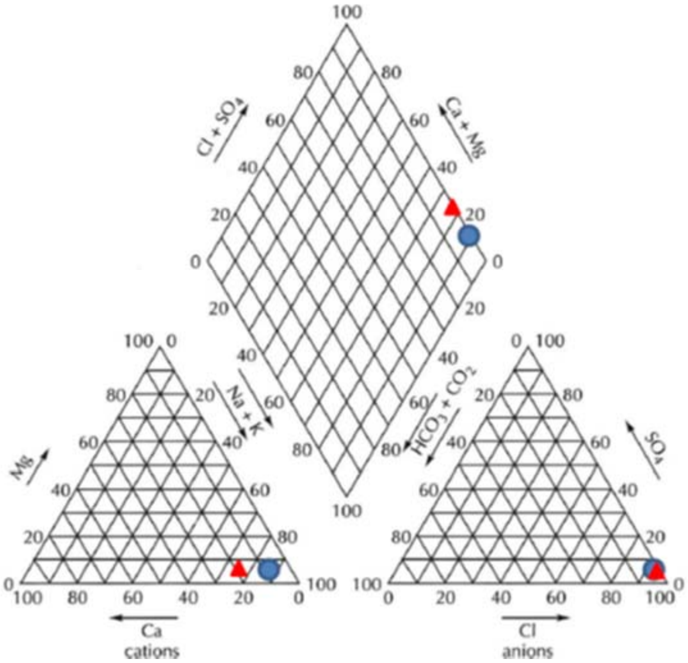
The water drawn from THEC site displayed relatively high Ca and Mg concentrations (2,491 and 860 ppm, respectively). Overall high Ca + Mg concentrations (activities) will exert an influence on the potential for carbonate mineralization for the formation waters. Core samples from all three well sites (JTEC, THEC, and SPP sites) were reacted in the 90°C high pressure $CO_2 + H_2O$ tests designed to accelerate mineral reactions. Alteration phases commonly included iron oxides.

Carbonate phases were also detected, but were sporadic in occurrence and minor in amount. These included rhombohedral-shaped grains with a composition consistent with the presence of dolomite

($Ca,Mg(CO_3)_2$), and a second phase tentatively identified as siderite ($FeCO_3$), though the latter was too small to get accurate compositional analysis. The potential for carbonate mineralization resulting from elements released directly from dissolving rock materials thus appears to be minimal, and will largely depend on the elements already present in the groundwater. The Goldich series reaction tests also support this view, with mineral phases commonly encountered in the Missouri strata (quartz, Na-rich plagioclase, orthoclase, kaolinite, illite, and glauconite) being slow to react with acidified fluids. Acid neutralization reactions and an associated pH rise that results from the interaction between $H_2CO_{3(aq)}$ and the mineral constituents, however, may have played more of a role in inducing carbonate mineralization.

The clay-sized particle fraction of all of the core samples from the THEC site, contained illite as the predominant clay mineral, along with lesser amounts of kaolinite, glauconite, and chlorite. The low turbidity of water samples collected from the borehole and the similarities of elemental concentrations in the water samples passed through different filter sizes suggest that the clays remain intact within the repository pore space and thus will not migrate and cause pore blockage. Iron oxide flocculates that formed in the core samples from the THEC sites after they were exposed to oxygenating conditions suggest a potential for iron flocculate formation in the subsurface. Such a process may induce pore plugging in the subsurface rocks if it does indeed occur during or following CO_2 injection.

FIGURE 5.82. PIPER DIAGRAM DISPLAYING THE RELATIVE COMPOSITION RATIOS OF THE NACL DOMINATED WATER SAMPLES FROM THE LAMOTTE SANDSTONE FROM THE THEC (BLUE CIRCLES) AND THE SPP (RED TRIANGLES) SITES. THE DATA PLOTTED REPRESENT MILLIEQUIVALENT VALUES (MOLAL CONCENTRATION * IONIC CHARGE).



3. IATAN GENERATING STATION

No work was performed at this site as the drilling in the borehole encountered difficulties so the site was plugged and abandoned.

4. SIOUX POWER PLANT

Task 4.a. Determine the Permeability of Core Samples from the Confining Layer and Target Formation at the Four Missouri Power Plant Sites

Task 4.b. Determine Porosity, Permeability, Grain Size Distribution, Pore Throat Size and Shape, and Minerals Present in Representative Core Samples at the Four Missouri Power Plant Sites

POROSITY AND PERMEABILITY

Table 5.29 summarizes the porosity and permeability measurements of core samples taken from the SPP borehole. Based on the previously good agreement of Missouri S&T and Core lab results for the JTEC site, no further core samples were sent to Core Labs for evaluation. Average porosity and permeability values are summarized in Tables 5.30 and 5.31. Figures 5.83 through 5.86 provide a graphical representation of the data in Table 5.30. Figures 5.87 through 5.89 provide graphical representation of data contained in Table 5.31.

TABLE 5.29. POROSITY AND PERMEABILITY RESULTS FOR THE SIOUX SITE

Formation	Sample ID	Depth	Porosity	Permeability	Grain Density
		Ft	%	md	g/cc
Derby-Doerun (Formation top: 2,775 ft)	1V	2836.1	7.06	0.0128	2.857
	1H	2836.1	7.51	0.4587	2.838
	3V	2929.8	7.43	0.0102	2.83
	3H	2929.8	6.10	0.0835	2.836
Davis Formation (Formation top: 2,933 ft)	6V	3047.9	2.89	-	2.595
	6H	3047.9	3.21	-	2.603
	7V	3096.1	13.51	0.0146	2.791
	7H	3096.1	2.28	0.0029	2.861
	10V	3177.5	1.95	-	2.736
	10H	3177.5	2.57	-	2.74
	12V	3222.2	1.71	-	2.767
	16V	3300.7	0.99	-	2.751
	16H	3300.7	0.87	-	2.731
	17V	3322.9	3.84	0.0088	2.853
Bonneterre/Lamotte Transition	20V	3353.2	15.46	34.748	2.635
	20H	3353.2	15.26	37.135	2.64

(Formation top: 3,329 ft)	28V	3460.0	14.21	12.723	2.681
	28H	3460.0	8.40	13.038	2.689
	31V	3476.1	20.52	11.454	2.642
	31H	3476.1	20.83	38.357	2.626
Lamotte (Formation top: 3,481 ft)	34T	3500.5	12.37	7.8459	2.647
	34B	3500.5	10.74	5.4457	2.569
	35T	3504.8	6.32	0.0047	2.64
	35B	3504.8	6.93	0.0165	2.637
	36T	3510.4	11.24	0.3659	2.635
	36B	3510.4	9.33	0.0755	2.635
	38T	3521.2	10.22	3.6815	2.692
	38B	3521.2	12.87	17.446	2.637
	40T	3524.2	12.01	5.0268	2.63
	40B	3524.2	11.91	2.4562	2.635
	42T	3537.8	12.58	22.144	2.636
	42B	3537.8	10.67	9.9942	2.635
	44T	3547.0	16.15	1.208	2.672
	44B	3547.0	12.39	3.3697	2.637
	46T	3558.4	13.74	12.701	2.636
	46B	3558.4	13.55	24.318	2.635
	48T	3567.0	15.46	7.3908	2.636
	48B	3567.0	10.39	4.1325	2.625
	49T	3576.5	10.82	60.837	2.632
	49B	3576.5	10.47	26.845	2.632
	50T	3580.1	16.33	99.247	2.639
	50B	3580.1	15.23	17.582	2.645
	53T	3589.7	9.17	0.1616	2.676
	53B	3589.7	8.98	0.6181	2.66
	55T	3595.7	21.05	0.0532	2.777
	55B	3595.7	21.33	0.0711	2.795
	56T	3597.2	6.06	0.0137	2.667
	56B	3597.2	8.31	0.0207	2.68
	58T	3607.6	16.58	5.5392	2.636
	58B	3607.6	13.33	1.6394	2.637
	59T	3615.2	11.56	0.6376	2.638
	59B	3615.2	11.76	0.5503	2.649
	60T	3618.0	10.12	0.8229	2.615
	60B	3618.0	15.14	2.4542	2.651
	61T	3622.0	14.68	2.4443	2.657
	61B	3622.0	13.56	1.2595	2.644

TABLE 5.30. POROSITY AND PERMEABILITY RESULTS FOR THE CONFINING LAYER AT THE SPP SITE

Depth	Average porosity	Vertical permeability	Horizontal permeability	Average grain density
ft	%	md	md	g/cc
2836.1	7.28	0.0128	0.4587	2.8475
2929.8	6.76	0.0102	0.0835	2.833
3047.9	3.05	-	-	2.599
3096.1	1.89	0.0146	0.0029	2.826
3177.5	2.26	-	-	2.738
3222.2	1.71	-		2.767
3300.7	0.93	-	-	2.741
3322.9	3.84	0.0088		2.853
3353.2	15.36	34.748	37.135	2.6375
3460	11.30	12.723	13.038	2.685
3476.1	20.67	11.454	38.357	2.634

FIGURE 5.83. DERBY-DOERUN, DAVIS AND BONNETERRE FORMATIONS POROSITY

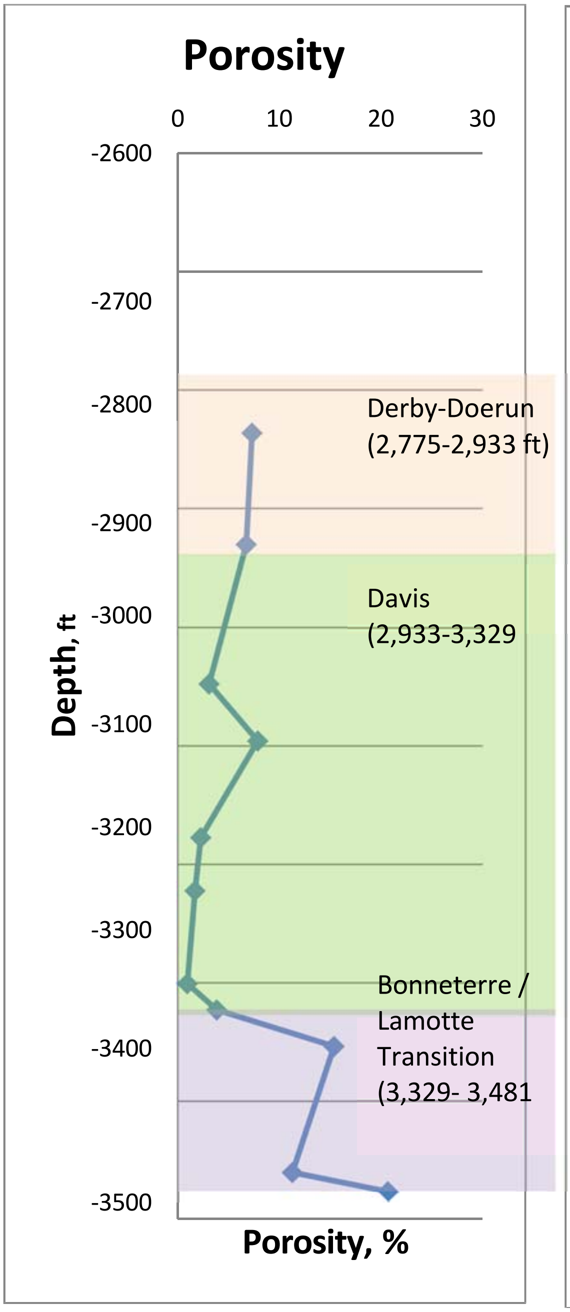


FIGURE 5.84. DERBY-DOERUN, DAVIS AND BONNETERRE FORMATIONS VERTICAL PERMEABILITY

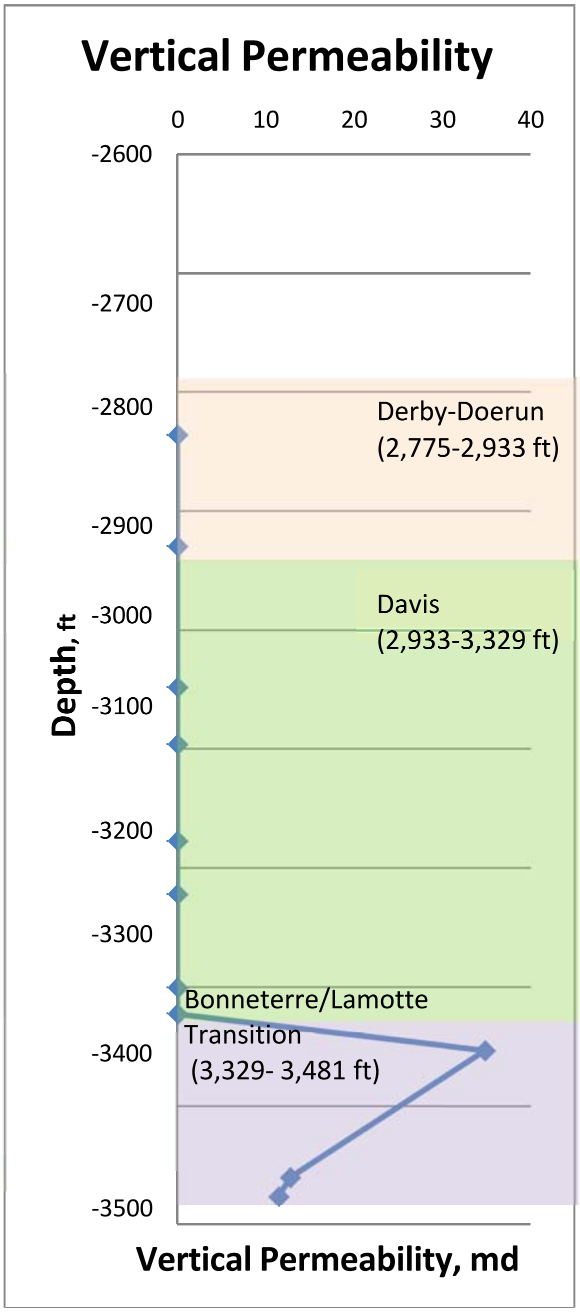


FIGURE 5.85. DERBY-DOERUN, DAVIS FORMATION AND BONNETERRE FORMATION HORIZONTAL PERMEABILITY

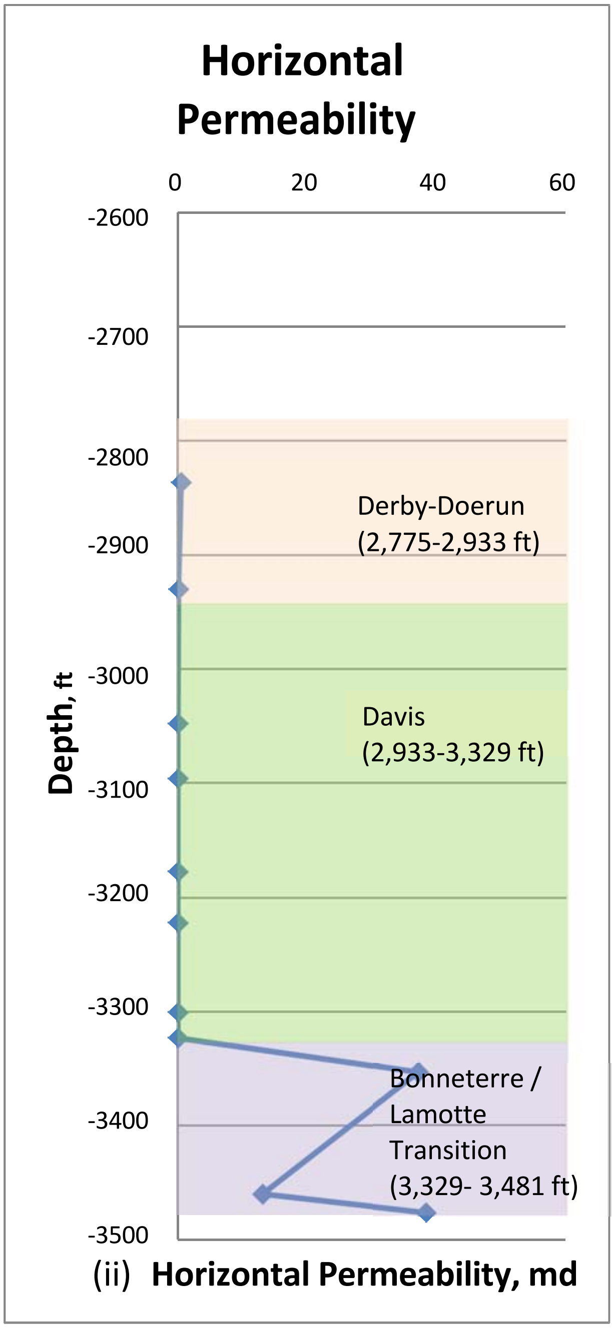
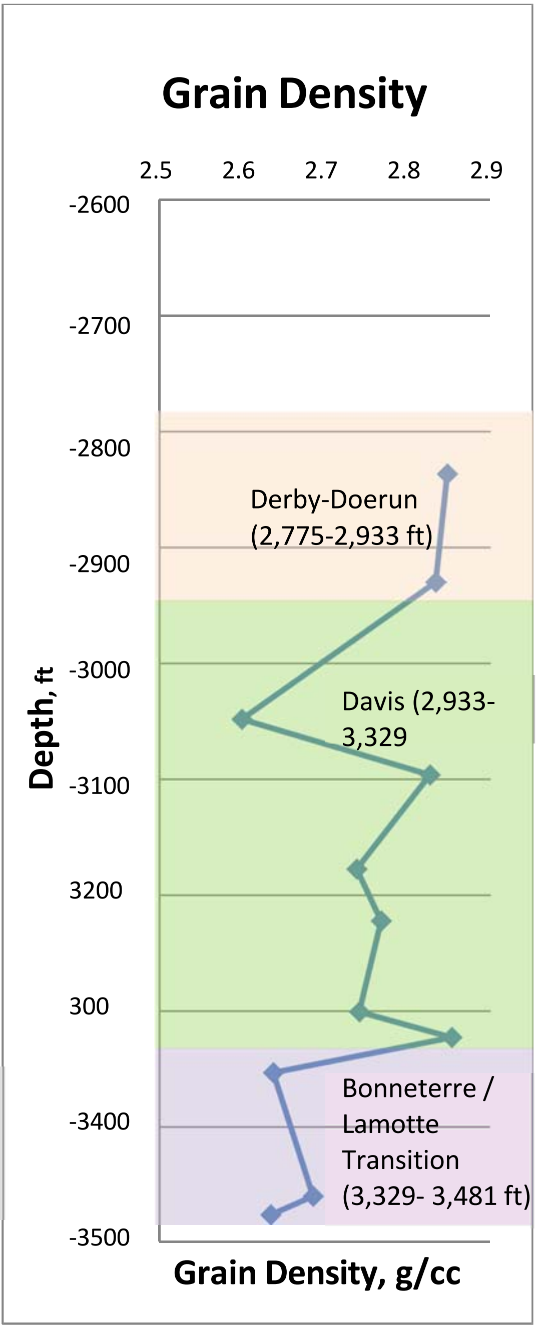


FIGURE 5.86. DERBY-DOERUN, DAVIS FORMATION AND BONNETERRE FORMATION GRAIN DENSITY



Core analysis of the confining layer indicates a range of permeability from 2.9 microdarcy to 0.015 millidarcies. Most Davis Formation samples had permeability so low it could not be measured.

The Davis Formation was encountered between 2,930 ft and 3323 ft, with an average porosity of 3%. By comparison, the Davis Formation at the SPP borehole has less porosity and less permeability than the other sites measured.

Average core porosity for the target formation was 12.3% with a range of 6% to over 21%. The porosity was high throughout the target formation, but especially at 3,596 ft, as shown in Table 5.29 and Figures 5.83 through 5.86. Average core permeability was approximately 10 md with a range of .02 md to 99 md. The highest permeability occurs between 3,577 ft and 3,580 ft.

TABLE 5.31. POROSITY AND PERMEABILITY RESULTS FOR THE TARGET FORMATION AT THE SPP SITE

Depth	Average porosity	Average permeability	Average grain density
ft	%	md	g/cc
3500.5	11.56	6.6458	2.608
3504.8	6.63	0.0106	2.6385
3510.4	10.29	0.2207	2.635
3521.2	8.46	10.5637	2.6645
3524.2	11.96	3.7415	2.6325
3537.8	11.63	16.0691	2.6355
3547	14.27	2.2889	2.6545
3558.4	13.65	18.5095	2.6355
3567	12.93	5.76165	2.6305
3576.5	10.64	43.841	2.632
3580.1	15.78	58.4145	2.642
3589.7	9.08	0.3899	2.668
3595.7	21.19	0.06215	2.786
3597.2	7.189	0.0172	2.6735
3607.6	14.95	3.5893	2.6365
3615.2	11.66	0.59395	2.6435
3618	12.63	1.6386	2.633
3622	14.12	1.8519	2.6505

FIGURE 5.87. LAMOTTE SANDSTONE POROSITY

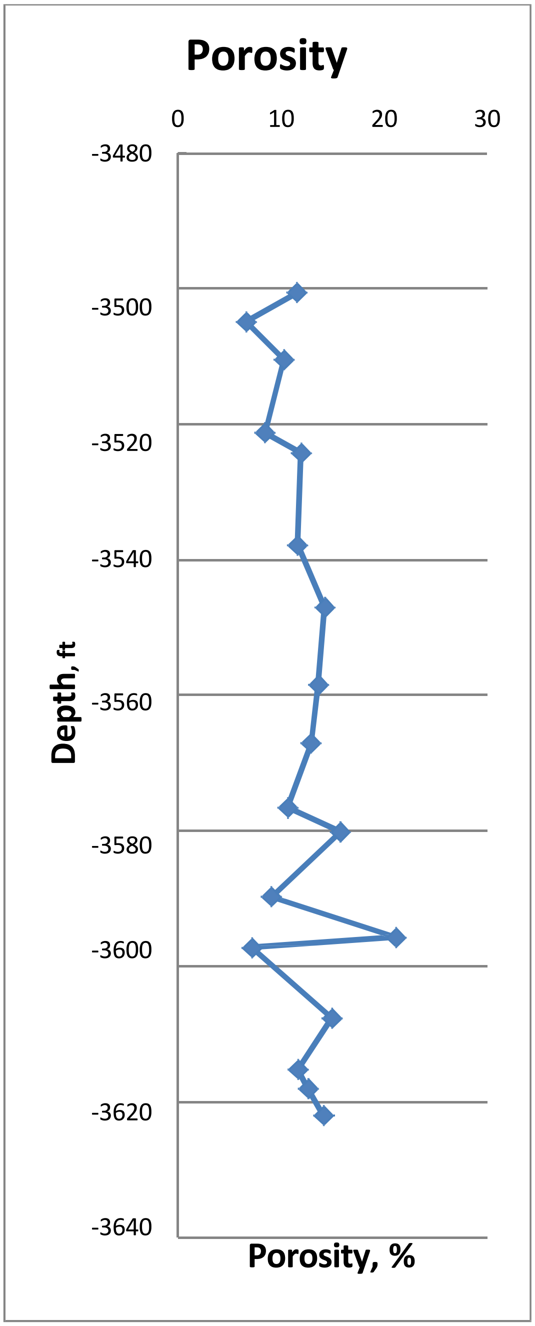


FIGURE 5.88. LAMOTTE SANDSTONE PERMEABILITY

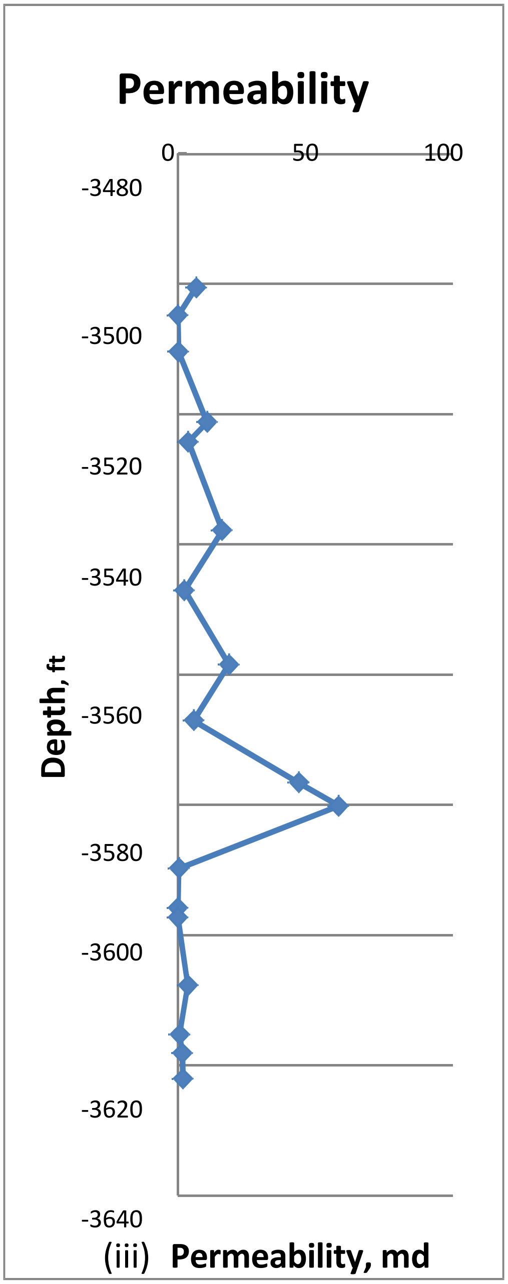
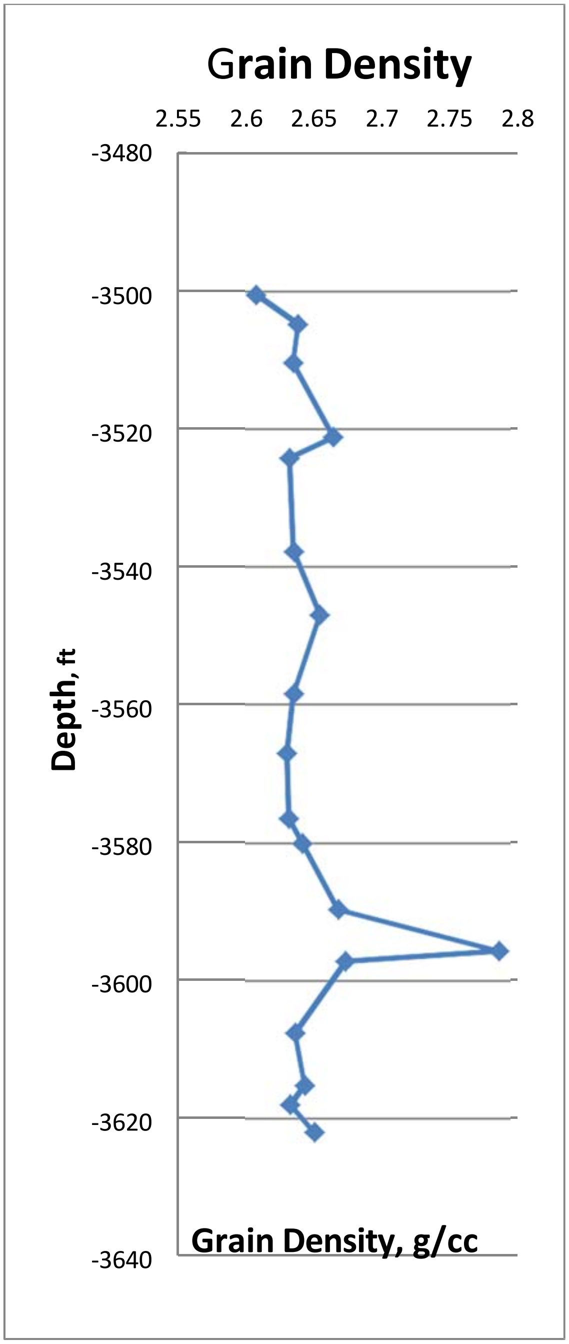


FIGURE 5.89. LAMOTTE SANDSTONE GRAIN DENSITY



CAPILLARY PRESSURES

Figures 5.90 through 5.97 provide the results of mercury injection of samples taken from SPP borehole. The SHg vs. Pc-Hg curves are obtained by collecting the mercury injection capillary pressure (MICP) data. From the equations given in Task 4.a. of the methodology section, the SW vs. Pc-co2 curves can be derived. The threshold pressure and the irreducible water saturation can be determined from these figures. All results are summarized in Table 5.32.

FIGURE 5.90. MERCURY CAPILLARY PRESSURE OF DERBY-DOERUN FROM THE SPP SITE (SAMPLE #3V)

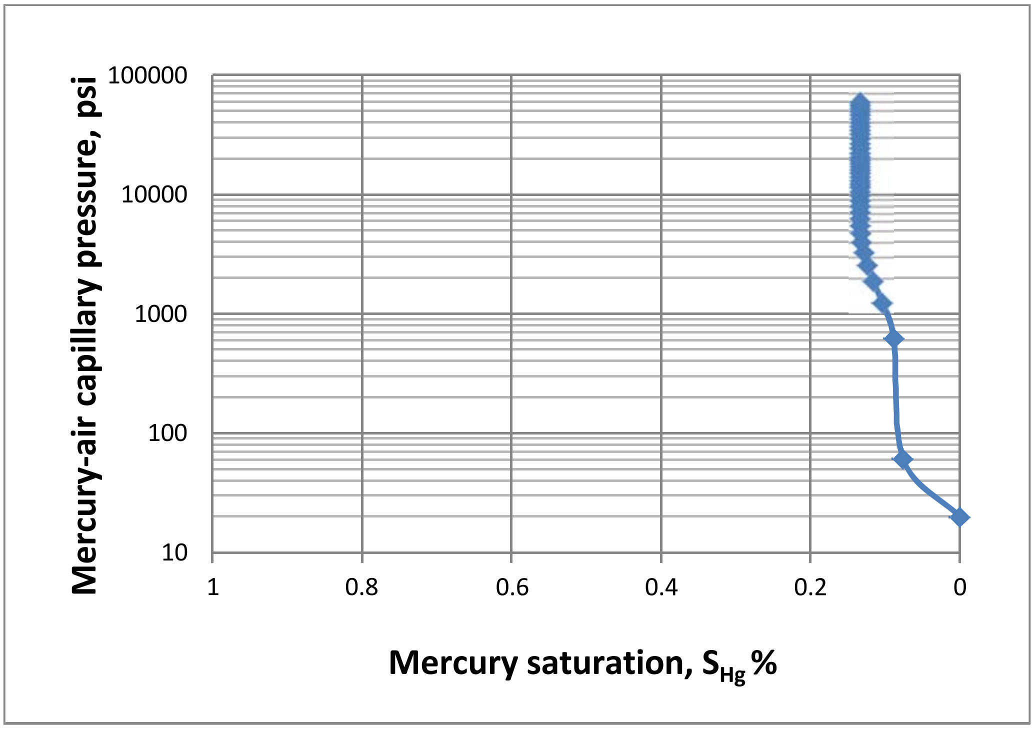


FIGURE 5.91. CO_2 CAPILLARY PRESSURE OF DERBY-DOERUN FROM THE SPP SITE (SAMPLE #3V)

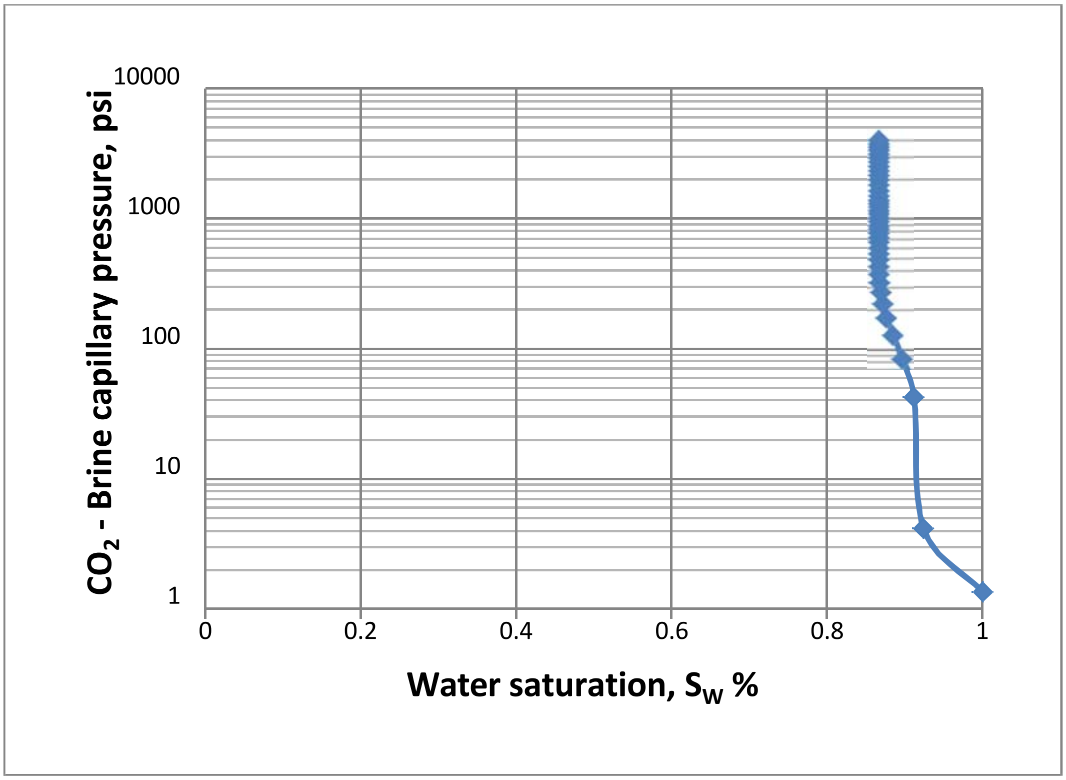


FIGURE 5.92. MERCURY CAPILLARY PRESSURE OF DAVIS FORMATION FROM THE SPP SITE (SAMPLE #16V)

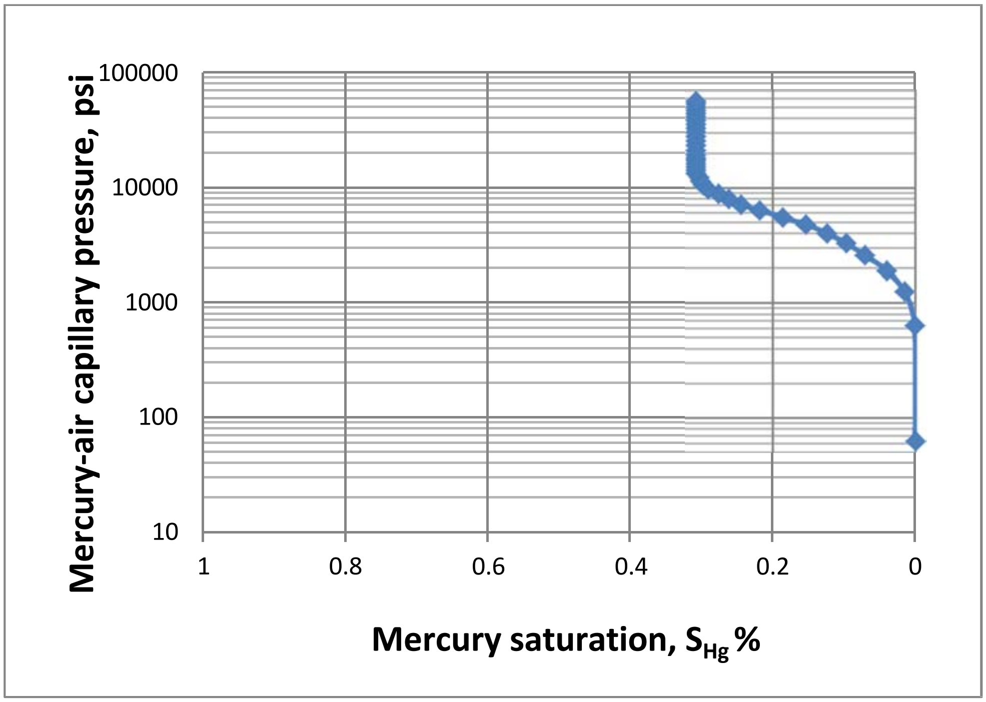


FIGURE 5.93. CO2 CAPILLARY PRESSURE OF DAVIS FORMATION FROM THE SPP SITE (SAMPLE #16V)

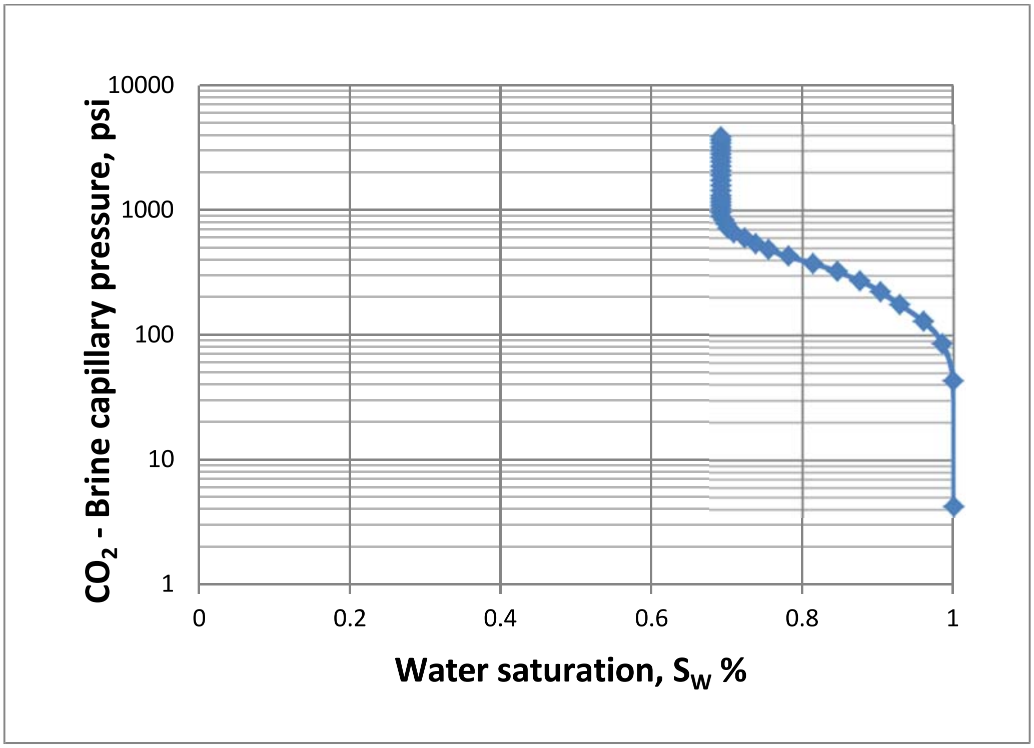


FIGURE 5.94. MERCURY CAPILLARY PRESSURE OF BONNETERRE/LAMOTTE TRANSITION FORMATION FROM THE SPP SITE (SAMPLE #28V)

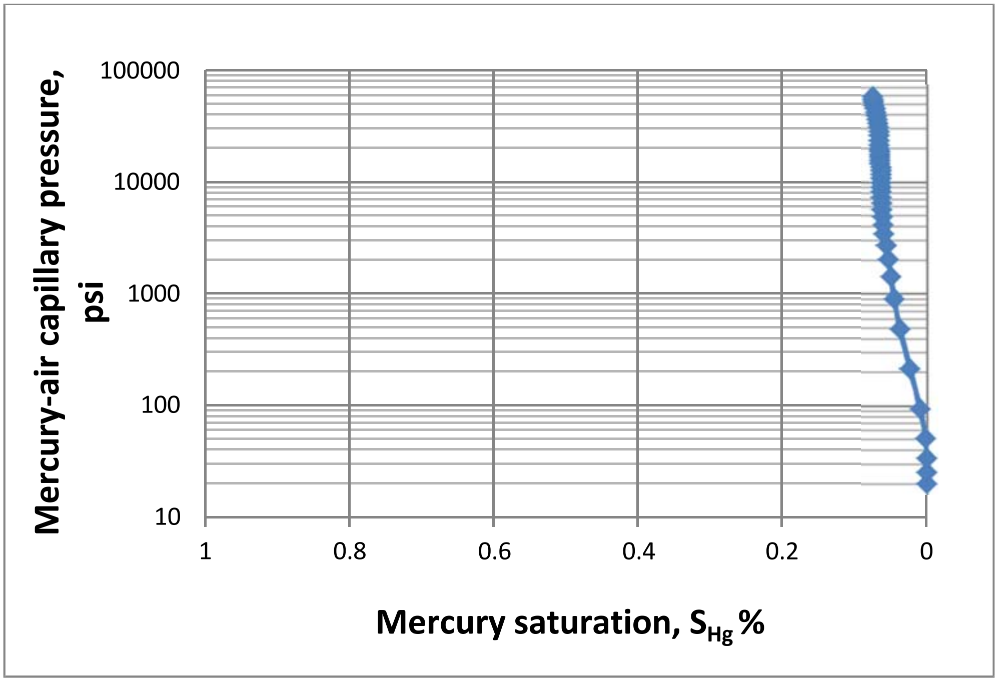


FIGURE 5.95. CO_2 CAPILLARY PRESSURE OF BONNETERRE/LAMOTTE TRANSITION FORMATION ROCK FROM THE SPP SITE (SAMPLE #28V)

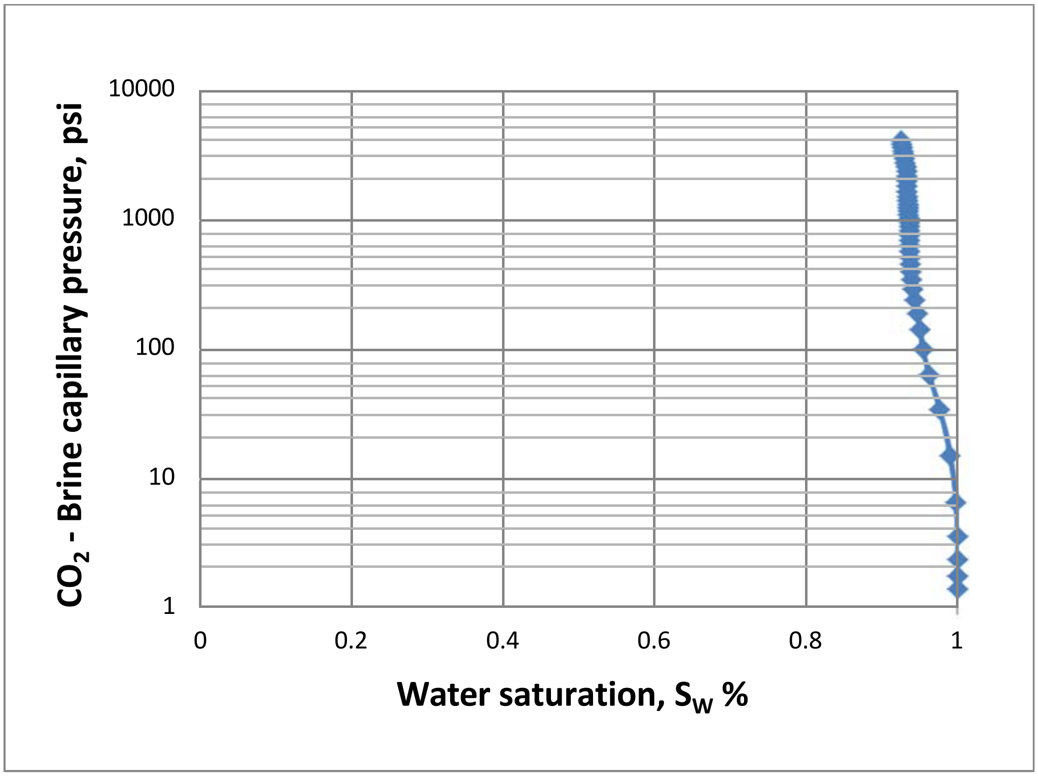


FIGURE 5.96. MERCURY CAPILLARY PRESSURE OF LAMOTTE SANDSTONE FROM THE SPP SITE (SAMPLE #35B)

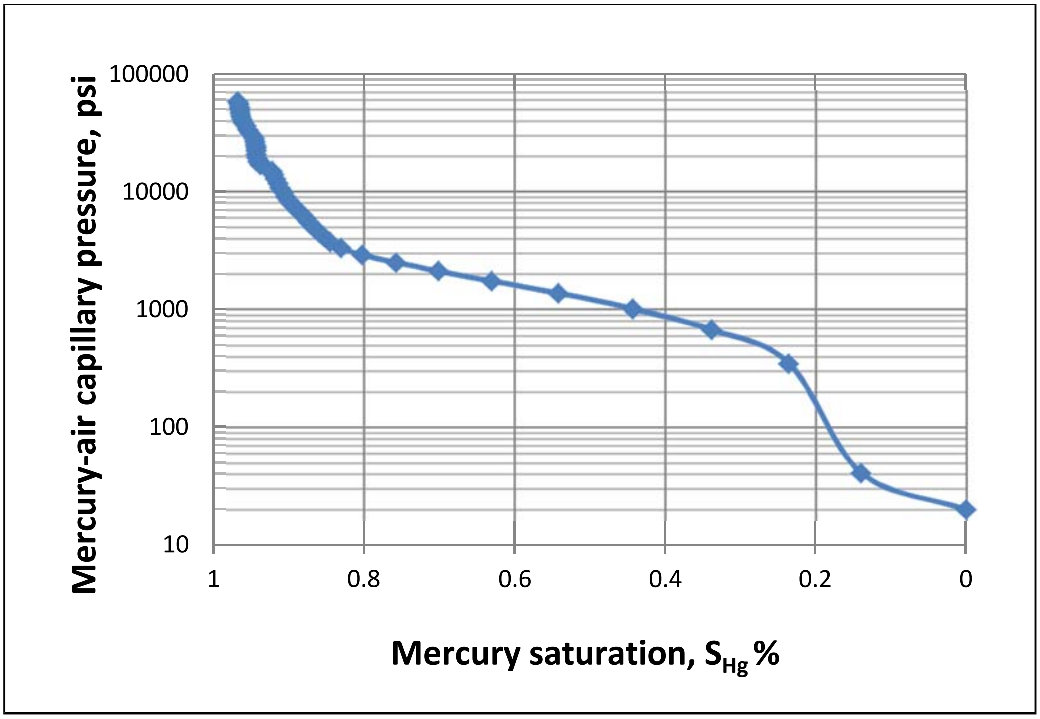


FIGURE 5.97. CO_2 CAPILLARY PRESSURE OF LAMOTTE SANDSTONE FROM THE SPP SITE (SAMPLE #35B)

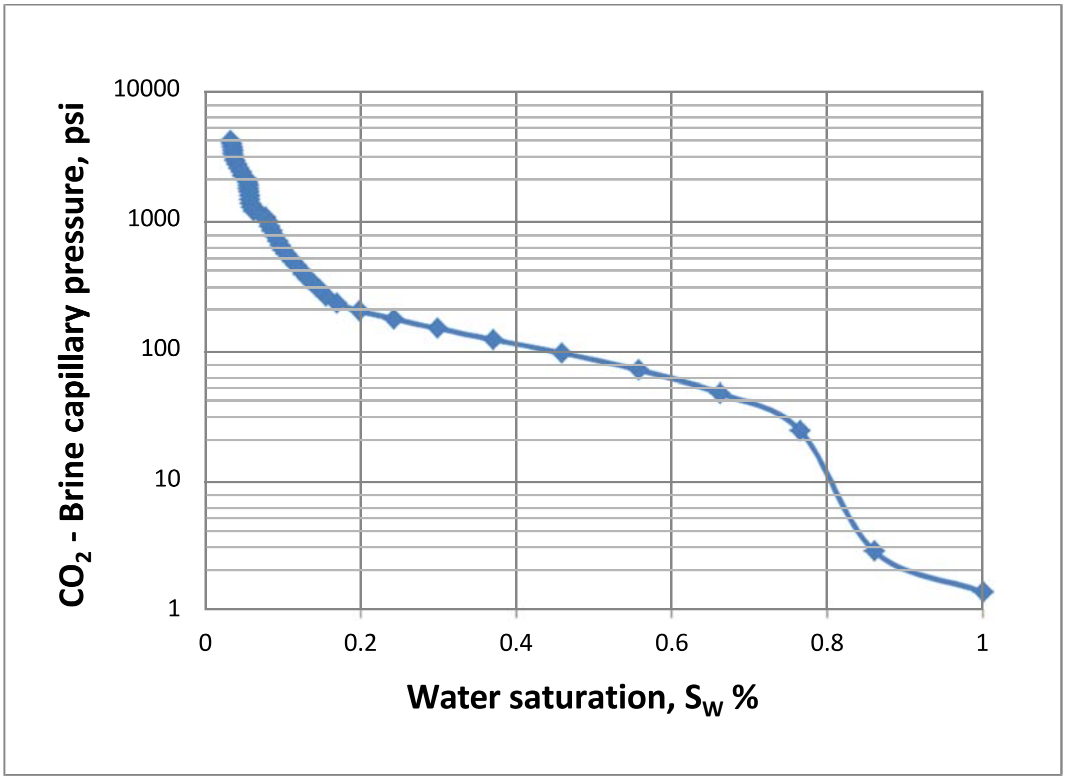


TABLE 5.32. PRIMARY AND DERIVED DATA FROM THE SPP SITE

Formation	Depth of sample	Pressure at sample depth	Temperature at sample depth	Threshold Pressure Entry (air-Hg system)	Threshold Entry Pressure (brine-CO_2 system)	Irreducible Water Saturation
	ft	psi	°F	psi	psi	
Derby-Doerun	2929.8	1333.11	118.596	20	1.361	0.867
Davis	3300.7	1500.015	126.014	632.746	42.02	0.692
Bonneterre /Lamotte Transition	3460	1571.7	129.2	51.173	3.479	0.926
Lamotte	3504.8	1591.86	130.096	20	1.361	0.033

CO_2 entry pressure for the Davis Formation at the SPP site (42 psi) was not high compared to values cited in the literature for caprock, but it was higher than the entry pressure see in Davis Formation samples in the THEC borehole. The Davis Formation appears to be a better caprock seal at the SPP site because the permeability of the shale is low and the threshold entry pressure is higher. However, only a limited number of samples were examined in the study and it is recommended that a statistically relevant number of samples be evaluated in the future.

Task 3.d. Determine the Injection Rate Profile for the Target Formation Geomechanical Testing of the Derby-Doerun, Davis, and Bonneterre Formations, and Lamotte Sandstone

Fifteen core samples from the SPP borehole were sent to Britt Rock Mechanics Laboratory for analysis. Six samples were not sufficient for analysis, either being too short or experiencing rock failure after cutting. Nine tri-axial compression tests were conducted with one test on core from the Derby-Doerun Formation, one test on the Davis Formation, two tests from the Bonneterre/Lamotte transition, and six tests conducted on the Lamotte Sandstone. These geomechanical tests were conducted as described in Task 3.d. of the methodology section.

Table 5.33 presents the results from the tri-axial compression tests for the SPP site. As shown in this table is the Poisson’s Ratio for the tests from each of the core sample tested. The average Poisson’s Ratio for Derby Doe Run top, Davis, Bonneterre/Lamotte Transition, and Lamotte Sandstone at SPP site was 0.38, 0.43, 0.20, and 0.17, respectively.

The Results of the tests indicate the Young’s modulus in the Derby Doe Run top Formation, Davis Formation at SPP site was 10.38 x 10^6 psi, 12.32 x 10^6 psi, respectively. The average Young’s modulus for the Bonneterre/Lamotte Transition tests at SPP site was 3.60 x 10^6 psi. Similarly, the average Young’s modulus for the Lamotte Sandstone at SPP site was 8.52 x 10^6 psi.

TABLE 5.33. TRI-AXIAL COMPRESSION TEST RESULTS FOR CORE SAMPLES FROM THE SPP SITE

Sioux Site							
Date/ID	**Depth (ft)**	**Formation Name**	**Sample ID**	**Bulk Modulus 1E+06**	**Young's Modulus 1E+06**	**Poisson's Ratio**	**Confining Pressure (kip/in^2)**
13100801	2930	Derby-Doerun top	3H	0.81	10.38	0.38	2.30
13100701	3301	Davis	16H	0.55	12.32	0.43	2.30
13071601	3460	Bonneterre/Lamotte Transition	28H	0.98	4.20	0.15	2.30
13071901	3476	Bonneterre/Lamotte Transition	31H	0.49	2.99	0.25	2.31
13072301	3501	Lamotte	34T	1.73	7.14	0.14	2.30
13072601	3505	Lamotte	35B	1.43	6.97	0.19	2.30
13072501	3510	Lamotte	36T	1.41	5.43	0.11	2.30
13072201	3547	Lamotte	44B	1.05	6.61	0.26	2.30
13100901	3577	Lamotte	49T	3.07	18.99	0.26	2.31
13071801	3597	Lamotte	56B	1.78	5.95	0.05	2.30
Sample Orientation : Native State Sample Storage: Horz							

Table 5.34 summarizes the results from the tri-axial compression tests by formation for both the THEC and SPP sites. Also shown in this table is the average Poisson's ratio for the tests from each of the formations tested. As shown, the average Poisson's ratio for the Derby-Doerun, Davis, Bonneterre, Bonneterre/Lamotte Transition, and Lamotte Sandstone is 0.384, 0.328, 0.253, 0.201, and 0.163, respectively.

TABLE 5.34. SUMMARY OF TRIAXIAL COMPRESSION TESTS BY FORMATION FOR THEC AND SPP SITES

Formation	**No. of Samples**	**Depth Interval, ft**	**Rock Type**	**Confining Pressure, psi**	**E, Mpsi**	**(frac)**
Derby-Doerun	1	2929.80	CaCO3	2,300	10.38	0.384
Davis	2	2024.0 & 3300.7	Shale/CaCO3	2,300	8.44	0.328
Bonneterre	3	2120.0 to 2327.0	CaCO3	2,300	5.96	0.253
B/L Transition	2	3460.0 & 3476.0	CaCO3	2,300	3.59	0.201
Lamotte	10	2362.0 to 3597.2	CaCO3	2,300	7.09	0.163

Task 3.e. Retrieve and Analyze Fluid Samples from the Target Formation

FORMATION WATER SAMPLING FROM THE SIOUX POWER PLANT SITE

Water samples from the Lamotte Sandstone at the SPP site were obtained on February 17, 2013. In situ measurements were made for conductivity, pH, Eh, dissolved oxygen and temperature. Ex situ measurements of the alkalinity, calcium hardness, and total hardness were conducted as soon as possible after removal from the borehole, with the alkalinity measurements being given top priority to minimize the effect from CO_2 loss. Additional aliquots of the water samples were collected and taken back to the Missouri S&T lab for further testing including analysis of cations by ICP-OES, TSS, and TDS.

In a pattern similar to the water samples from the THEC site, turbidity values were very low at 2.79+/- 0.55 NTU (nephelometric turbidity unit), but began precipitating reddish orange ferric-iron oxide and/or hydroxide particles after approximately 30 minutes (Figure5. 71). The addition of approximately 2% by volume of high-purity HNO_3rapidly dissolved the particles and restored the fluid to a visibly clear state within one hour. The solution pH averaged 6.57 +/- 0.02, Eh +13 +/- 2 millivolts, and the water temperature was 20.5 +/- 0.0^{o}C (Table5.35a). The water conductivity was 63.9 +/- 0.4 milliSiemens/cm, but displayed slight fluctuations while being measured, indicating non-equilibrium water conditions, possibly due to loss of CO_2 from the system as the measurements were being made. Alkalinity values, however, were a near constant 169 mg/L. All of the above measurements were averaged from three replicate readings taken over a 55 minute period. Dissolved oxygen readings were made, but the value was abnormally high, approximately 13.8mg/L and assumed to result from a faulty probe. Since the salinity, Eh, and iron oxide precipitation behavior at the SPP site was similar to that of the water samples from the THEC site, it is assumed that the dissolved oxygen content at the SPP site was likely also similar (approximately 0.5 mg/kg).

Filtered water samples for cation (UF-unfiltered; -5.0 µm, -0.45µm, and -0.02 µm) and anion (-0.45µm) analysis also were collected, with all filtering and sample splits performed onsite immediately after the primary water sample was collected from the borehole. The difference between cation concentrations in unfiltered and various filtered size fractions could not be detected with any statistical significance. The waters are NaCl dominated, but also contain abundant Ca, Mg, K, and SO_4^{2-} (Table 5.35b). The concentration of Na in the SPP site brine was about 14% lower than that for the THEC site, while Cl contents were similar. The SPP brines also were enriched in Ca (+10%), while being depleted in Mg (-40%) and SO_4^{2-} (-50%) relative to that for the THEC site. Examination of the TDS evaporation residue solids revealed the presence of gypsum, anhydrite, and halite ($CaSO_4{\cdot}2H_2O$, $CaSO_4$, and NaCl, respectively; Figure 5.98).

BRINE DENSITY

A density comparison was made between the water samples from the SPP site and a standard of deionized water (Table 5.24). These water samples averaged a density of 1.0316 g/cm^3 for two measurements, slightly less dense that for the THEC site average density of 1.0360 g/cm^3.

The same three analytical procedures were used to evaluate the TDS or salinity content of the SPP site as were used for the THEC site:

1. <u>Total Dissolved Solids (TDS) by Evaporation to Dryness</u>*:* Measured by evaporating a known quantity of water to dryness and then weighing the beaker to determine the accumulated residue

(TDS fraction). Samples were first dried at 95°C for several days. When there was no more visible fluid, heat was then turned up to 180°C and the vessels were periodically weighed over several days until a stable weight reading was obtained. The TDS values for the 150 ml sample splits averaged 42,055 +/- 213 mg/kg for three separate samples.

Crystals that formed during the evaporation process were similar to those seen with the THEC samples (compare Figures 5.71 and 5.98). These included gypsum, anhydrite, halite, and a few other minor phases that were not identified.

2. Tabulating cation and anion analytical determinations: A second method is to tabulate the ppm (mg/kg) content of all species detected in solution (Table 5.35). This tabulation would include the major and minor cations Na, Ca, Mg, K, Si, Fe, and Mn (ICP-OES), alkalinity ions (predominantly HCO_3^-), and anion analysis for SO_4^{2-} and Cl (Ion Chromatography). The combined results indicate the following:

    a) Cation analysis (0.45 micron filtered) = 15,913 mg/kg
    b) HCO_3^- (alkalinity) = 169 mg/kg
    c) Anion analysis (0.45 micron filtered) = 26,380 mg/kg
    Measured – Calculated Total = 42,462 mg/kg

Conductivity Measurements: The third method uses the conductivity value and a multiplication factor of 0.667 to convert conductivity reading to TDS value. Multiplying the conductivity of the water sample from the Lamotte Sandstone from the SPP site – 63,900 ± 400 microSiemens/cm (Table 5.35a; 63.9 milliSiemens/cm) by the 0.667 multiplication factor gives a calculated salinity value of 42,621 ± 267 mg/kg.

FIGURE 5.98. PHOTOGRAPH AND MICROGRAPHS OF WATER SAMPLES FROM THE SPP SITE A) UPPER-LEFT SHOWING CRYSTALS THAT HAD ACCUMULATED IN THE BEAKER FOLLOWING EVAPORATION OF FORMATION WATER FOR THE TOTAL DISSOLVED SOLIDS (TDS) TEST, B) UPPER-RIGHT SHOWING CUBIC HALITE (NACL), RED IRON OXIDES, AND ACICULAR CA-SULFATE CRYSTALS, C) LOWER-LEFT HALITE CRYSTALS DISPLAYING CUBIC "HOPPER- CAR" MORPHOLOGY, AND D) ASSORTMENT OF CRYSTALS ON BEAKER BOTTOM INCLUDING LARGER WHITE PSEUDO-HEXAGONAL ANHYDRITE (CASO4), CLEAR NEEDLES OF GYPSUM (CASO4.2H2O) AND IRON OXIDES.

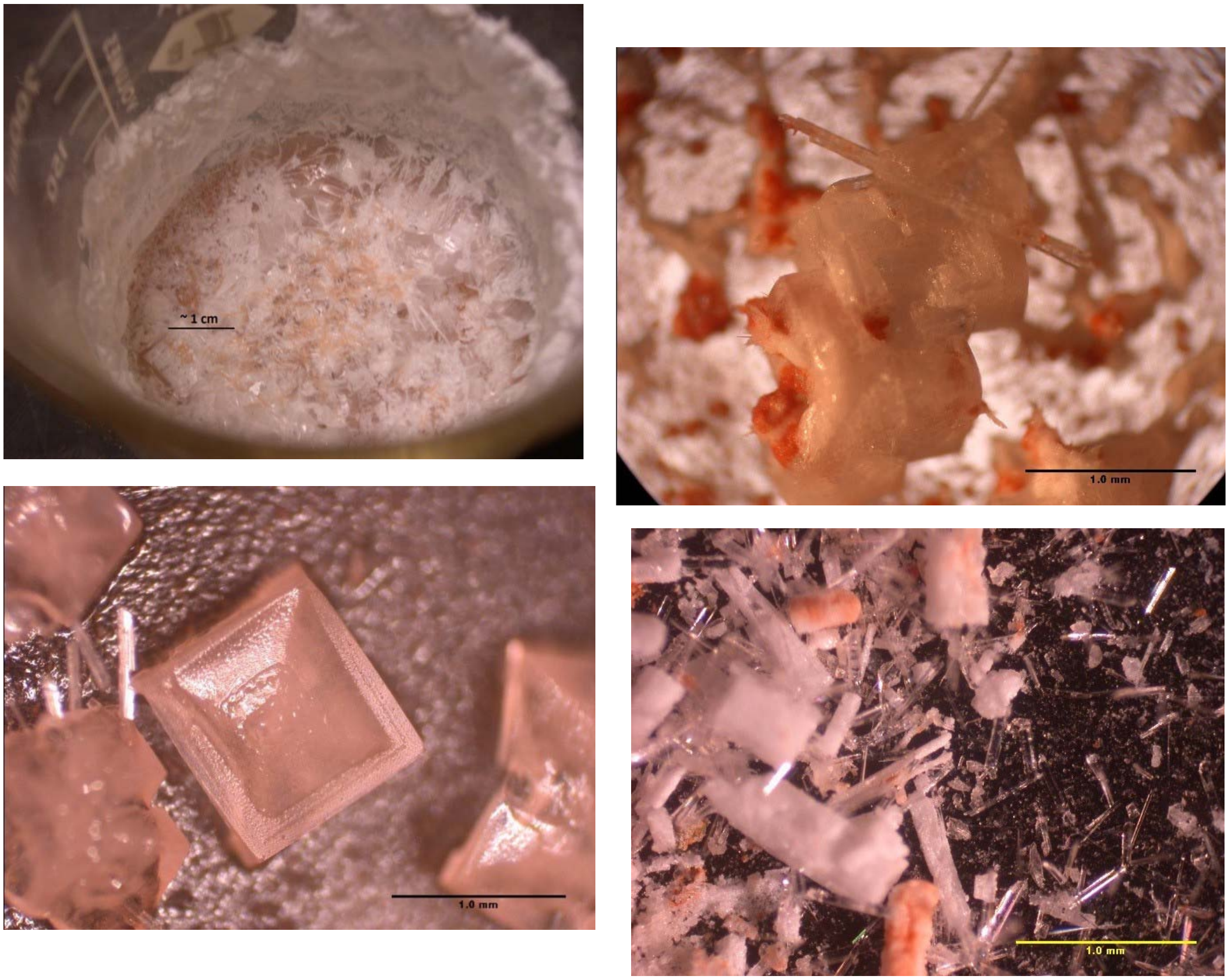
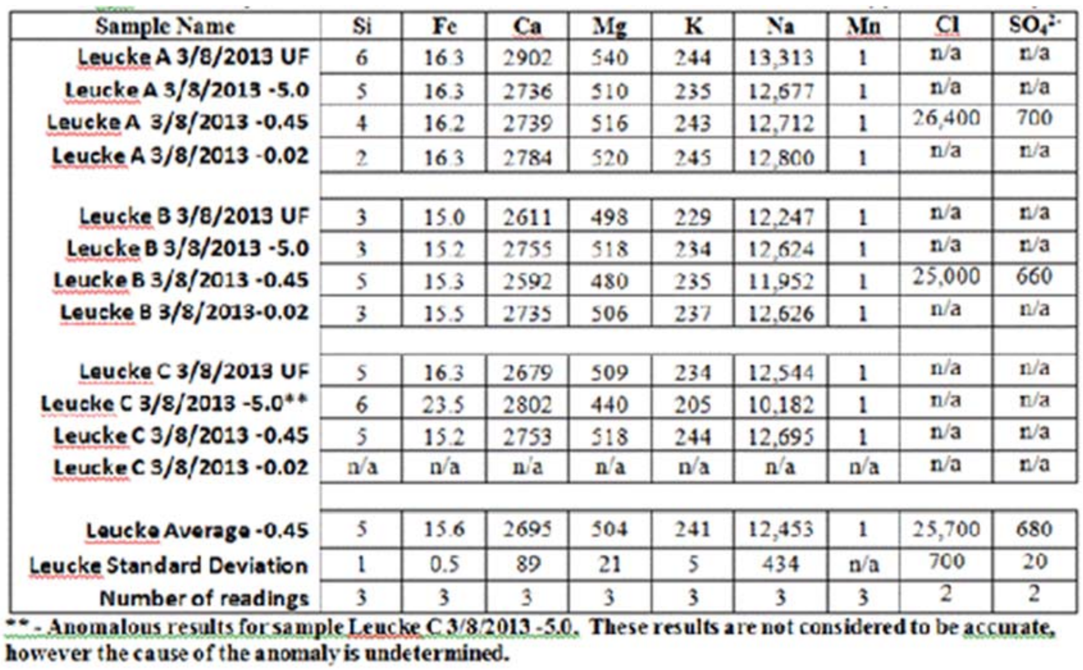


TABLE 5.35A. WATER QUALITY DATA FROM SAMPLES COLLECTED FROM THE LAMOTTE SANDSTONE AT THE SPP SITE N/A = NOT ANALYZED. NTU = NEPHELOMETRIC TURBIDITY UNIT.

Sample Number	Time	pH	Eh mV	Water Temp °C	Conduct. milliS/cm	Alkalinity mg/L	Ca Hardness mg/L	Mg Hardness mg/L.	Turbidity NTU
Luecke A UF	10:27am	6.78	+11	20.5	63.2-63.5	168	7000	1900	2.91
Luecke B UF	10:50 am	6.74	+15	20.4	63.4 – 64.1	169	6900	2000	1.58
Luecke C UF	11:22 am	6.77	+13	20.5	64.2	169	7000	1900	1.88
Sioux Average		6.76	+13	20.5	63.9	169	6967	1933	2.12
Sioux **Standard Deviation**		0.02	2	0.0	0.4	0	47	47	0.57
# of readings		3	3	3	3	3	3	3	3

TABLE 5.35B. MAJOR ELEMENT CATION ANALYSIS OF THE WATER SAMPLES COLLECTED FROM THE LAMOTTE SANDSTONE AT THE SPP SITE. ALL VALUES ARE IN MG/KG (PPM). UF=UNFILTERED; -5.0= MICROMETER FILTERED; -0.45=0.45 MICROFILTERED; -0.02=0.02 MIRCOMETER FILTERED; N/A = NOT ANALYZED. ALUMINUM WAS MEASURED AND DETERMINED TO BE <0.1 PPM FOR ALL SAMPLES. LUECKE = SIOUX



Sample Name	Si	Fe	Ca	Mg	K	Na	Mn	Cl	SO_4^{2-}
Leucke A 3/8/2013 UF	6	16.3	2902	540	244	13,313	1	n/a	n/a
Leucke A 3/8/2013 -5.0	5	16.3	2736	510	235	12,677	1	n/a	n/a
Leucke A 3/8/2013 -0.45	4	16.2	2739	516	243	12,712	1	26,400	700
Leucke A 3/8/2013 -0.02	2	16.3	2784	520	245	12,800	1	n/a	n/a
Leucke B 3/8/2013 UF	3	15.0	2611	498	229	12,247	1	n/a	n/a
Leucke B 3/8/2013 -5.0	3	15.2	2755	518	234	12,624	1	n/a	n/a
Leucke B 3/8/2013 -0.45	5	15.3	2592	480	235	11,952	1	25,000	660
Leucke B 3/8/2013-0.02	3	15.5	2735	506	237	12,626	1	n/a	n/a
Leucke C 3/8/2013 UF	5	16.3	2679	509	234	12,544	1	n/a	n/a
Leucke C 3/8/2013 -5.0**	6	23.5	2802	440	205	10,182	1	n/a	n/a
Leucke C 3/8/2013 -0.45	5	15.2	2753	518	244	12,695	1	n/a	n/a
Leucke C 3/8/2013 -0.02	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Leucke Average -0.45	5	15.6	2695	504	241	12,453	1	25,700	680
Leucke Standard Deviation	1	0.5	89	21	5	434	n/a	700	20
Number of readings	3	3	3	3	3	3	3	2	2

**** - Anomalous results for sample Leucke C 3/8/2013 -5.0. These results are not considered to be accurate, however the cause of the anomaly is undetermined.**

HIGH PRESSURE AND TEMPERATURE CO_2 + H_2O TESTS FOR CORE SAMPLES FROM THE SPP SITE

Six samples from the SPP site were reacted in the 90°C high pressure CO_2 + H_2O tests (Table 5.36). The experiments included duplicate tests with the carbonate-rich shale samples from the Davis Formation at 3,177.8 ft. These were reacted for 36 days. A non-carbonate shale sample from the Davis Formation at 3,269.9 ft was reacted for 20 days. Three different Lamotte Sandstone samples were also tested; a sample from 3,500.5 ft reacted for 36 days, a sample from 3,529.2 ft reacted for 28 days, and a third sample from 3,589.7 ft reacted for 36 days.

The pH value for the blank test was 3.9 and represents the acidification process where $H_2CO_{3(aq)}$ is produced by the reaction $CO_2 + H_2O \rightarrow H_2CO_{3(aq)}$ (Table 5.37). This result was similar to the ~3.5 to

4.0 values for the blank tests that were run with the previously discussed THEC samples. The pH values of the leachate solutions following the reaction of the SPP site samples had increased to values between 5.90 and 6.49 for all of the Davis Formation tests. The increase reflects the neutralization process where the rock samples are altered and/or dissolved and consume the protons from the $H_2CO_{3(aq)}$ rich solution. There was a clear difference between the pH changes resulting from tests between the Davis Formation and the Lamotte Sandstone samples. The Lamotte Sandstone samples produced final pH values ranging from 3.2 to 4.8, reflecting the absence of significant amounts of acid-neutralizing mineral components. The decrease in the pH to approximately 3.2 for the L53 samples, relative to the blank test results, may reflect the generation of sulfuric acid following the dissolution of pyrite. Pyrite was noted in the optical microscopy examination of un-reacted samples.

The core samples reacted in the high pressure $CO_2 + H_2O$ tests may lose mass due to corrosion processes or gain mass through the hydration of solid phases and/or precipitation of alteration phases. Most samples lost < 1% of their starting mass during the testing period (Table 5.37).

Several of the Davis Formation samples had lost between 2.5 and 6% of their mass, possibly resulting from disaggregation of the clay-rich portions of these samples. One of the Lamotte Sandstone samples from the 3500.5 ft depth also lost 3% of its mass, although a duplicate sample disk reacted in the same vessel only lost only 0.15%.

The carbonate-rich shale sample from the Davis Formation (3177.5 ft; duplicate samples of L10; Tables 5.38a and b) released the highest concentrations of Ca and Mg at an average of 2.70E-02 and 1.04E-03 molal, respectively after 36 days of reaction. High release values for these elements were expected given the carbonate-rich nature of the samples (e.g., calcite ($CaCO_3$) and/or dolomite ($Ca,Mg(CO_3)_2$). The slightly elevated Ca/Mg release ratio of 2.6 suggests that either calcite dominates over dolomite during dissolution, or Mg is being precipitated in secondary alteration phases. Both Na and K were released at concentrations of 5.44E-04 and 2.98E-04 molal. It was expected that the concentrations of these two elements would be high given the high concentration of Na and K in the brine solution that was in contact with the samples while they resided in the subsurface (Table 5.35). Thus, even though the samples were rinsed in deionized water during the cutting and cleaning procedures there still was a significant amount of adsorbed Na and K on the samples. The decreased Na/K ratios from the $CO_2 + H_2O$ corrosion tests, relative to the brines, also suggests that some of the dissolved K was released from a mineral phase(s) present in the samples. Illite ($\sim KAl_2(AlSi_3O_{10})(OH)_2$) was the most predominant clay mineral present (Table 5.39) and is thus the most likely source for this released K. Silicon was released at a concentration of 2.30E-04 molal and may be derived from either dissolving illite or quartz (SiO_2).

All other elements (Fe, Mn, Al) were present in low concentrations that were near ICP-OES detection limits, or near background concentrations determined for the blank tests.

The Davis Formation sample from 3,269.9 ft was relatively free of carbonate minerals as it did not produce any notable effervescence of CO_2 when a dilute hydrochloric acid solution was applied to its surface. As discussed previously in the THEC section, these non-carbonated shale horizons represent the potential cap-rock that would prevent leakage of injected CO_2 from the St. Francois Aquifer. The single sample of the Davis Formation tested for 20 days from this depth (L14; Tables 5.38a and b) displayed a Ca release concentration of 9.76E-03 which was only slightly lower than the average value of 2.70E-02 previously noted for the 3177.5' carbonate-rich Davis Formation sample. The Mg concentration at 3.25E-03 molal is indistinguishable from the 3177.5' sample. Release concentrations of Na, K, and Si were enhanced relative to the 3,177.8 ft sample, while Mn, Fe, and Al were present in very low to undetectable concentrations. The 3,269.9 ft sample also induced a pH rise (i.e. neutralizing carbonic acid; Table 5.37). The relatively rapid pH rise for this sample, coupled with the relatively high release rates of rock components, suggests a fair susceptibility to acid attack and corrosion.

Three core samples from the Lamotte Sandstone were reacted in the high pressure and temperature $CO_2 + H_2O$ corrosion tests, including samples from 3,500.5 ft (L34, 36 days), 3,529.2 ft (L40, 28 days), and 3,589.7 ft depths (L53, 36 days). The elemental release for all three samples was similar to one another and thus they can be discussed collectively as a group (Table 5.38a and b). All samples had notably lower release concentrations for Ca and Mg (average 5.75E-04 and 2.73E-04 molal, respectively) relative to the Davis Formation samples. Averaged Na and K concentrations (8.03E-04 and 3.61E-04 molal) were similar to those from the Davis Formation shales, although Na release from sample L40 was below the background sample determined for the blank vessel test. Released concentrations of Fe, Mn, and Al were present in low but detectable concentrations for the 3,589.7ft Lamotte Sandstone, while concentrations of these elements in the remaining two sandstones located higher in the stratigraphic section were below ICP-OES detection limits (<0.1 ppm).

TABLE 5.36. BRIEF LITHOLOGICAL DESCRIPTION FOR CORE SAMPLES SELECTED FROM SPP SITE FOR CO_2 TESTING.

Core Sample ID	Depth (ft)	Formation	Description
L10A-D	3177.5	Davis	Carbonate shale
L14 A-D	3269.9	Davis	Non-carbonate shale
L34 A-D	3500.5	Lamotte	Quartz arenite
L40 A-D	3529.2	Lamotte	Quartz arenite
L53 A-D	3589.7	Lamotte	Quartz arenite with small pyrite inclusions

TABLE 5.37. REACTED CORE SAMPLES FROM THE SPP SITE WITH MEASUREMENTS TAKEN AFTER HIGH- PRESSURE CORROSION TESTING WAS COMPLETED. ALL SAMPLES WITH WEIGHT LOSS >5% WERE SHALE SAMPLES THAT HAD PARTIALLY DISINTEGRATED INTO FRAGMENTS DURING THE EXPERIMENTS. THE PH AND EH READINGS WERE MADE FROM THE SOLUTIONS CONTACTING THE SAMPLES AFTER THE EXPERIMENTS WERE COMPLETED.

Sample ID	Formation	Depth (ft)	Test time (d)	Rock Wt. (g)	Final Wt. (g)	Change in wt. (g)	% loss	% gain	pH	Eh (mV)
L10 A	Davis	3177.5	36	1.4908	1.4806	-0.0102	0.68%		5.90	+61
L10 B			36	0.8179	0.8088	-0.0091	1.11%		5.90	+61
L10 C			36	0.7268	0.7227	-0.0041	0.56%		5.99	+56
L10 D			36	1.3206	1.2407	-0.0799	6.05%		5.99	+56
L14 C		3269.9	20	0.8125	0.7921	-0.0204	2.51%		6.49	+6.7
L14 D			20	0.3413	0.3267	-0.0146	4.28%		6.49	+6.7
L34 C	Lamotte	3500.5	36	1.7295	1.7269	-0.0026	0.15%		4.77	+126
L34 D			36	0.8010	0.7769	-0.0241	3.01%		4.77	+126
L40 C		3529.2	28	0.7645	0.7633	-0.0012	0.16%		4.67	+136
L40 D			28	1.2478	1.2464	-0.0014	0.11%		4.67	+136
L53 C		3589.7	36	1.5871	1.5809	-0.0062	0.39%		3.21	+218
L53 D			36	0.9284	0.9245	-0.0039	0.42%		3.21	+218
Blank		N/A	36						3.90	+174

TABLE 5.38A. MAJOR ELEMENT SOLUTION DATA FROM THE SIOUX SITE CO_2 + H_2O TESTS (VALUES IN PPM).

Sample # and test length in days	Depth (ft)	Ca	Mg	K	Na	Mn	Fe	Si	Al
L10 A,B; 36d	3177.5	1109	20.2	13.1	11.5	0.2	0.3	5.3	<0.1
L10 C,D; 36d	3177.5	1053	30.3	9.4	13.5	0.1	0.1	7.6	<0.1
L14 C,D; 20d	3269.9	391	79.1	96.0	78.4	0.1	<0.1	15.1	<0.1
L34 C,D; 36d	3500.5	28.5	5.4	9.8	22.8	<0.1	<0.1	7.8	<0.1
L40 C,D; 28d	3529.2	17.2	9.2	13.8	4.8	<0.1	<0.1	7.0	<0.1
L53 C,D; 36d	3589.7	23.4	5.3	18.7	27.8	0.2	1.6	15.4	0.1
Blank; 36d	N/A	1.5	<0.1	2.6	7.7	<0.1	<0.1	0.3	<0.1

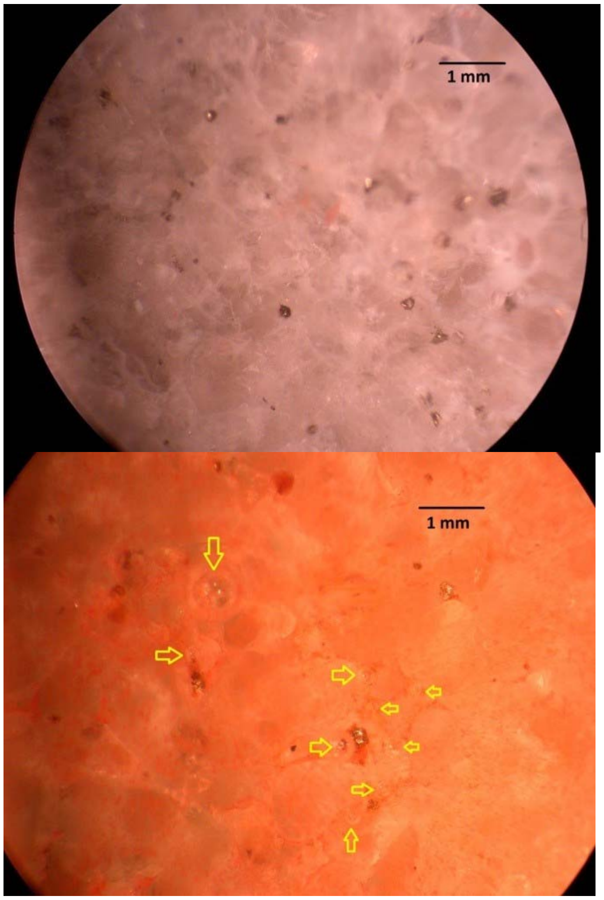
TABLE 5.38B. MAJOR ELEMENT SOLUTION DATA FROM THE SPP SITE CO_2 + H_2O TESTS (VALUES IN MOLAL UNITS). N/A = NOT APPLICABLE BECAUSE ANALYSES WERE BELOW DETECTION LIMITS.

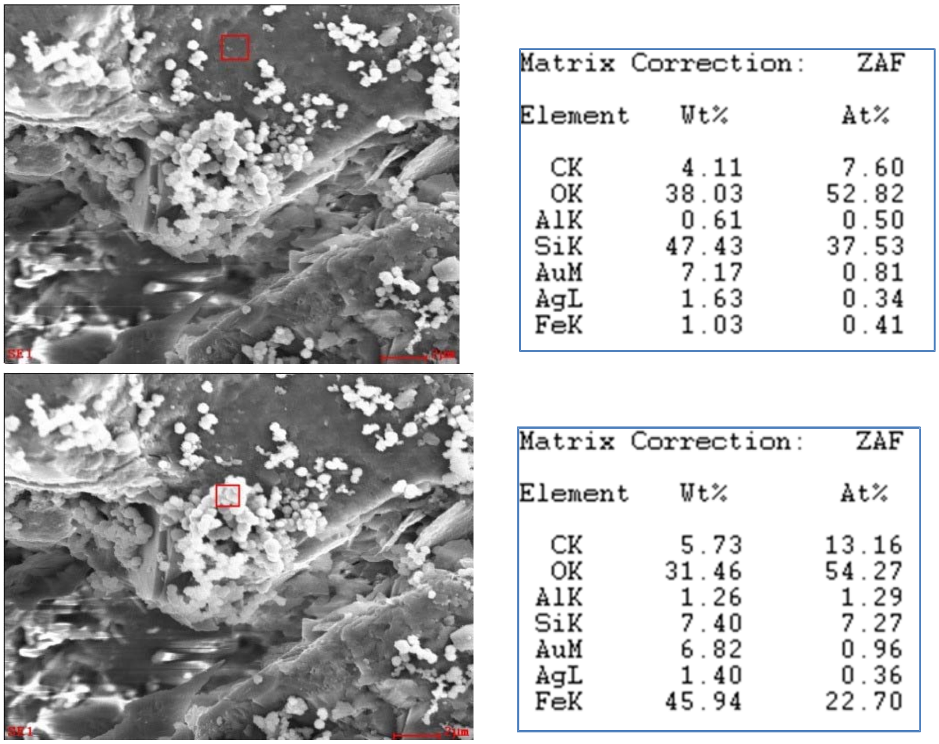
Sample #	Ca	Mg	K	Na	Mn	Fe	Si	Al
L10 A,B	2.77E-02	8.31E-04	3.35E-04	5.00E-04	3.9E-06	5.4E-06	1.89E-04	N/A
L10 C,D	2.63E-02	1.25E-03	2.40E-04	5.87E-04	1.8E-06	1.8E-06	2.71E-04	N/A
L14 C,D	9.76E-03	3.25E-03	2.46E-03	3.41E-03	1.8E-06	N/A	5.38E-04	N/A
L34 C,D	7.11E-04	2.22E-04	2.51E-04	9.92E-04	N/A	N/A	2.78E-04	N/A
L40 C,D	4.29E-04	3.78E-04	3.53E-04	2.09E-04	N/A	N/A	2.49E-04	N/A
L53 C,D	5.84E-04	2.18E-04	4.78E-04	1.21E-03	3.6E-06	2.9E-05	5.48E-04	5.11E-06
Blank	3.74E-05	N/A	6.65E-05	3.35E-04	N/A	N/A	1.1E-05	N/A

SEM-EDS analysis of the quartz sandstone Lamotte Sandstone sample (depth 3,589.7 ft) from the SPP site that was reacted for 36 days displayed the formation of carbonate microspheres that were deposited as alteration grains. These microspheres did not appear on the non-corroded sample. A dilute 5% hydrochloric acid solution was added to both the pre- and post-corrosion samples. The non-corroded sample did not show any effervescence while being viewed under an optical microscope. By contrast, the sample reacted in the CO_2 + H_2O environment effervesced lightly following the application of the acid, indicating the presence of carbonate mineralization (Figure 5.99). An EDS analysis of the microspheres and background was conducted, however, the small size of the grains made it difficult to obtain a quantitative analysis as the SEM electron beam likely had interacted with and produced X-rays from a volume of sample that is much larger than the individual microspheres. Rhombohedral-shaped grains also were detected in another region of the sample and these grains revealed a SEM-EDS composition indicating the presence of Ca, Mg, C, and O, with an atomic ratio of approximately 1:1:2:6 (Figure 5.100). The morphology and composition of the phase is consistent with the presence of dolomite, while the un-pitted nature of the grain surfaces suggests that they formed during the corrosion tests as such fine-grained crystals would likely dissolve under the low pH conditions that would exist following the initiation of the tests.

The SEM-EDS results in all three Lamotte Sandstone samples consistently showed the presence of iron, oxygen, and carbon enrichment over the background concentration. This leads to the belief that they may potentially have synthesized an iron carbonate (siderite; $FeCO_3$) during the reactions. The carbon to oxygen ratio of the iron-rich phase was approximately 1:4, and thus had a slightly lower than the 1:3 ratio expected for siderite. Siderite, if truly present, would be of great importance to CO_2 sequestration as this would allow carbon to be sequestered as a stable mineral form by complexing with dissolved iron and/or iron oxide minerals often present in the subsurface provided that the iron can be reduced to the Fe^{2+} form.

FIGURE 5.99. MICROGRAPHS AND EDS ANALYSIS OF CORE SAMPLES FROM THE LAMOTTE SANDSTONE AT THE SPP SITE AT A DEPTH OF 3,589.7 FT. NOTE INDIVIDUAL DARK REFLECTIVE GRAINS OF PYRITE AS AN ACCESSORY MINERAL. B) REACTED SAMPLE AFTER APPLICATION OF 5% HCL SOLUTION WITH ARROWS INDICATING AREAS WHERE BUBBLES ARE COALESCING ON THE SURFACE. C) MIDDLE LEFT SHOWS AREA OF BACKGROUND SUBSTRATE WITH EDS SPECTRA (AREA OF BOX) SHOWN IN TABLE TO MIDDLE RIGHT. AU AND AG ARE DUE TO COATING APPLIED TO THE SAMPLE SURFACES TO REDUCE CHARGING DURING ANALYSIS. D) BOTTOM LEFT SHOWS CLUSTER OF MICROSPHERES WITH EDS DATA (AREA OF BOX) SHOWN IN TABLE TO BOTTOM RIGHT. NOTE THE ABUNDANCE OF CARBON IN THE REACTED SAMPLE IS NEARLY DOUBLE THAT OF THE BACKGROUND SUBSTRATE INDICATING LIKELY PRESENCE OF A CARBONATE PHASE.

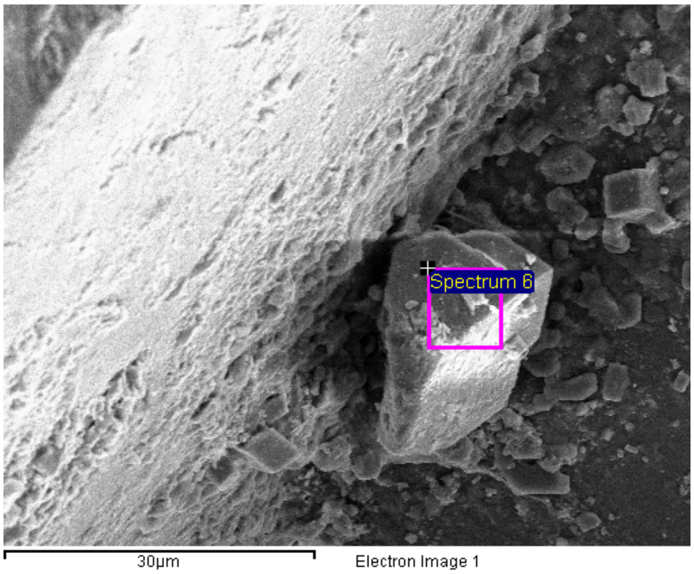




```
Matrix Correction:    ZAF

Element    Wt%         At%

  CK        4.11        7.60
  OK       38.03       52.82
 AlK        0.61        0.50
 SiK       47.43       37.53
 AuM        7.17        0.81
 AgL        1.63        0.34
 FeK        1.03        0.41
```

```
Matrix Correction:    ZAF

Element    Wt%         At%

  CK        5.73       13.16
  OK       31.46       54.27
 AlK        1.26        1.29
 SiK        7.40        7.27
 AuM        6.82        0.96
 AgL        1.40        0.36
 FeK       45.94       22.70
```

FIGURE 5.100. CORE SAMPLE FROM THE LAMOTTE SANDSTONE AT A DEPTH OF 3,589.7 FT. IT WAS REACTED AT 90°C UNDER A PRESSURIZED CO_2 + H_2O ENVIRONMENT. A) BOTH SMALL AND LARGE RHOMBOHEDRAL SHAPED GRAINS (TO RIGHT) ON LARGER PITTED AND SEMI-ROUNDED QUARTZ GRAIN. BOX SHOWS AREA OF EDS ANALYSIS. INSET TABLE SHOWS CA, MG, C, O ATOMIC RATIOS OF APPROXIMATELY 1:1:2:6 DETECTED DURING EDS ANALYSIS.



Element	Weight%	Atomic%
C K	12.28	18.43
O K	58.20	65.56
Mg K	9.37	6.94
Ca K	20.15	9.06
Totals	100.00	

X-RAY DIFFRACTION (XRD) ANALYSIS OF CORE SAMPLES FROM THE SPP SITE

Nearly all core samples from the SPP site contained some illite (or muscovite), except for samples from 3,460.0 ft and 3,500.5 ft, the latter of which did not display peaks for any clay minerals (Table 5.39). Illite and muscovite are difficult to distinguish in XRD analysis due to their having similar d- spacing (9.97-9.98 Å for illite, 10.01 Å for muscovite). Illite is presumed to be present as it more commonly occurs in mature sedimentary rocks. Both chlorite (14.2 Å; 3,269.9 ft, 3,460.0 ft, 3,589.7 ft) and kaolinite (7.16 Å; 3,269.9 ft, 3,441.0 ft, 3,576.5 ft) occurred sporadically throughout the Davis and Bonneterre Formations, and Lamotte Sandstone. The Davis Formation sample from 3,024.7 ft showed an unexpected decrease in the glycolated peak intensity, as well as a drop in background over the range of 2-10^{o} 2-theta although no peak shift was observed (Figure 5.101).

Illite, quartz, dolomite, and halite were detected in this sample. The Davis Formation sample from 3,269.9 ft was dominated by illite and kaolinite, and showed chlorite as a trace component (Figure 5.102). The Bonneterre Formation sample from 3,460.0 ft displayed the presence of chlorite, quartz, calcite and halite (Figure 5.103).

TABLE 5.39A. RESULTS FROM THE X-RAY DIFFRACTION ANALYSIS OF SELECTED CORE SAMPLES FROM THE SPP SITE.

Core Depth (ft)	Clay Mineral Types Found	Non-Clay Strong Peaks	Formation
3024.7	Illite	Quartz, dolomite, halite	Upper Davis
3177.5	Illite	Quartz, halite, calcite	Davis
3222.2	Illite	Quartz, calcite	Davis
3242.9	Illite	Quartz	Davis
3269.9	Illite, minor chlorite, minor kaolinite	Quartz, halite	Davis
3441.0	Illite, minor kaolinite	Quartz, halite	Bonneterre
3460.0	Chlorite	Quartz, calcite, halite	Bonneterre
3481.4	Illite	Halite	Upper Lamotte
3500.5	No clay minerals detected	Quartz, calcite	Lamotte
3529.2	Illite	Quartz., calcite	Lamotte
3576.5	Illite, kaolinite	Quartz, calcite,	Lamotte
3589.7	Illite, minor chlorite	Quartz, halite	Lamotte

TABLE 5.39B. CLAY FRACTIONS FOR EACH CORE SAMPLE ANALYZED FROM THE SPP SITE. "ND" – NONE DETECTED.

Sample ID	Depth (ft)	Formation	% Illite	% Kaolinite	% Chlorite
L5	3024.7	Davis	100	nd	nd
L10	3177.5	Davis	100	nd	nd
L12	3222.2	Davis	100	nd	nd
L13	3242.9	Davis	100	nd	nd
L14	3269.9	Davis	55	45	Trace
L26	3441.0	Bonneterre	95	5	nd
L28	3460.0	Bonneterre	nd	nd	100
L32	3481.4	Lamotte	100	n	nd
L34	3500.5	Lamotte	No	Cl	Dete
L40	3529.2	Lamotte	100	n	nd
L49	3576.5	LaMotte	35	6	nd
L53	3589.7	Lamotte	100	n	nd

FIGURE 5.101. X-RAY DIFFRACTION SPECTRA INTENSITY PLOT FOR AN UNTREATED, LITHOLOGICAL GLYCOLATED, AND HEAT-TREATED CORE SAMPLE FROM THE DAVIS FORMATION AT THE SPP SITE AT A DEPTH OF 3,024.7 FT. THE LARGE PEAK AT 8.8 2-THETA AS WELL AS THE SMALLER PEAK AT 17.6 REFLECTS THE PRESENCE OF ILLITE AS THE PRIMARY CLAY CONSTITUENT. THE PEAK AT 26.6 CORRESPONDS TO QUARTZ, AND THE PEAK AT 30.9 SHOWS THE PRESENCE OF DOLOMITE. NOTE THE DROP IN PEAK HEIGHT AND BACKGROUND FOR THE GLYCOLATED SAMPLE, AND SUBSEQUENT RETURN TO NEAR ORIGINAL POSITION UPON HEAT TREATING.

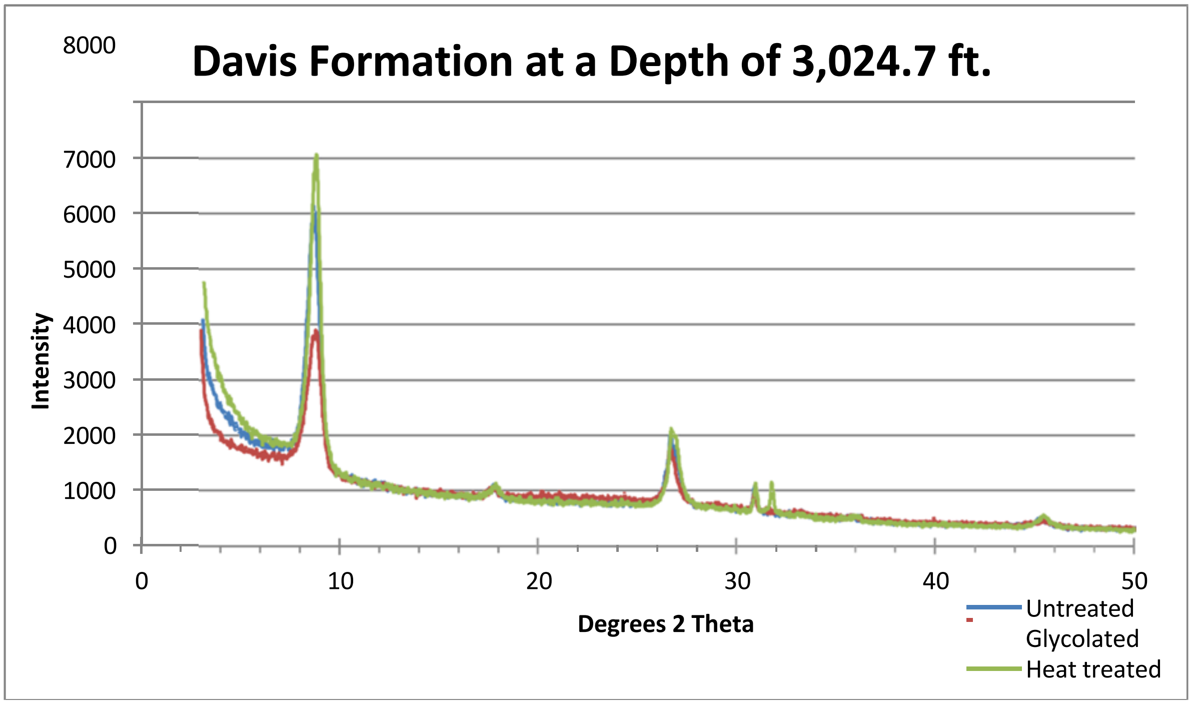


FIGURE 5.102. X-RAY DIFFRACTION SPECTRA INTENSITY PLOT FOR AN UNTREATED, GLYCOLATED, AND HEATED CORE SAMPLE FROM THE DAVIS FORMATION OF THE SPP SITE AT A DEPTH OF 3,269.2 FT. THERE IS A MINOR SPIKE AT 6.2 WHICH INDICATES THE PRESENCE OF CHLORITE, PEAKS AT 8.5 AND 17.8 INDICATE THE PRESENCE OF ILLITE, 12.4 INDICATES KAOLINITE, 26.8 INDICATES QUARTZ, AND THE PEAK AT 27.5 INDICATES THE PRESENCE OF HALITE.

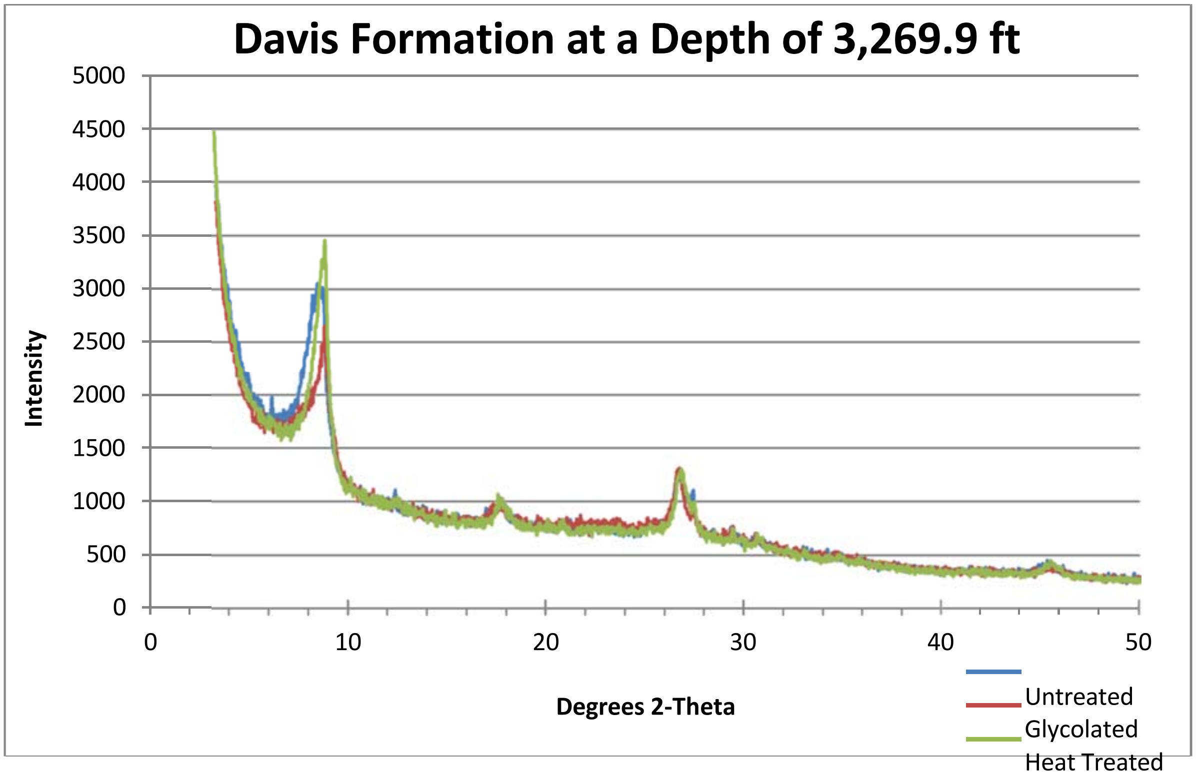
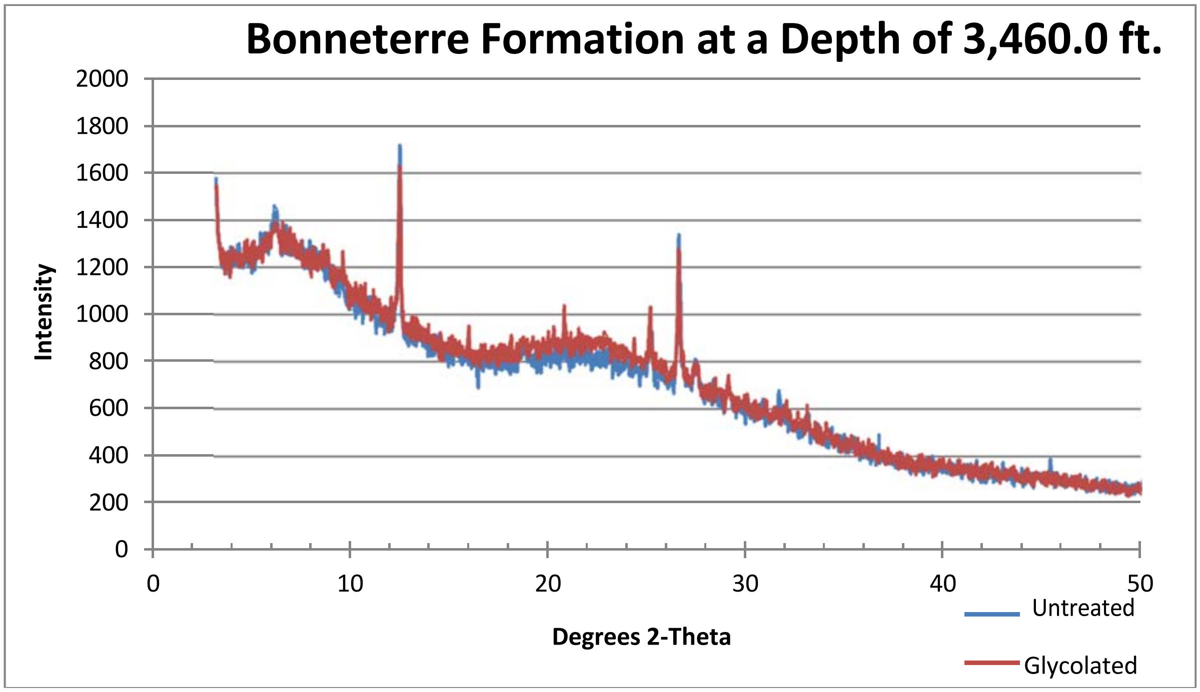


FIGURE 5.103. X-RAY DIFFRACTION SPECTRA INTENSITY PLOT FOR A CORE SAMPLE FROM THE BONNETERRE FORMATION AT THE SPP SITE AT A DEPTH OF 3,460.0 FT. THIS ANALYSIS SHOWS THE PRESENCE OF LARGE CHLORITE PEAKS AT 6.2, 12.6, AND 25.2 DEGREES 2-THETA. THE NON-CLAY PHASES IDENTIFIED WERE QUARTZ AT 20.8 AND 26.6, AND A SMALL CALCITE PEAK AT 29.1.



In summary, the borehole drilled at the SPP site encountered a good section of Lamotte Sandstone, from approximately 3,500 ft to 3,622 ft. Average porosity over this interval is 10.7% with an average permeability of 10.1 md. Permeability ranged from nearly 0 to 99 md.

No well logs were run at the SPP site and no injection pressure tests were conducted.

GEOMECHANICAL ROCK PROPERTIES

Geomechanical testing of core samples from the SPP site indicate that the Lamotte modulus is approximately 6×10^6 and the Davis Formation is 12×10^6. This value for the shale is high. No pump-in tests were conducted to measure breakdown pressure directly; the fracture gradient could not be calculated as logs were not run in the borehole.

The Davis Formation was encountered from 3,048-3,323 ft, and the Bonneterre/Lamotte transition was found from 3,323- 3,476 ft. The Davis Formation had a porosity of nearly zero to a single point maximum of 13%, but the average porosity was approximately 2%. Permeability varied from .0029 to .08 md, but many samples could not be measured. It is likely that these samples have a permeability <0.001 md. Capillary pressure measurements indicate a high CO_2 entrance pressure. The Davis Formation at the SPP site may be slightly better than the section of Davis Formation encountered at the THEC site.

The Lamotte Sandstone is located considerably deeper than found at the JTEC and THEC sites which may aid in CO_2 storage capacity. Lamotte Sandstone porosity is similar to that found at both the JTEC and THEC sites, although the permeability is about five times better than at the JTEC site (2 md versus 10 md). Since the CMG simulation was based on a Lamotte permeability of 20 md, the injectivity and storage capacity at the SPP site should be similar to that calculated for the JTEC site.

Water samples from the Lamotte Sandstone unit at the SPP site were also a NaCl dominated brine with a significant Ca-Mg-bicarbonate fraction (Figure 5.30). Iron oxide flocculation also occurred after the water had been brought to the surface and exposed to atmospheric oxygen. The TDS evaporation method produced a salinity value of 42,055 +/- 213 mg/kg, the cumulative total cation + anion + bicarbonate content method was 42,462 mg/kg, and conductivity value calculation gave a value of 42,621 ± 267 mg/kg. The SPP site had salinity values that were approximately 10% lower than for the THEC site, although both sites contained dissolved salts concentrations that were well above the 10,000 mg/kg EPA limit for classification as a Class VI injection facility. Thus, both sites are ranked to be equally effective for potential use as a CO_2 injection facility based on total water salinity.

Water samples drawn from SPP site displayed higher relative and total proportions of Ca than that for the THEC site (2,695 versus 2,491 ppm, respectively), but had a correspondingly lower Mg concentration (504 versus 860 ppm, respectively). Overall Ca + Mg concentrations (activities) will exert an influence on the potential for carbonate mineralization for the formation waters. Both locations have similar groundwater concentrations of Ca and Mg, rendering each equally effective with regards to their potential ability to induce carbonate mineralization in the subsurface. As previously discussed with the THEC site, reactions with core samples in the $90^{\circ}C$ high pressure $CO_2 + H_2O$ tests indicate only a minimal potential for carbonate mineralization resulting from elements released directly from dissolving core materials.

Reactions with non-carbonate shale samples in the $90^{\circ}C$ high pressure $CO_2 + H_2O$ tests (e.g., 3,269.9 ft Davis Formation sample from the SPP site) displayed a relatively rapid pH rise (i.e. neutralizing $H_2CO_{3(aq)}$) and relatively high release rates of core components. These reactions suggest a fair susceptibility to acid attack and corrosion. As these non-carbonated shale horizons represent the potential cap-rock that would preventing leakage of injected CO_2 from the St. Francois Aquifer, their integrity against acid attack may be critical to the log-term retention of injected CO_2. It is recommended that additional samples from these shale horizons be tested to ensure their integrity when exposed to $H_2CO_{3(aq)}$ solutions.

The clay-sized particle fraction of all of the SPP site subsurface formations contained illite as the predominant clay mineral, along with lesser amounts of kaolinite, and chlorite. As with the THEC site, the low turbidity of water samples collected from the well sites and the similarities of elemental concentrations in the waters that were passed through different filter sizes suggest that the clays remain intact within the repository pore space and thus will not migrate and cause pore blockage. Iron oxide flocculates that formed when that SPP site water samples were exposed to oxygenating conditions suggests a potential for iron flocculate formation in the subsurface that could potentially induce pore plugging if it occurs.

GOLDICH MINERAL STABILITY SERIES

In a classic study of natural mineral weathering, Goldich (1938) devised a natural “mineral stability series” from observations of natural rock outcrop samples from the 1) Morton Gneiss, MN; 2) Diabase Hill, MN, 3) Medford Diabase, MA; and Black Hills Amphibolite, SD. Goldich recorded in his observations that silicate minerals in these exposed rock formations have a natural tendency to weather or react at rates that occur in the inverse order at which the minerals would have crystallized in cooling igneous systems (i.e. Bowen’s Reaction Series; Figure 5.104). Olivine, being the mineral that tends to crystallize the earliest, and at the highest temperature, was thus the fastest mineral to weather. Conversely quartz, which crystallized at the lowest temperature, would be the slowest minerals to weather.

In order to evaluate the potential of utilizing the Goldich Mineral Stability series with regards to predicting mineral alteration rates in a simulated CO_2 sequestration environment, minerals were reacted in a HNO_3solution prepared to a pH of 3.78. This represents the approximate condition that would be expected with a dilute water solution in contact with a CO_2 rich atmosphere. The mineral samples were reacted in the following groups:

A) A series of nine mineral samples similar to those used in the Goldich (1938) classic study on natural weathering rates of minerals including: Mg-rich olivine-forsterite, pyroxene- augite, amphibole-hornblende, quartz, two orthoclase feldspar samples (K-feldspar), and three plagioclase feldspar samples (ranging from a nearly pure $NaAlSi_3O_8$ albite phase, Na- rich oligoclase, and Ca-rich bytownite). Quartz is ubiquitous throughout the stratigraphic sequence of Missouri and is the dominant mineral throughout much of the Lamotte Sandstone. Of these minerals, only quartz, albite, and K-feldspar are expected to be present in the Lamotte Sandstone with any abundance.

B) Eight clay minerals were used in the experiments and represent a potential range of matrix materials in sedimentary rocks or those formed during the alteration of other aluminosilicate phases. Seven of these were obtained from the “Source Clay Minerals Repository” standards and include: Na-montmorillonite (Wyoming bentonite), Ca- montmorillonite (STX-1), nontronite H33a), hectorite (H34), kaolinite “well-crystallized” (KGa-1), kaolinite “poorly crystallized” (KGa-2), and illite (IMT-1). The eighth clay sample tested, glauconite, was obtained from the mineral collections at Missouri S&T. Compositions for the clay standards can be found at the United States Geological Surveys Spectroscopy Lab Website. Illite, kaolinite, and glauconite are common minerals in the Bonneterre, Davis, and Derby-Doerun Formations.

C) Minerals that are often found as cementing materials in sandstones (calcite, hematite, plus the previously mentioned quartz), chlorite (often found as a matrix or cementing material in low-grade metamorphic rocks), and epidote (often found as an alteration phase in Mg-Fe rich rocks). All of these minerals may be encountered in the Missouri rock strata.

D) Blank tests with 200 ml HNO_3 but no mineral or rock samples were run as controls.

The batch of samples with Goldich-series and feldspar minerals have been run for time periods of 6,900 hours (287 days), while the cement and clay minerals were reacted for 4,300 hours (179 days). For each of the reactions, an increase in pH was commonly observed that reflects a chemical buffering reaction following the exchange of $nH^+ \Leftrightarrow M^{n+}$, where M^{n+} corresponds to any metal cation (e.g., Na^+ K^+, Ca^{2+}, Mg^{2+}, Fe^{2+} etc.). Minerals that react more rapidly with acids have a greater buffering capacity for neutralizing solutions, and thus the associated test solution would be characterized by a more rapid increase in pH relative to the blank test. The rise in pH will eventually plateau as the excess acids are consumed in the buffering reaction(s). Conversely, the experiments containing minerals that are relatively inert to acid attack would display only minor pH rises and thus should closely mimic the flat pH patterns of the control tests. The pH values for some of the more rapidly reacting samples also may show a later decrease in pH, apparently as OH^- ions are being incorporated in clay minerals and/or other phases containing hydroxides.

In the Goldich mineral stability series tests, solutions displayed a decreasing order of reactivity in the order of olivine, hornblende, pyroxene orthoclase feldspar, Ca-plagioclase (bytownite), Na- plagioclase (oligoclase), and finally quartz. Thus, these experiments were in good agreement with the Goldich (1938) study, though a switching of the order of pyroxene and hornblende was noted, plus a switching of Na-Plagioclase with K-Feldspar (Figures 5.104 and 5.105a). The reaction of feldspar minerals was further tested by the addition of two more samples; K-feldspar from Georgia and a Na-rich albite plagioclase from North Carolina (Figure 5.105b). The plagioclase series samples ($NaAlSi_3O_8$ to $CaAl_2Si_2O_8$) reacted as anticipated based on the Goldich (1938) observations, with the Ca-rich end member showing the fastest reaction rate. The second K- feldspar sample tested (K-spar from Georgia) also reacted at a slow rate in agreement with the original observations of Goldich. Of these minerals, only the slower reacting quartz, albite- plagioclase, the orthoclase (K-feldspar) are expected to be present in the Lamotte Sandstone with any frequency.

The clay minerals montmorillonite, nontronite (iron-montmorillonite), hectorite (magnesium montmorillonite), kaolinite, illite, and glauconite are often present as pore-filling minerals in sandstones and are dominant minerals in impermeable shale layers that may represent trap rocks in a CO_2 injection repository. Some of these clay minerals may even be generated as alteration phases following the reaction of the primary igneous minerals displayed in Figure 5.105a.

Hectorite was the most reactive clay mineral, displaying a rapid spike in the pH value of the test solution contacting this mineral (Figure 5.106). Na-montmorillonite and illite generally reacted to produce a near neutral pH by 800 hours. Filling out the bottom of the list for the least reactive components were, in decreasing order of buffering efficiency, nontronite, Ca-montmorillonite, chlorite, glauconite, and the two samples of kaolinite. The acid solutions in contact with these latter five minerals remained below a pH of 5.5 with both of the kaolinite sample experiments remaining near the original HNO_3 starting leachant pH level of 3.78. Clay minerals often display highly variable chemical compositions, thus some caution should be used in extrapolating the results from these experiments to other mineral systems without giving careful consideration to the specific mineral compositions. Of these minerals, only illite, glauconite, and kaolinite are expected be present in the Lamotte Sandstone and overlying units.

Calcite, hematite, and the previously discussed quartz often occur as cement materials in sandstones. As expected, calcite reacted quite readily with the acid solution to produce a leachate pH of eight within the first two hours of testing (Figure 5.106). The calcite test solution continued to display a pH rise, reaching a plateau at 8.82 between 96 and 168 hours; then decreased to approximately 8.5 after approximately 1,200 hours. The calcite solids in the test were never completely consumed in the reaction so the plateau and subsequent slight decrease in pH represented the reaction as it approached an equilibrium state. The rapid reaction of calcite cement is expected to enhance the porosity and permeability of rocks that are cemented by this material. By contrast, hematite was only slightly reactive in the tests with a long-term pH rise only from the initial 3.78 to 4.2 after 336 hours of testing. These results suggest that both hematite and quartz cement (quartz was previously discussed above) should behave in a relatively inert manner under the slightly acidic conditions produced during CO_2 injection into a subsurface repository. An increase in the solubility of iron may also occur when more reducing conditions are encountered and/or salinities are higher.

The mineral epidote [$Ca_2Al_2Fe^{3+}[Si_2O_7][SiO_4]$ (OH)] is often found as an alteration product where hydrothermal waters interact with Ca and/or Fe bearing minerals and occurs sporadically in basement rocks exposed in the St Francois Mountains of Missouri. Epidote reacted quickly with the leachant solution, rapidly buffering the solution pH to a value of approximately 6.3 after 96 hours of exposure, and then continued to a pH value of 6.8 after 1,512 hours (Figure 5.106). The reaction of epidote would also release Ca^{2+} and Fe to solution, potentially enhancing mineralization processes that sequester CO_2 in $CaCO_3$ or $FeCO_3$ if the iron can be reduced into its Fe^{2+} state.

FIGURE 5.104. RELATIVE ORDERING OF MINERAL CRYSTALLIZATION DURING THE COOLING AND SOLIDIFICATION OF A HYPOTHETICAL IGNEOUS BODY ACCORDING TO BOWEN'S CRYSTALLIZATION SERIES. THE GOLDICH WEATHERING SERIES (GOLDICH, 1938) PREDICTS THAT THE BOWEN'S SERIES MINERALS WILL PROGRESSIVELY WEATHER AT A RATE THAT IS INVERSE TO THEIR CRYSTALLIZATION ORDER, WITH CRYSTALS SUCH AS OLIVINE AND CA-PLAGIOCLASE THAT FORM AT THE HIGHEST TEMPERATURES WEATHERING AT THE FASTEST RATES.

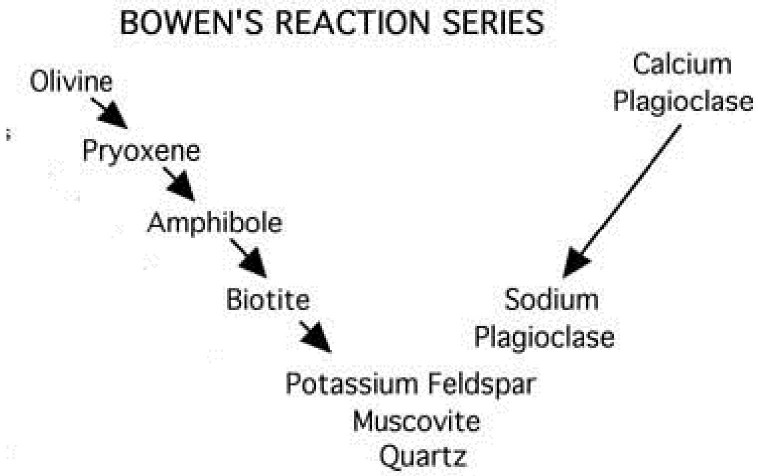
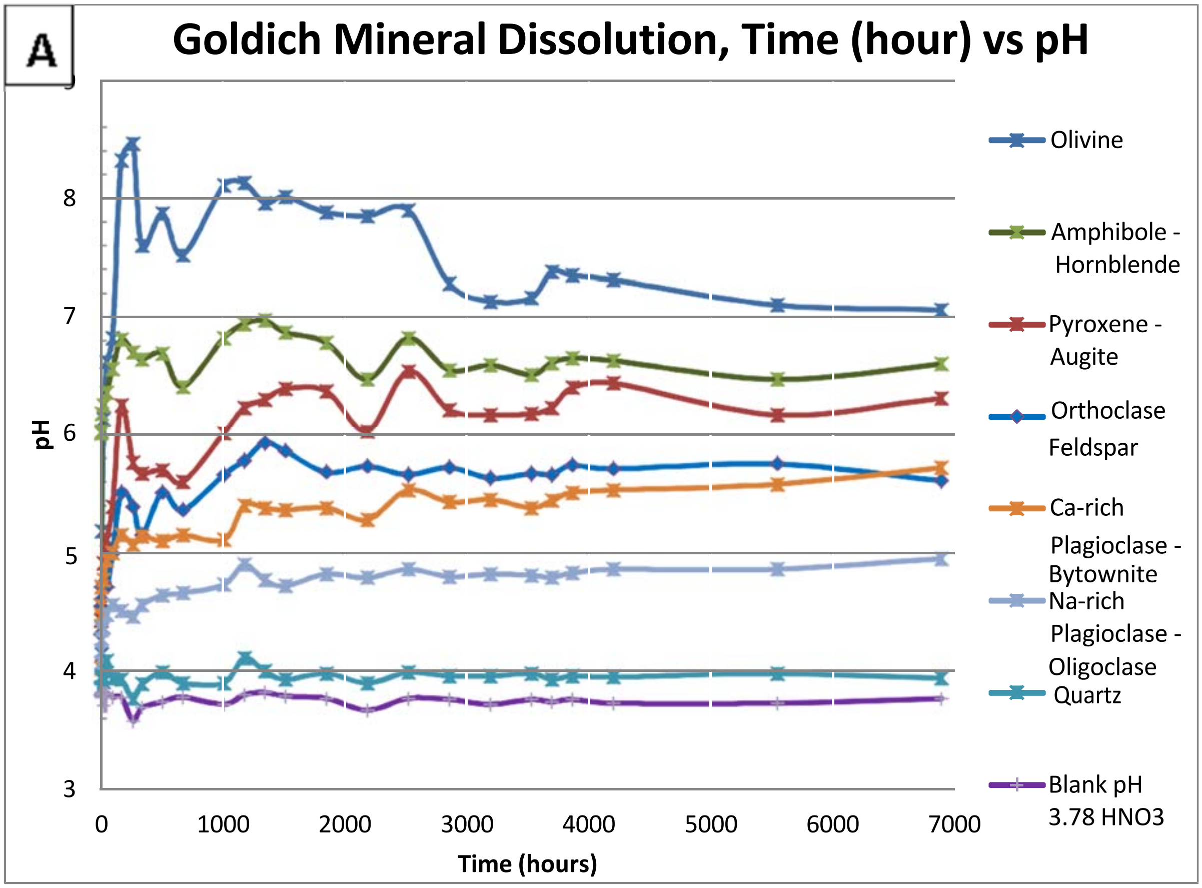


FIGURE 5.105. GOLDICH TEST MINERAL ALTERATION RATES. A) RELATIVE ORDERING OF GOLDICH SERIES MINERAL REACTIONS AND REACTION RATES FOLLOWING EXPOSURE TO A DILUTE HNO_3 SOLUTION AT A PH ~3.78. THE BLANK TEST PH TREND IS THE LOWEST TREND THAT PLOTS AT THE BOTTOM. THE EXTENT OF MINERAL REACTIONS IS PROPORTIONAL TO THE SOLUTION PH INCREASE, AND B) REACTIONS WITH ONLY THE FELDSPAR MINERALS. THE ORTHOCLASE, CA-RICH PLAGIOCLASE – BYTOWNITE, NA-RICH PLAGIOCLASE – OLIGOCLASE, AND THE BLANK TESTS ARE DUPLICATED IN BOTH FIGURES 5.105A AND B.



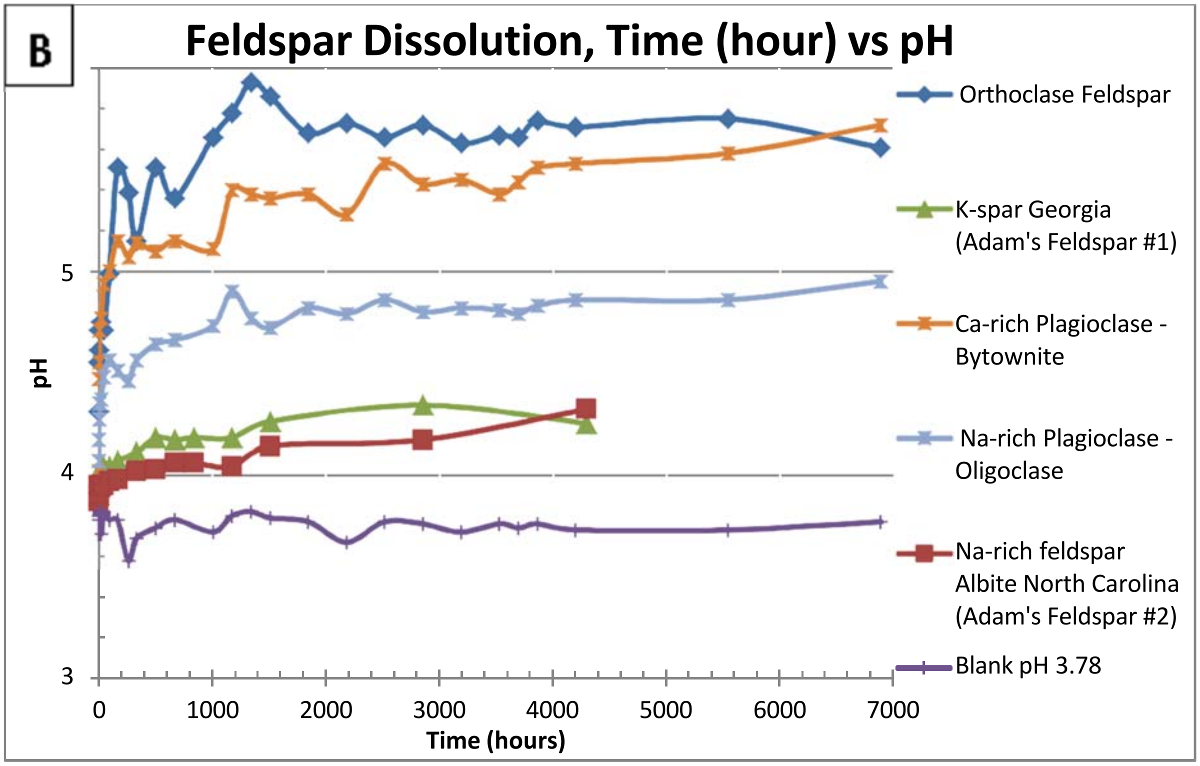
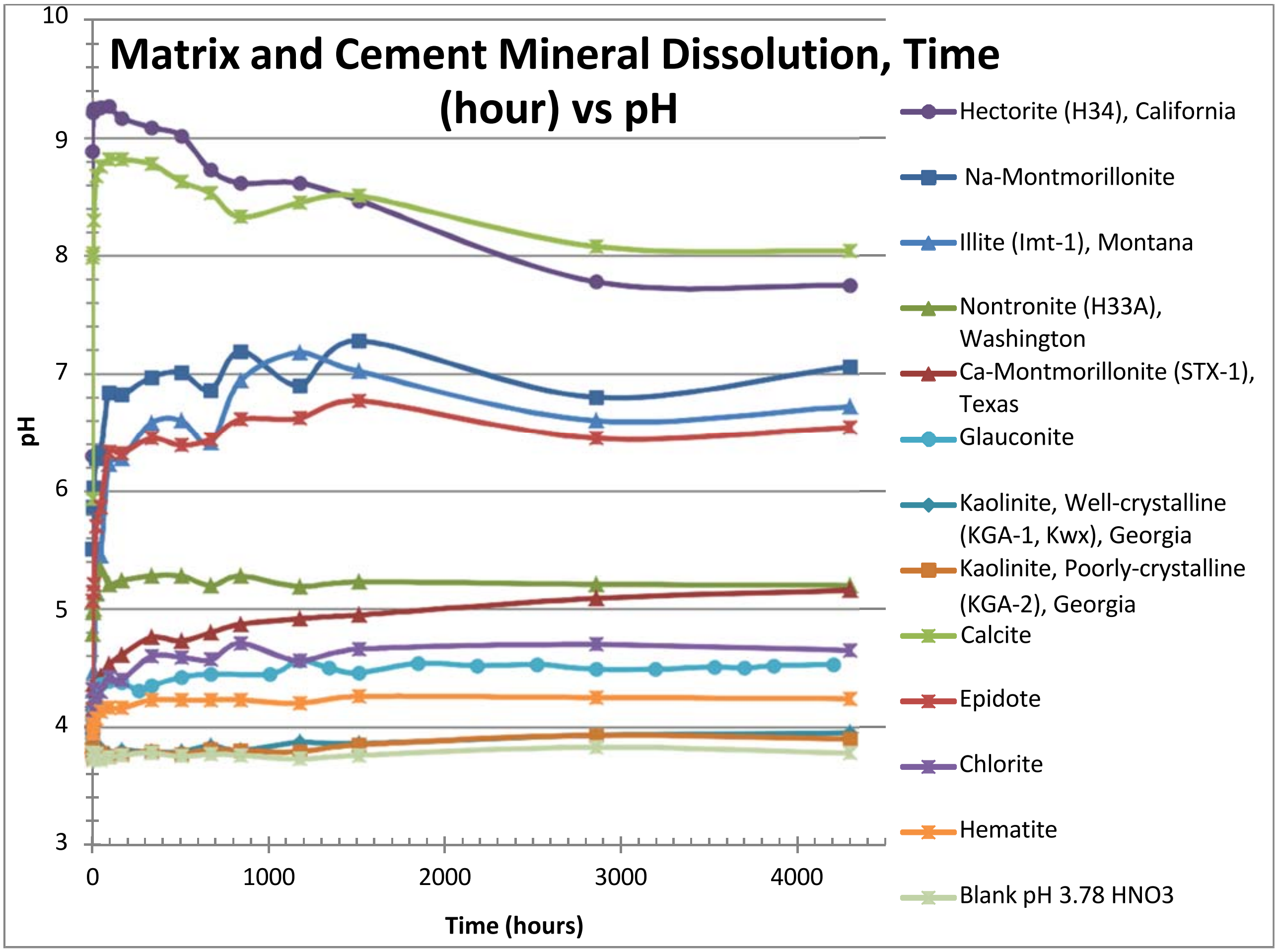

B
Feldspar Dissolution, Time (hour) vs pH
pH
3
4
5
0
1000
2000
3000
4000
5000
6000
7000
Time (hours)
Orthoclase Feldspar
K-spar Georgia (Adam's Feldspar #1)
Ca-rich Plagioclase - Bytownite
Na-rich Plagioclase - Oligoclase
Na-rich feldspar Albite North Carolina (Adam's Feldspar #2)
Blank pH 3.78

FIGURE 5.106. ORDERING OF MINERAL REACTIONS AND REACTION RATES OF MATRIX CLAYS (SOLID FILLED IN SYMBOLS), CEMENTS, AND POTENTIAL ALTERATION MINERALS (THE LATTER TWO USING THE SYMBOL "X"). THE TESTS WITH HECTORITE AND CALCITE HAD THE MOST DRAMATIC PH INCREASE WHILE THE TWO KAOLINITE SAMPLES WERE RELATIVELY INERT, PRODUCING A TEST SOLUTION THAT REMAINED CLOSE TO THE ORIGINAL STARTING LEACHANT BLANK SOLUTION PH OF 3.78.



D. CONCLUSIONS

Three boreholes have been successfully drilled and cored through the Davis Formation and Lamotte Sandstone to evaluate the potential for CO_2 sequestration in the Lamotte Sandstone in Missouri. All three boreholes exhibited average porosity of 10% to 13%. Lamotte thickness varied from 120 ft at the JTEC site, to 190 ft at the THEC site, and 122 ft at the SPP site. The Reagan Sandstone formation may add storage capacity to the Lamotte Sandstone in southwest Missouri, and elsewhere the Bonneterre Formation may also contribute some small storage capacity above the Lamotte Sandstone.

In the THEC borehole, the Lamotte Sandstone has the highest permeability of the three boreholes, with an average permeability of 47 md, and an excellent section from 2,420 to 2,500 ft with an average of 90 md.

Reservoir simulation using CMG software for the JTEC site indicated a storage capacity of 5.63×10^8 lb of CO_2 over a 15.8 year period, using an 800 m x 800 m (2,624 x 2,624 ft) reservoir volume and water withdrawal through a 5-spot patter. An ideal injection rate of $60m^3$/day was determined assuming a fracture gradient of 0.61 psi/ft. This value is consistent with the calculated gradient for the THEC site, but is less than the observed breakdown pressures at the JTEC site.

Although reservoir simulation was not performed for the THEC site as the activity was beyond the extended project guidelines, the increased quality of the formation implies that a greater amount of CO_2 could sequester over the same injection period in this borehole.

The Davis Formation was present in all three boreholes, with the thinnest section at the THES site. The Davis found in the SPP site had the highest capillary pressure entry pressure, but the Davis Formation permeability was similar in all three boreholes (microdarcy permeability). Further study is suggested to evaluate the Davis Formation as a caprock for CO_2 sequestration.

Water samples drawn from both the Reagan and Lamotte Sandstone units at the JTEC site were Ca-Mg-bicarbonate dominated solutions with low total salinities. Three water samples analyzed from the JTEC Site from various stratigraphic horizons produced TDS values from between 159 and 227 mg/L. The US EPA currently defines an Underground Source of Drinking Water (USDW) as an aquifer that contains <10,000 mg/L TDS and the JTEC salinities were a factor of approximately 45- fold below this level. Hence, CO_2 injection at this site is not feasible.

Water samples drawn from the Lamotte Sandstone unit at the THEC site are NaCl dominated brines with minor Ca, and very minor Mg-bicarbonate-sulfate fractions. The iron concentration was also high enough to produce a visible amount of precipitated iron oxide and/or hydroxide particles (Fe_2O_3, $FeO(OH)$, $Fe(OH)_3$) at both sites after conversion of Fe^{2+} that was present in the subsurface, into Fe^{3+} upon exposure to the oxygenated atmosphere. The three methods used to determine salinity in the water samples from the Lamotte Sandstone at the THEC site were in close agreement, varying by <3%. The TDS evaporation method for determining salinity produced a value of 46,287 ± 11 mg/kg, the cation + bicarbonate + anion tabulation method produced a value of 45,723 mg/kg, while the conductivity value calculation resulted in a salinity value of 47,090 ± 67 mg/kg.

Water samples from the Lamotte Sandstone unit at the SPP site was also a NaCl dominated brine with a significant Ca-Mg-bicarbonate fraction. Iron oxide flocculation also occurred after the water had been brought to the surface and oxidized. The TDS evaporation method produced a salinity value of 42,055

+/- 213 mg/kg, the cumulative total cation + anion + bicarbonate content method was 42,462 mg/kg, and conductivity value calculation produced a value of 42,621 ± 267 mg/kg. The THEC site had salinity values that were approximately 10% higher than the SPP site, although both sites contained dissolved salts concentrations that were well above the 10,000 mg/kg EPA limit for classification as a Class VI injection facility. Thus, both sites are ranked to be equally effective for potential use as a CO_2 injection facility based on total water salinity.

Water samples drawn from SPP site display had a higher relative and total proportions of Ca than the THEC site (2,695 versus 2,491 ppm, respectively) but the SPP site had correspondingly lower Mg concentrations (504 versus 860 ppm, respectively). Overall Ca + Mg concentrations (activities) will exert an influence on the potential for carbonate mineralization for the formation waters.

Both locations have similar enough concentrations in this regard to render each equally effective with regards to their potential ability to induce carbonate mineralization in the subsurface.

Samples from all three sites with core collected were reacted in the $90^{o}C$ high pressure CO_2 + H_2O tests designed to accelerate mineral reactions. Alteration phases commonly included iron oxides. Carbonate phases were detected, but were sporadic in occurrence and minor in amount. These included rhombohedral-shaped grains with a composition consistent with the presence of dolomite ($Ca,Mg(CO_3)_2$), and a second phase tentatively identified as siderite($FeCO_3$), though the latter was too small to get accurate compositional analysis. Thus, the potential for carbonate mineralization reactions resulting from elements released directly from dissolving rock materials thus appears to be present, but quantities and/or rates of minerals produced may be minimal due to slow reactions. Acid neutralization reactions resulting from the interaction between $H_2CO_{3(aq)}$ and the mineral constituents can induce carbonate mineralization reactions. However, the Goldich series reaction tests also indicated that phases commonly encountered in the Missouri strata (quartz, Na-rich plagioclase, orthoclase, kaolinite, illite, and glauconite) will be slow to react with acidified fluids.

Reactions with non-carbonate shale samples in the $90^{o}C$ high pressure CO_2 + H_2O tests (e.g., one from 3,269.9 ft in the Davis Formation from the SPP site) displayed a relatively rapid pH rise (i.e. neutralizing carbonic acid) and relatively high release rates of rock components. These reactions suggest a fair susceptibility to acid attack and corrosion. As these non-carbonated shale horizons represent the potential cap-rock that would preventing leakage of injected CO_2 from the St.

Francois Aquifer their integrity to acid attack may be critical to the log-term retention of injected CO_2. It is recommended that additional samples from these shale horizons be tested to ensure their integrity when exposed to $H_2CO_{3(aq)}$ solutions.

The clay-sized particle fraction of all core samples from the Davis and Lamotte Sandstones from the THEC site contained illite as the predominant clay mineral, along with lesser amounts of kaolinite, glauconite, and chlorite. The low turbidity of water samples collected from the borehole sites and the similarities of elemental concentrations in the water samples that were passed through different filter sizes suggest that the clays remain intact within the repository pore space and thus will not migrate and cause pore blockage problems. Iron oxide flocculates that formed in the water samples from the THEC and SPP sites when exposed to oxygenating conditions suggests a potential for iron flocculate formation in the subsurface during CO_2 injection. Such a process may induce pore plugging in the subsurface rocks if it occurs.

E. References

ASTM-C1285-94: "Standard Test Methods for Determining Chemical Durability of Nuclear Waste Glasses: The Product Consistency Test (PCT)," American Society for Testing and Materials (ASTM) C1285 – 94 (1995) 1-19.

Bachu S, Bonijoly D, Bradshaw J, Burruss R, Holloway S, Christensen N P, and Mathiassen O M. CO_2 storage capacity estimation: methodology and gaps. International Journal of Greenhouse Gas Control, 2007, 1(4): 430-443

Balanis, Constantine, *Advanced Engineering Electromagnetics*, John Wiley & Sons, Inc., New York, NY, 1989.

Bennion D B and Bachu S. Relative Permeability Characteristics for Supercritical CO_2 Displacing Water in a Variety of Potential Sequestration Zones in the Western Canada Sedimentary Basin. Paper SPE 95547 presented at SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, 2005

Bennion D B and Bachu S. Drainage and Imbibition Relative Permeability Relationships for Supercritical CO_2/Brine and H2S/Brine Systems in Intergranular Sandstone, Carbonate, Shale, and Anhydrite Rocks. SPE Reservoir Evaluation & Engineering 2008, 11(3): 487-496

Blackburn, J. Lewis, *Protective Relaying – Principles and Applications*, Marcel Dekker, Inc., New York, NY, 1987.

Boyd, C.E.: "Specific Conductance, Alternative Salinity Measurement," *The Advocate* (Feb. 2002) 70-71. http://pdf.gaalliance.org/pdf/gaa-boyd-feb02.pdf

Burton M, Kumar N, and Bryant S L. Time-dependent injectivity during CO_2 storage in aquifers. Paper SPE 113937 presented at SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA, 2008

Buscheck T, Sun Y, Hao Y, Court B, Celia M A, Wolery T, Tompson A F, Aines R D, Friedmann J. Active CO_2 Reservoir Management: A Strategy for Controlling Pressure, CO_2 and Brine Migration in Saline-Formation CCS. In: Proceedings of American Geophysical Union Annual Meeting, San Francisco, USA, 2010

Court B, Celia M A, Nordbotten J M, Elliot. Active and integrated management of water resources throughout CO_2 capture and sequestration operations. Energy Procedia, 4: 4221-4229, 2011

Craig F F. The reservoir engineering aspects of waterflooding. Monograph volume 3. Dallas: Society of Petroleum Engineers of AIME, 1971.

Daniel R. Carbon Dioxide Seal Capacity Study, Vlaming Sub-basin, Perth Basin, Western Australia. CO2CRC report, Aug, 2005, RPT05-0044.

Fleury M, Pironon J, Le Nindre Y M, Bildstein O, Berne P and Lagneau V. Evaluating sealing efficiency of caprocks for CO2 storage: an overview of the geocarbone integrity program and results. Oil & gas science and technology, rev. IFP, 2009.

Goldich, S.S.: “A study in Rock Weathering,” *Journal of Geology* (1938) v. 46, 17–58.

Hassanzadeh H, Pooladi-Darvish M, and Keith D. Accelerating CO_2 dissolution in saline aquifers for geological storage-mechanistic and sensitivity studies. Energy and Fuels, 2009, 23: 3328-3336

Iverson W P, Martinsen R S and Surdam, R.C. Pressure Compartments in the Powder River Basin. SPE 24357 presented at the SPE rocky mountain regional meeting, Casper, Wyoming, 18- 21 May, 1992.

JTEC, 2012, “Final Report for the CU JTEC Well”, December, 2012.

Kobos P H, Roach J D, Klise G T, Krumhansl J L, Dewers T A, Dwyer B, Borns D J. Storing Carbon Dioxide in Saline Formations: Analyzing Extracted Water Treatment and Use for Power Plant Cooling. Energy and the Environment: Conventional and Unconventional Solutions, online proceedings, 2010

Koederitz L F, Mohamad Ibrahim M N. Developing a proficient relative permeability resource from historical data. In: Proceedings of Petroleum Society’s Canadian International Petroleum Conference, Calgary, Alberta, Canada, 2002

Leonenko Y and Keith D. Reservoir engineering to accelerate the dissolution of CO_2 stored in aquifers. Environmental Science and Technology, 42(8): 2742-2747, 2008

Macknick J, Newmark R, Heath G, Hallet K C. A review of operational water consumption and withdrawal factors for electricity generating technologies. Technical report NREL/TP-6A20-50900, 2011

Mason, C. Russell, *The Art and Science of Protective Relaying*, John Wiley & Sons, Inc., New York, NY, 1956.

McNemar A. Carbon sequestration and water: A Department of Energy perspective. In: Proceedings of Water/Energy Sustainability Symposium, Salt Lake City, Utah, USA, 2009

Newmark R L, Friedmann S J, and Carroll S A. Water challenges for geologic carbon capture and sequestration. Environmental Management, 2010, 45:651-661

Sunde, Erling D., *Earth Conductor Effects in Transmission Systems*, Dover Publications, New York, NY, 1968.

F. Appendices

APPENDIX 5 A - PROCEDURE FOR SEQUENTIAL FILTRATION OF WATER SAMPLES

MATERIALS NEEDED FOR FIELD COLLECTION AND FIELD SAMPLING OF WATER SAMPLES

1) Pre-cleaned 1000 ml polyethylene (PE) container (see below for cleaning procedure).
2) Pre-cleaned and pre-weighed 125 ml PE containers (one for each cation filtered sample to be collected, generally two to four per sampling site).
3) One pre-cleaned anion vessel ~ 30 ml.
4) Injection Syringe (one for each sample site where samples are to be collected).
5) Syringe filters – (note filter composition in notebook).
    a) 5 μm – Nylon (optional filtration step)
    b) 0.45 μm cellulose acetate filter.
    c) 0.02 μm – alumina (optional filtration step).
6) Pre-cleaned opaque glass bottle for organic carbon sample is desired.
    a) 0.45 μm glass-wool filter (non-organic filter for organic carbon analysis).
7) Items #1 through 6 should be placed in a clean plastic zip-lock bag to prevent inadvertent contamination in the field. One individual packet should be prepared for each sampling site. All vessels should be prelabled in the lab if field locations are known, otherwise labeled in the field.
8) Large carboys for collection and preservation of water samples for future laboratory testing.
9) Clear flow-through cell for *in situ* water measurement on well testing
10) Large graduated cylinder (if flow rate information is desired)
11) Stopwatch
12) Portable field table
13) Disposable table covers
14) Latex gloves, non-powdered
15) 1000 ml pipette and pipette tips
16) Deionized water in squirt bottles
17) Kim-wipes
18) Data log sheets
19) Ice and ice chest if organic carbon and/or volatile components are to be analyzed upon return to the laboratory.
20) Clean spatula
21) Trash bags
22) *In situ* or on-site sampling equipment (calibrated as per manufacturer instructions but a minimum of calibration prior to use and a field check with standard as unknown between each sample for *in situ* testing)
    a) HACH alkalinity kit
    b) HACH hardness kit. Calcium and total (Ca + Mg) hardness measurement.
    c) Conductivity meter + appropriate calibration standards
    d) pH-Eh meter + appropriate calibration standards
    e) Dissolved oxygen probe

   f) Water turbidity meter
   g) Digital thermometer
   h) Extra batteries for all previously listed instruments

MATERIALS NEEDED FOR LABORATORY PREPARATION OF SAMPLES

1) High purity nitric acid (Ultrex).
2) Pipette, pipette tips

VESSEL CLEANING PROCEDURE

1) Wash sample vessels with a dilute soap solution of phosphate free detergent.
2) Rinse thoroughly with tap water.
3) Fill vessel with 3 to 5% HNO_3 solution and soak for 30 minutes.
4) Rinse three times with ASTM Type I water. Discard water.
5) Fill vessels with ASTM Type I water and place in 90°C oven overnight.
6) Remove vessels and dispose of water.
7) Rinse with ASTM Type I water and discard water.
8) Place vessels in 90°C oven to dry for ½ hour.
9) Remove vessels from oven, allow to cool, and then screw on vessel caps.
10) Label the 1000 ml PE vessel according to sample field location; label 125 and 30 ml PE vessels according to sample field location and sample filtration type. These will include: **a)** unfiltered sample, **b)** 5 μm filtered sample, **c)** 0.45 μm filtered sample, **d)** 0.02 μm filtered sample, and **e)** filtered sample for anion analysis.
11) Determine the tare weights for all 125 ml vessels to be used for **a)** unfiltered sample, **b)** 5 μm filtered sample, **c)** 0.45 μm filtered sample, and **d)** 0.02 μm filtered sample. Record weights on vessel and in notebook.
12) Also label a small plastic bag (to hold filters) with sample field location.
13) Store all vessels and filters in a labeled zip lock plastic bag until needed.

WATER SAMPLING PROCEDURE

1) <u>Water Collection Process</u>

   Samples should be collected in an appropriate manner as to be representative of the bulk water conditions. Details on water sampling should be recorded in log book/log sheets. Water should be collected into precleaned one liter bottle for field sampling and the one liter bottle plus larger carboys for return to the laboratory.

   a) For water sampling from wells: The water sampling procedure outlined here will follow the general spirit (although is not identical) to the procedure entitled “Low Stress (low flow) Purging and Sampling Procedure for the Collection of Ground Water Samples from Monitoring Wells” U.S. Environmental Protection Agency, July 30, 1996, Revision 2. Low pumping rates will be used to minimize drawdown in the well to less than 0.3 feet and indicator parameters such as turbidity and pH should be stabilized as much as possible (although gas loss following pressure change may prevent a completely stable reading).

b) Stream sampling sites should be selected upstream of bridges, boat ramps, tributaries, etc. to avoid local point sources of contamination and poorly mixed stream conditions. Locations should also be chosen to avoid unusually fast moving water (riffles, rapids, falls) and slow moving water (stagnant pools). Collect stream water sample using isokinetic sampler, being careful to avoid collecting sediment material being transported along bottom and floating material on the water surface.

2) Water Filtering Process

Filtered water samples should be processed as in the field, as soon as possible after collection to minimize the transfer of chemical constituents between the fluid and particulate phases. Temperature change and loss of gasses may induce these potential transfers. Once samples are filtered, they may be kept on ice if potentially volatile components (e.g., Hg, organics) are to be analyzed. Samples should not iced or allowed to warm before filtering. Appropriate quality assurance samples should also be obtained including a field triplicate minimum one per day and one for every 10 sampling sites, lab blanks (with DIW), trip blanks (with DIW processed at field site), and a field sample for a matrix spike.

a) Collect water sample in the one liter bottle and allow water to sit undisturbed for 20 seconds to all sediment particles >0.125 mm diameter (fine sand and larger particles) to settle to the bottom of the vessel. Any particles floating on the surface should also be discarded at this time by pouring from the surface or using a spatula.

b) Decant ~125 ml of solution from the 1000 ml PE vial into the 125 mL vessel for unfiltered analysis and close vessel lid.

c) (optional) Attach 5 μm syringe filter to syringe, pour water from 1000 ml PE vial into syringe until full. Inject water through filter, discarding first few ml of solution. Continue to inject water through syringe into the 125 ml PE collection vessel. A minimum of 25 ml of solution must be collected; filling to near capacity – but not total capacity is best. Save spent filter by placing into plastic bag.

d) You may reuse the same injection syringe, attach the 0.45 μm cellulose acetate syringe filter and repeat the injection procedure starting with 2c as described above.

e) You may reuse the same injection syringe and reuse the cellulose acetate 0.45 μm syringe filter to collect the solution for anion analysis in the 30 ml vial.

f) (optional) You may reuse the same injection syringe again, attach the 0.02 μm syringe filter and repeat the injection procedure starting with 2c as described above. Note: if water contains a large amount of suspended sediment it may be necessary to use more than one 0.02 μm filter. Blockage of filters will likely affect pore size - record procedure in notebook.

g) (optional) Filter and collect organic carbon sample in opaque glass vial using 0.45 μm glass-wool filter. Organic carbon sample should be placed on ice immediately after collection and kept refrigerated until analysis is completed.

3) *In Situ* and *Ex Situ* Field Measuring Processes

a) The alkalinity analysis should performed in the field, as rapidly as possible after water collection to avoid potential loss of CO_2 from a system. Use HACH alkalinity field kit for testing. If field conditions prevent immediate testing then decant ~125 ml of solution into the vessel for return to lab. This vessel should be filled with water to the top to remove as much air head space as possible. The eventual measurement temperature should be kept as close to the water collection temperature as possible – both should be recorded.

b) Hardness (Ca and Total Ca+Mg) testing. The preference for immediate field testing is still desired, but not as critical as for alkalinity testing.
c) Measure conductivity of free flowing water *in situ*.
d) Measure pH, Eh, dissolved oxygen, and temperature of water *in situ*. Flow-through chamber may be used in well testing after establishing steady state flow. Since water chemistry may change with gas loss and temperature change, some pH variability may be expected. Rapidly moving water may also inhibit a proper measurement for pH. If necessary, water should be collected in a separate vessel and analyzed as soon as possible after collection. Repeat measurements three to five minutes to confirm stable conditions.
e) Collect pipette water sample into glass vial for turbidity measurement.

4) <u>Laboratory Water Collection and Flow Rate Measurement</u>
   a) Drain the previously used 1000 ml PE vessel. Refill completely with water from the same location and screw cap on tightly. This solution will be brought back to the laboratory and used for any additional desired analyses (e.g., TDS, TSS).
   b) Use stopwatch combined with graduated cylinder for low flow conditions, or carboy with known volume for higher flow conditions to measure water flow rate from well.
   c) Fill carboy with well water and transport back to laboratory.

RETURN TO LABORATORY

1) Record weights of all 125 ml vessels (vessel plus collected water). Data should be recorded on vessels and in notebook.
2) Acidify all 125 ml vessels for cation analysis with Ultrex HNO_3. Add HNO_3 to the vessels in an amount equivalent to 0.2 wt % of the vessel contents. For example, for 125 ml solution we would add 0.25 ml of HNO_3. We can add the same amount of HNO_3 to all vessels if their weights are approximately similar. The goal is to produce a solution with a pH value of approximately two or lower. This will prevent metals from precipitating out of solution prior to chemical analysis (Note for highly alkaline solutions pH > 9, acidification may induce the precipitation of silica colloids). Samples for anions and organic carbon analysis should NOT be acidified.
3) Reweigh the 125 ml vessels again after the addition of HNO_3. Record weights on vessel and log sheet.
4) Perform TSS and TDS analyses if desired.
5) Place organic samples in refrigerator until analysis is performed.

Date:

Site ID:

Time:

GPS Location of Van:
Acc:
Elevation:
UTM:

GPS Location of Site:
Acc:
Elevation:
UTM:

Air Temperature: _ Alkalinity: _ Type:
____

Water Temperature: _ Total Hardness: _

pH:_ Ca Hardness:_

Conductivity: _ Eh mV _

Turbidity: _ Dissolved Oxygen: _

_ Water Samples collected and filtered (list here)

_ Heavy sediments collected (list here)

_ Sieved Sediments collected (list here)

_ Area clean before leaving

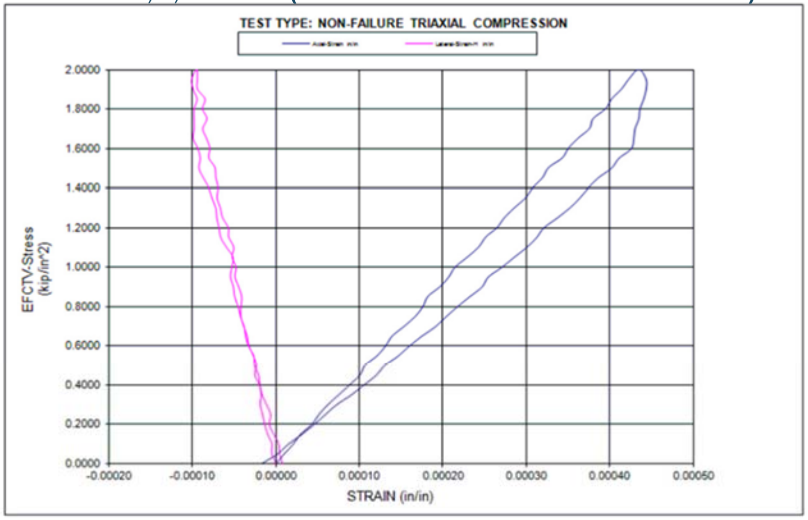
Notes about site:

Description of water flow conditions; flow rate, turbidity, flooding, etc.:

Recent weather (precipitation etc.) that may have altered flow conditions

APPENDIX 5 B STRESS STRAIN CURVES - GEOMECHANICS TESTING

FIGURE B-1: ID 8V, 2,024.00 FT (DAVIS FORMATION STRESS-STRAIN CURVE)

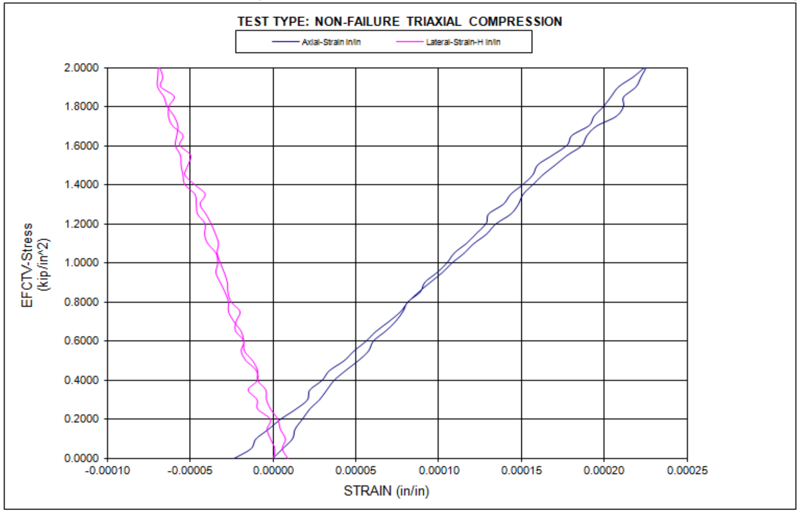


Date/ID: 13071501
A.P.I. Number:
Well Name: Thomas Hill Well No. 2
Trust/Field: 8V
Province/Area/County:
Country/State:
Formation: Davis Shale
Sample Length (inches): 1.6555
Sample Diameter (inches): 0.9965
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 0.846

Young's Modulus (1E6): 4.561
Poisson's Ratio: 0.222
Ultimate EFCTV-Stress (kip/in^2): 2.0003
Ultimate Axial-Strain (in/in): 0.00043472
Ultimate Lateral-Strain (in/in): -0.00009500
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.301
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000032
Depth (feet): 2024.00
Axial Transducer Length (inches): 0.500

FIGURE B-2: ID 18V, 2,120.00 FT (BONNETERRE FORMATION STRESS-STRAIN CURVE)

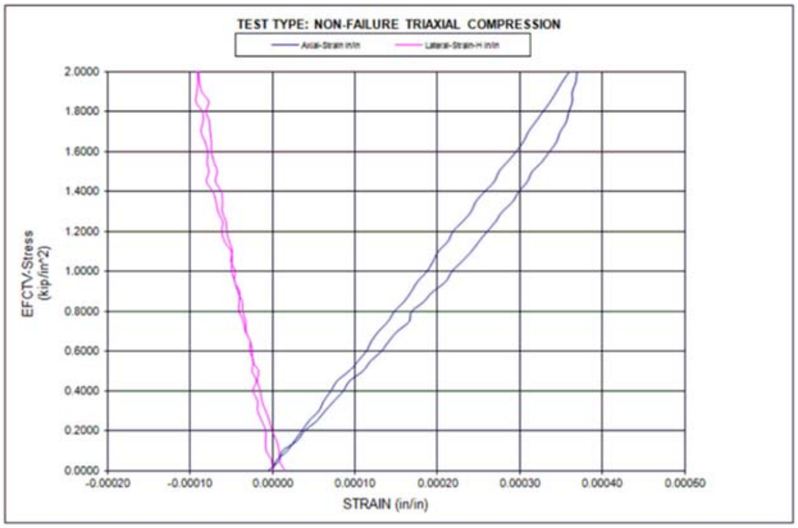


Date/ID: 13071701
A.P.I. Number:
Well Name: Thomas Hill Well No. 2
Trust/Field: 18V
Province/Area/County:
Country/State:
Formation: Bonneterre
Sample Length (inches): 1.4735
Sample Diameter (inches): 0.9970
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 1.199

Young's Modulus (1E6): 9.433
Poisson's Ratio: 0.309
Ultimate EFCTV-Stress (kip/in^2): 1.9994
Ultimate Axial-Strain (in/in): 0.00022475
Ultimate Lateral-Strain (in/in): -0.00006902
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.303
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000026
Depth (feet) - ID: 2120.00
Axial Transducer Length (inches): 0.500

FIGURE B-3: ID 35V, 2,282.00 FT (BONNETERRE FORMATION STRESS-STRAIN CURVE)

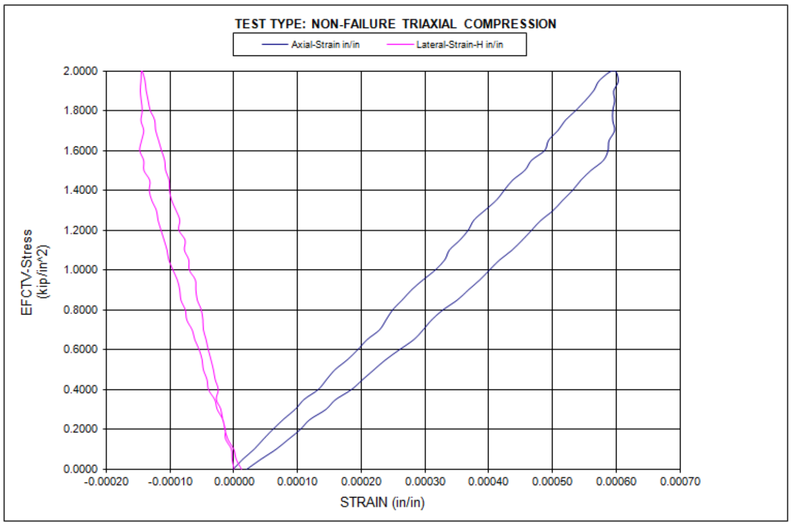


Date/ID: 13100301
A.P.I. Number:
Well Name: Thomas Hill Well No. 2
Trust/Field: 35V
Province/Area/County:
Country/State:
Formation: Bonneterre
Sample Length (inches): 1.4745
Sample Diameter (inches): 0.9975
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 0.912

Young's Modulus (1E6): 5.282
Poisson's Ratio: 0.241
Ultimate EFCTV-Stress (kip/in^2): 2.0492
Ultimate Axial-Strain (in/in): 0.00037705
Ultimate Lateral-Strain (in/in): -0.00009147
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.301
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000032
Depth (feet) - ID: 2282.00
Axial Transducer Length (inches): 0.500

FIGURE B-4: ID 40V, 2,327.00 FT (BONNETERRE FORMATION STRESS-STRAIN CURVE)

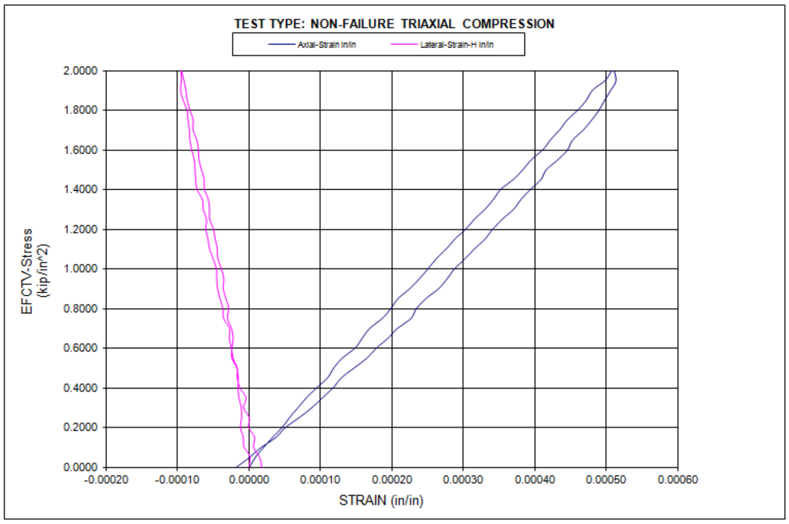


Date/ID: 13101001
A.P.I. Number:
Well Name: Thomas Hill Well No. 2
Trust/Field: 40V
Province/Area/County:
Country/State:
Formation: Bonneterre
Sample Length (inches): 1.3215
Sample Diameter (inches): 0.9970
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 0.613

Young's Modulus (1E6): 3.173
Poisson's Ratio: 0.210
Ultimate EFCTV-Stress (kip/in^2): 2.0016
Ultimate Axial-Strain (in/in): 0.00059589
Ultimate Lateral-Strain (in/in): -0.00014452
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.302
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000045
Depth (feet) - ID: 2327.00
Axial Transducer Length (inches): 0.500

FIGURE B-5: ID 44V, 2,362.00 FT (LAMOTTE SANDSTONE STRESS-STRAIN CURVE)

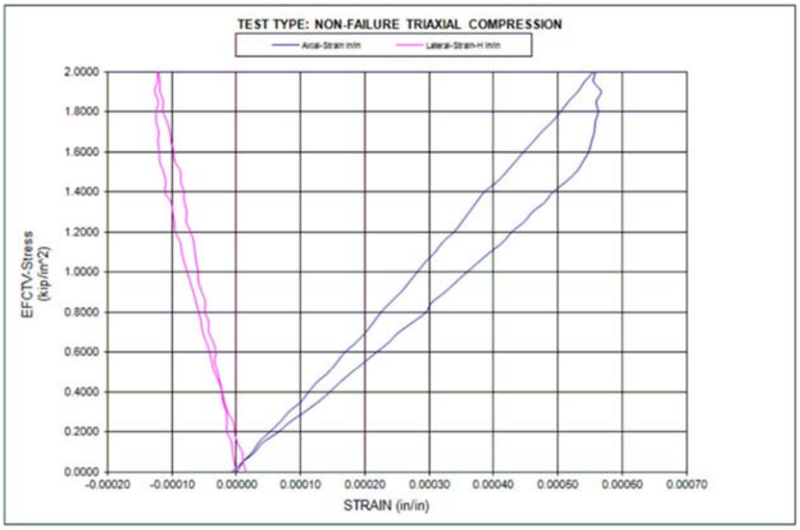


Date/ID: 13100201
A.P.I. Number:
Well Name: Thomas Hill Well No. 2
Trust/Field: 44V
Province/Area/County:
Country/State:
Formation: Lamotte
Sample Length (inches): 1.4590
Sample Diameter (inches): 0.9950
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 0.931

Young's Modulus (1E6): 3.939
Poisson's Ratio: 0.145
Ultimate EFCTV-Stress (kip/in^2): 2.0008
Ultimate Axial-Strain (in/in): 0.00050865
Ultimate Lateral-Strain (in/in): -0.00009476
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.303
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000041
Depth (feet) - ID: 2362.00
Axial Transducer Length (inches): 0.500

FIGURE B-6: ID 51T, 2,429.00 FT (LAMOTTE SANDSTONE STRESS-STRAIN CURVE)

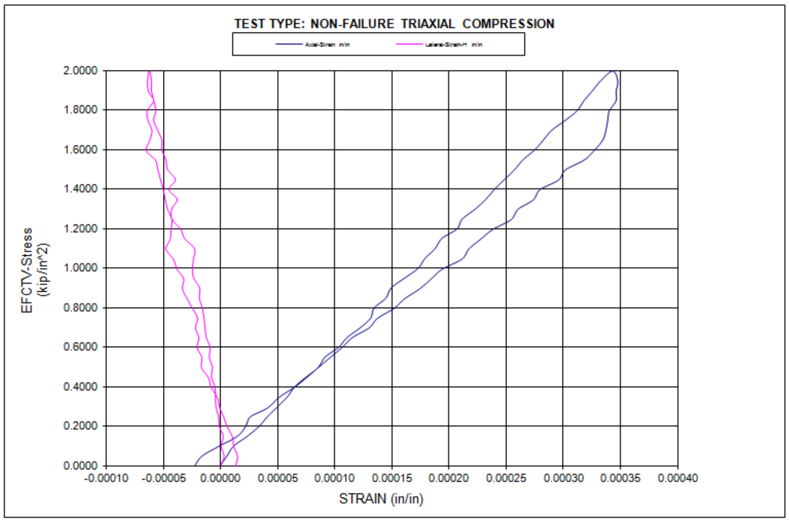


Date/ID: 13100401
A.P.I. Number:
Well Name: Thomas Hill Well No. 2
Trust/Field: 51T
Province/Area/County:
Country/State:
Formation: Lamotte
Sample Length (inches): 1.4975
Sample Diameter (inches): 0.9964
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 0.682

Young's Modulus (1E6): 3.481
Poisson's Ratio: 0.206
Ultimate EFCTV-Stress (kip/in^2): 2.0014
Ultimate Axial-Strain (in/in): 0.00055745
Ultimate Lateral-Strain (in/in): -0.00012132
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.302
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000038
Depth (feet) - ID: 2429.00
Axial Transducer Length (inches): 0.500

FIGURE B-7: ID 55V, 2,468.0 FT (LAMOTTE SANDSTONE STRESS-STRAIN CURVE)

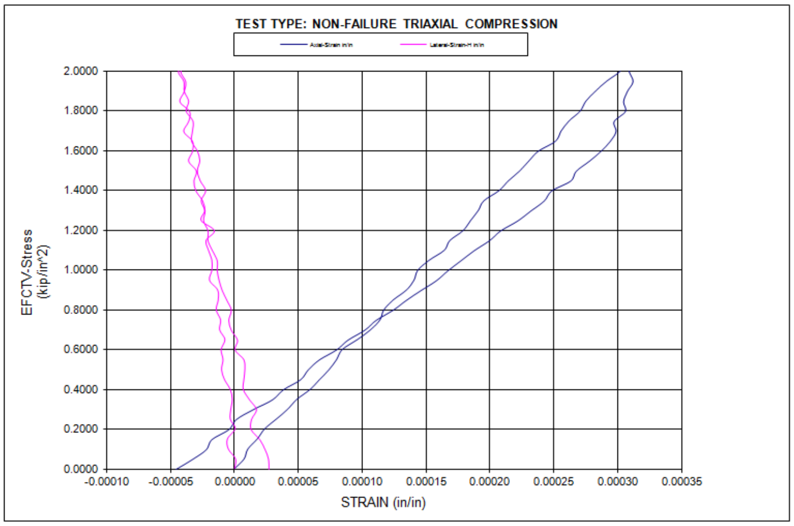


Date/ID: 13071101
A.P.I. Number:
Well Name: Thomas Hill Well No. 2
Trust/Field: 55V
Province/Area/County:
Country/State:
Formation: Lamotte
Sample Length (inches): 1.7185
Sample Diameter (inches): 0.9975
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 1.341

Young's Modulus (1E6): 5.765
Poisson's Ratio: 0.151
Ultimate EFCTV-Stress (kip/in^2): 1.9995
Ultimate Axial-Strain (in/in): 0.00034304
Ultimate Lateral-Strain (in/in): -0.00006251
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.301
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000027
Depth (feet): 2468.00
Axial Transducer Length (inches): 0.500

FIGURE B-8: ID 63A, 2,539.0 FT (LAMOTTE SANDSTONE STRESS-STRAIN CURVE)

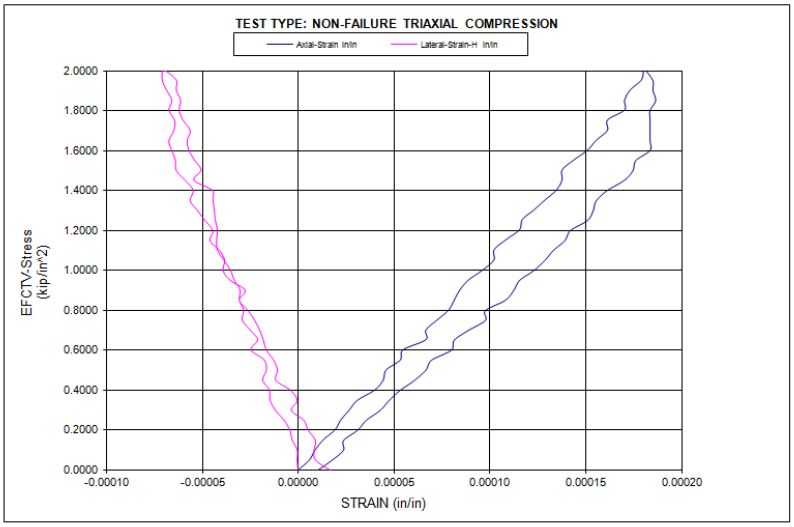


Date/ID: 13071001
A.P.I. Number:
Well Name: Thomas Hill Well No. 2
Trust/Field: 63A
Province/Area/County:
Country/State:
Formation: Lamotte
Sample Length (inches): 1.8080
Sample Diameter (inches): 0.9965
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 1.692

Young's Modulus (1E6): 6.612
Poisson's Ratio: 0.116
Ultimate EFCTV-Stress (kip/in^2): 2.0511
Ultimate Axial-Strain (in/in): 0.00030756
Ultimate Lateral-Strain (in/in): -0.00003853
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.301
Pore Pressure (kip/in^2): -0.003
Strain Rate (strain/second): 0.00000016
Depth (feet): 2539.00
Axial Transducer Length (inches): 0.500

FIGURE B-9: ID 3H, 2,929.80 FT (DERBY-DOERUN FORMATION STRESS-STRAIN CURVE)

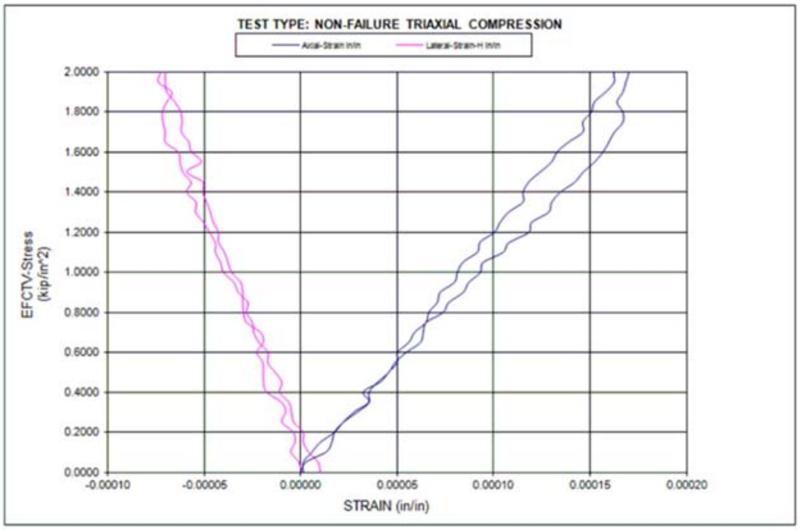


Date/ID: 13100801
A.P.I. Number:
Well Name: Sioux Power Plant Well
Trust/Field: 3H
Province/Area/County:
Country/State:
Formation: Derby Doe Run
Sample Length (inches): 1.3695
Sample Diameter (inches): 0.9920
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 0.805

Young's Modulus (1E6): 10.380
Poisson's Ratio: 0.384
Ultimate EFCTV-Stress (kip/in^2): 1.9996
Ultimate Axial-Strain (in/in): 0.00018039
Ultimate Lateral-Strain (in/in): -0.00007014
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.302
Pore Pressure (kip/in^2): -0.003
Strain Rate (strain/second): 0.00000016
Depth (feet) - ID: 2929.80
Axial Transducer Length (inches): 0.500

FIGURE B-10: ID 16H, 3,300.70 FT (DAVIS FORMATION STRESS-STRAIN CURVE)

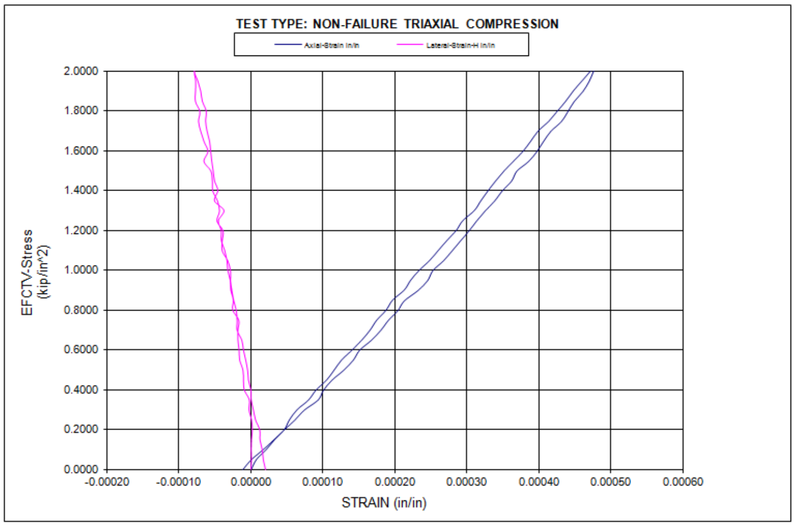


Date/ID: 13100701
A.P.I. Number:
Well Name: Sioux Power Plant Well
Trust/Field: 16H
Province/Area/County:
Country/State:
Formation: Davis Shale
Sample Length (inches): 1.3445
Sample Diameter (inches): 0.9955
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 0.548

Young's Modulus (1E6): 12.318
Poisson's Ratio: 0.433
Ultimate EFCTV-Stress (kip/in^2): 2.0508
Ultimate Axial-Strain (in/in): 0.00016856
Ultimate Lateral-Strain (in/in): -0.00007065
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.302
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000013
Depth (feet) - ID: 3300.70
Axial Transducer Length (inches): 0.500

FIGURE B-11: ID 28H, 3,460.00 FT (BONNETERRE/LAMOTTE TRANSITION ZONE STRESS-STRAIN CURVE)

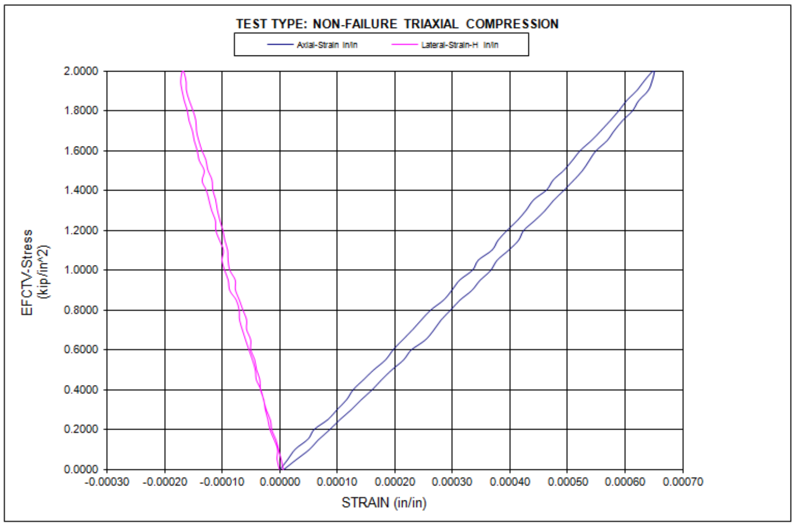


Date/ID: 13071601
A.P.I. Number:
Well Name: Sioux Power Plant Well
Trust/Field: 28H
Province/Area/County:
Country/State:
Formation: Bonterre/Lamotte Transition
Sample Length (inches): 1.4725
Sample Diameter (inches): 0.9990
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 0.984

Young's Modulus (1E6): 4.203
Poisson's Ratio: 0.149
Ultimate EFCTV-Stress (kip/in^2): 2.0507
Ultimate Axial-Strain (in/in): 0.00048203
Ultimate Lateral-Strain (in/in): -0.00007535
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.300
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000059
Depth (feet) - ID: 3460.00
Axial Transducer Length (inches): 0.500

FIGURE B-12: ID 31H, 3,476.10 FT (BONNETERRE/LAMOTTE TRANSITION ZONE STRESS-STRAIN CURVE)

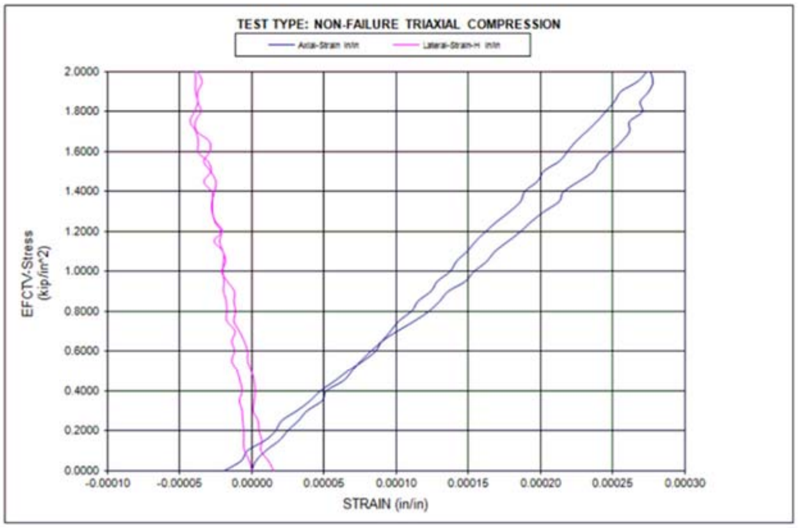


Date/ID: 13071901
A.P.I. Number:
Well Name: Sioux Power Plant Well
Trust/Field: 31H
Province/Area/County:
Country/State:
Formation: Bonterre/Lamotte Transition
Sample Length (inches): 1.4700
Sample Diameter (inches): 0.9965
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 0.492

Young's Modulus (1E6): 2.986
Poisson's Ratio: 0.253
Ultimate EFCTV-Stress (kip/in^2): 2.0014
Ultimate Axial-Strain (in/in): 0.00064912
Ultimate Lateral-Strain (in/in): -0.00016902
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.305
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000097
Depth (feet) - ID: 3476.10
Axial Transducer Length (inches): 0.500

FIGURE B-13: ID 34T, 3,500.50 FT (LAMOTTE SANDSTONE STRESS-STRAIN CURVE)

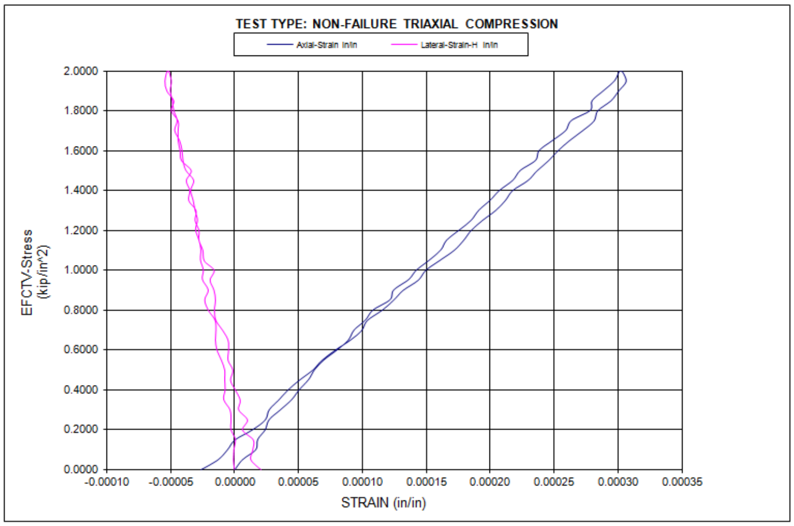


Date/ID: 13072301
A.P.I. Number:
Well Name: Sioux Power Plant Well
Trust/Field: 34T
Province/Area/County:
Country/State:
Formation: Lamotte
Sample Length (inches): 1.4720
Sample Diameter (inches): 0.9950
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 1.726

Young's Modulus (1E6): 7.143
Poisson's Ratio: 0.137
Ultimate EFCTV-Stress (kip/in^2): 2.0029
Ultimate Axial-Strain (in/in): 0.00027503
Ultimate Lateral-Strain (in/in): -0.00003897
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.304
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000025
Depth (feet) - ID: 3500.50
Axial Transducer Length (inches): 0.500

FIGURE B-14: 35B, 3,504.80 FT (LAMOTTE SANDSTONE STRESS-STRAIN CURVE)

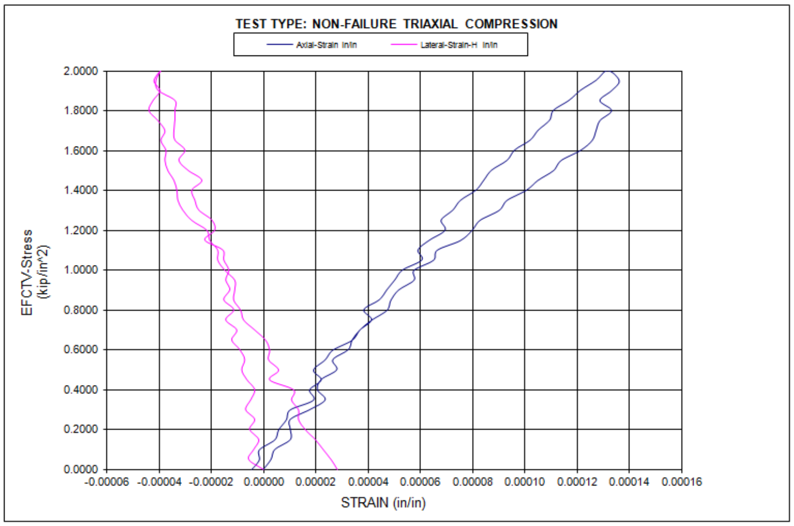


Date/ID: 13072601
A.P.I. Number:
Well Name: Sioux Power Plant Well
Trust/Field: 35B
Province/Area/County:
Country/State:
Formation: Lamotte
Sample Length (inches): 1.4700
Sample Diameter (inches): 0.9935
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 1.433

Young's Modulus (1E6): 6.972
Poisson's Ratio: 0.192
Ultimate EFCTV-Stress (kip/in^2): 2.0002
Ultimate Axial-Strain (in/in): 0.00030164
Ultimate Lateral-Strain (in/in): -0.00005243
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.301
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000039
Depth (feet) - ID: 3504.80
Axial Transducer Length (inches): 0.500

FIGURE B-15: ID 36T, 3,510.4FT (LAMOTTE SANDSTONE STRESS-STRAIN CURVE)

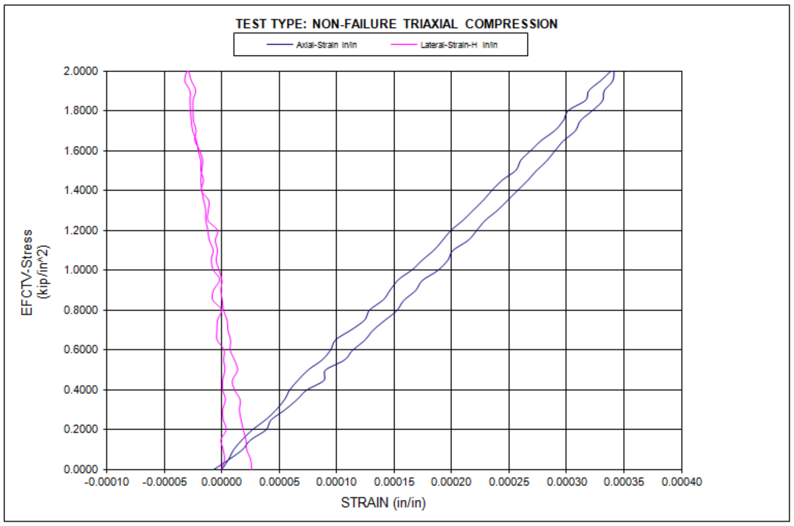


Date/ID: 13100901
A.P.I. Number:
Well Name: Sioux Power Plant Well
Trust/Field: 49T
Province/Area/County:
Country/State:
Formation: Lamotte
Sample Length (inches): 1.3525
Sample Diameter (inches): 0.9965
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 3.067

Young's Modulus (1E6): 18.989
Poisson's Ratio: 0.258
Ultimate EFCTV-Stress (kip/in^2): 2.0003
Ultimate Axial-Strain (in/in): 0.00013160
Ultimate Lateral-Strain (in/in): -0.00003930
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.305
Pore Pressure (kip/in^2): -0.003
Strain Rate (strain/second): 0.00000008
Depth (feet) - ID: 3576.50
Axial Transducer Length (inches): 0.500

FIGURE B-16: ID 44B, 3,547.00 FT (LAMOTTE SANDSTONE STRESS-STRAIN CURVE)

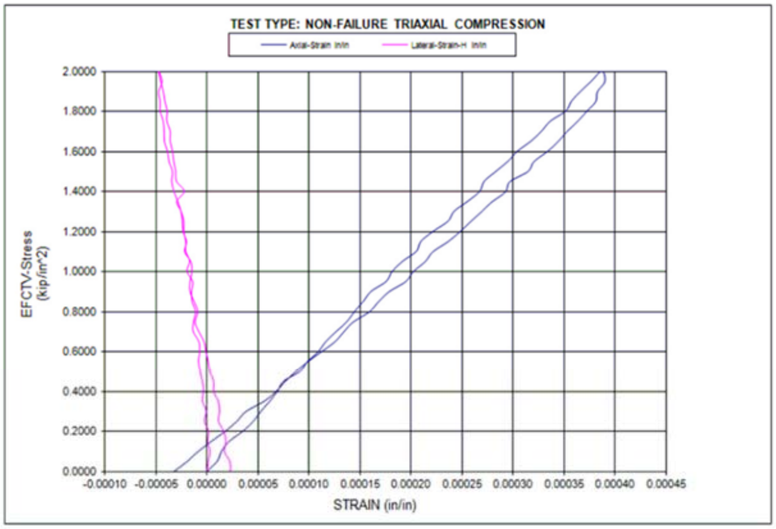


Date/ID: 13071801
A.P.I. Number:
Well Name: Sioux Power Plant Well
Trust/Field: 56B
Province/Area/County:
Country/State:
Formation: Lamotte
Sample Length (inches): 1.4680
Sample Diameter (inches): 0.9935
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 1.782

Young's Modulus (1E6): 5.949
Poisson's Ratio: 0.051
Ultimate EFCTV-Stress (kip/in^2): 2.0013
Ultimate Axial-Strain (in/in): 0.00034009
Ultimate Lateral-Strain (in/in): -0.00002985
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.303
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000040
Depth (feet) - ID: 3597.20
Axial Transducer Length (inches): 0.500

FIGURE B-17: ID 49T, 3,576.50 FT (LAMOTTE SANDSTONE STRESS-STRAIN CURVE)

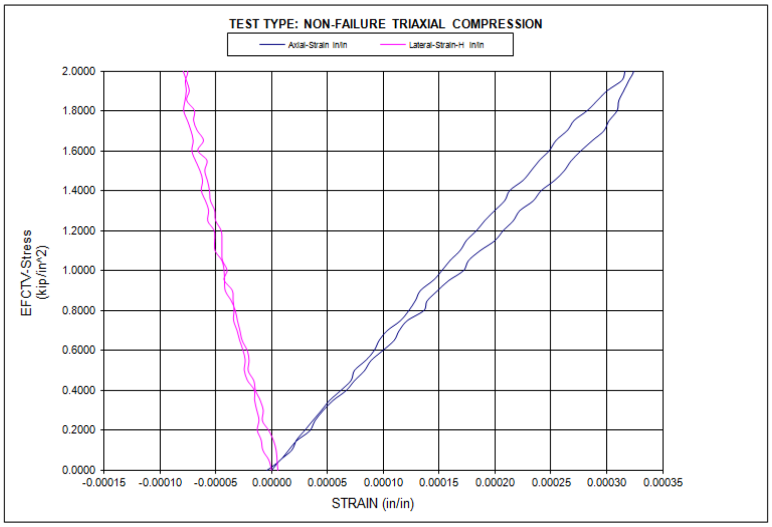


Date/ID: 13072501
A.P.I. Number:
Well Name: Sioux Power Plant Well
Trust/Field: 36T
Province/Area/County:
Country/State:
Formation: Lamotte
Sample Length (inches): 1.4700
Sample Diameter (inches): 0.9925
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 1.406

Young's Modulus (1E6): 5.432
Poisson's Ratio: 0.112
Ultimate EFCTV-Stress (kip/in^2): 2.0009
Ultimate Axial-Strain (in/in): 0.00038740
Ultimate Lateral-Strain (in/in): -0.00004750
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.302
Pore Pressure (kip/in^2): -0.002
Strain Rate (strain/second): 0.00000035
Depth (feet) - ID: 3510.40
Axial Transducer Length (inches): 0.500

FIGURE B-18: ID 56B, 3,597.20 FT (LAMOTTE SANDSTONE STRESS-STRAIN CURVE)



Date/ID: 13072201
A.P.I. Number:
Well Name: Sioux Power Plant Well
Trust/Field: 44B
Province/Area/County:
Country/State:
Formation: Lamotte
Sample Length (inches): 1.4685
Sample Diameter (inches): 0.9905
Sample Environment: Native State
Sample Orientation: Horz

Bulk Modulus (1E6): 1.054

Young's Modulus (1E6): 6.606
Poisson's Ratio: 0.261
Ultimate EFCTV-Stress (kip/in^2): 2.0514
Ultimate Axial-Strain (in/in): 0.00032086
Ultimate Lateral-Strain (in/in): -0.00008137
Temperature (degrees f): 69
Confining Pressure (kip/in^2): 2.304
Pore Pressure (kip/in^2): -0.003
Strain Rate (strain/second): 0.00000029
Depth (feet) - ID: 3547.00
Axial Transducer Length (inches): 0.500

CHAPTER VI - CARBON SEQUESTRATION FOR MISSOURI

A. Overview

The four exploratory drilling sites, shown in Figure 6.1, were selected for their proximity to sponsors' generating stations and to provide good areal distribution. The sites also provide good distribution among the various geologic settings in Missouri and fill an important gap in the Department Of Energy national carbon sequestration database. Exploratory Borehole No. 1 was sited at CU's John Twitty Energy Center in Springfield, on the western flank of the Ozark Dome. Exploratory Borehole No. 2 was sited at AECI'S Thomas Hill Energy Center near Moberly, on the Dissected Till Plains. Borehole No. 3 was sited at KCP&L's Iatan Generating Station near Weston in the Forest City Basin. Borehole No. 4 was sited near Ameren Missouri's Sioux Power Plant in Florissant close to the Lincoln Fold/Florissant Dome complex.

FIGURE 6.1 - EXPLORATORY DRILLING SITES

B. Summary of Results from Each Site

1. John Twitty Energy Center – Exploratory Borehole No. 1

The first borehole was extended to Precambrian basement rock at John Twitty Energy Center (JTEC). JTEC is located on the Springfield Plateau, which is topographically and stratigraphically one of the highest areas of the state. Although the elevation of the top of casing was the highest of the four boreholes, the elevation of target formation was also the highest. This is due, in large part, to the Ozark Dome being an asymmetrical, elongated dome with an axis that extends from the St. Francois Mountains through the Springfield area. Structurally, the drilling site is located between two northwest- southeast trending structural features - the Sac River-Battlefield Graben and the Fassnight Fault. Based on surrounding well logs, a small local anticline may be present in the subsurface. The regional dip, measured at the top of the Elvins Group (Derby-Doerun Dolomite and Davis Formation) is approximately 4 m/km (20 feet per mile) to the northeast.

Elevation at the top of the surface casing for this borehole was 376.830 m (1,236.32 feet) above mean sea level (msl). The St. Francois confining unit (Derby-Doerun and Davis Formations) was encountered at a depth of 459.3 m (1,507 feet), and had a measured thickness of 59.1 m (194 feet). The St. Francois Aquifer (Bonneterre Formation and Lamotte Sandstone) was encountered at a depth of 518.5 (1,701 feet) and had a measured thickness of 135.9 m (446 feet). Precambrian basement rock was encountered at a depth of 654.4 m (2,147 feet). The borehole was advanced through the Precambrian weathered zone to a total depth of 666.3 m (2,186 feet). For purposes of reservoir calculations, the weathered Precambrian basement rock may be considered to be part of the target formation.

The vertical conductivity of the confining unit was calculated by the MSU research team to be 1.0E-13 m/sec, which is approximately equivalent to a permeability of 1E-5 millidarcies. This is an extraordinarily low value, meaning that these formations form a highly effective seal between the target formation and the overlying strata. The target formation included four different stratigraphic units with varying permeability. Two sandstones (an upper sand unit and a lower sand unit, both within the Lamotte Formation) are separated by dolomitic silts and shales. The upper sand unit is approximately 30 m (100 feet) thick, while the lower sand unit is approximately 50 m (160 feet) thick, and the intervening silts and shales are approximately 34 m (110 feet) thick. The well bore was completed to a depth of approximately 12 m (40 feet) beneath the Lamotte Formation within a jointed granite.

Pumping tests were conducted to determine the conductivity of the stratigraphic units. The upper sand unit was found to have a hydraulic conductivity of 1.2E-6 m/sec, which is approximately equivalent to a permeability of 125 millidarcies. The lower sand unit/granite was found to have a hydraulic conductivity of 1E-7 m/sec; approximately one tenth that of the upper sand unit. Therefore, most of the permeability within the target formation at this site appears to be concentrated within the upper sand unit.

The Missouri S&T team conducted numerous reservoir simulations for the JTEC site in an effort to identify the potential of the Lamotte Sandstone for carbon sequestration. Rock mechanics tests and pressure injection tests conducted by researchers at Missouri S&T provided key values of Young's Modulus, Poisson's ratio, breakdown pressure and minimum in-situ stress. Findings from these tests enabled an estimation of the carbon sequestration potential for this site. Based on an 800m x 800m reservoir, and allowing for 5-spot water withdrawal, an injection rate of 60 m^3/day is feasible with a total CO_2 storage capacity of 2.55 X 10^5 metric tons over 15.8 years. This estimate includes displacement of water in the pore space and CO_2 solubility trapping, but does not include mineral trapping due to the long time characteristic of that process.

The Missouri S&T team also conducted water quality analysis of target formation water, and found Total Dissolved Solids (TDS) to average 159.1 mg/L in the upper sand unit and 226.5 mg/L in the lower sand unit. Since these values are well below the 10,000 mg/L threshold, the St. Francois Aquifer beneath the JTEC site would be classified as an Underground Source of Drinking Water (USDW), which would exclude any disposal or storage injection by federal law. This finding terminated any additional work at the JTEC site and led to rescoping the project as a state-wide assessment of carbon sequestration feasibility.

2. Thomas Hill Energy Center – Exploratory Borehole No. 2

The second borehole was extended to Precambrian basement rock at AECI's Thomas Hill Energy Center (THEC). THEC is located in the Dissected Till Plains physiographic province of rural north-central Missouri and is comprised of three electrical units, built from 1966 to 1982 and totaling 1,153 megawatts, and a coal mine that is actively being reclaimed after closing in 1993. AECI owns approximately 14,000 hectares (35,000 acres) at the site.

Structurally, the drilling site is located between two regional features; the College Mound-Bucklin and Salisbury-Quitman anticlines. The axis of the College Mound–Bucklin anticline is located 10 km (six miles) to the northeast of the site and is a northwest-southeast trending anticline that plunges to the northwest. The axis of the Salisbury–Quitman anticline is located 20 km (12 miles) to the southwest of the site. This anticline also is gently plunging to the northwest. Between these regional structures are numerous small faults; the Thomas Hill fault, Hubbard fault, Prairie Hill Cemetery fault, Middle Fork Little Chariton River fault, Dark Creek fault. The regional dip of the top of the Derby–Doerun Dolomite is approximately 2 m/km (11 feet per mile) to the northwest.

Elevation at the top of the surface casing for this borehole was 240.92 m (790.41 feet) msl. The St. Francois Confining Unit (Derby-Doerun and Davis Formations) was encountered at a depth of 547.8 m (1,797 feet), and had a measured thickness of 88.4 m (290 feet). The St. Francois Aquifer (Bonneterre Formation and Lamotte Sandstone) was encountered at a depth of 636.1 m (2,087 feet) and had a measured thickness of 138 m (453 feet). Precambrian basement rock was encountered at a depth of 774.2 m (2,540 feet). The borehole was advanced through the Precambrian weathered zone to a total depth of 785.5 m (2,577) feet.

MSU personnel conducted a 24-hour single-well pumping test at the Thomas Hill site to determine the characteristics of the target formation. The transmissivity and hydraulic conductivity of the target formation were calculated by the MSU research team to average 1.8E- 5 m2/sec and 3.0E-7 m/sec, respectively. Because no individual pressure testing was conducted at the Thomas Hill site, only a bulk analysis of permeability of the entire target formation can be developed. Therefore, no injection rate profile is available for this site based on the research activities.

The Missouri S&T research team conducted laboratory analysis of confining unit and target formation core samples to determine porosity and permeability. Core analysis of the confining unit indicated a range of permeability from less than one microdarcy to 3 millidarcies. Two samples, at 631.2 m (2,071 feet) and 637.9 m (2,093) feet, exhibited permeability of one microdarcy or less. The vertical permeability was measured by rotating core samples and indicated very low (<.001 millidarcies) vertical permeability from 631.2 m to 646.2 m (2,071 feet to 2,120 feet). Average porosity for the confining unit was approximately 6%, with a range of 0.2% to 12.9%. Average core porosity for the target formation was 10.8% with a range of 8.6% to over 13%. The permeability was high throughout the target formation, and averaged 47 millidarcies with a range of 5.7 millidarcies to 307 millidarcies.

Porosities calculated from the geophysical well logs were compared to core laboratory measurements and found to be in good agreement. Well logs confirm there is a low porosity zone in the Davis Formation from approximately 631.2 m to 646.2 m (2,071 to 2,120 ft). This zone corresponds with a low permeability zone (<.001 millidarcies). The Davis Formation in the THEC borehole is similar to that found in the JTEC borehole, and appears to offer similar potential as a seal for CO2 sequestration. The Lamotte Sandstone in the Thomas Hill borehole has approximately a 36 m (120 foot) section with average core porosity of 10.8%. Although the target formation porosity at THEC is similar to that found at JTEC, the permeability is significantly higher at THEC.

The Missouri S&T team also conducted water quality analysis of target formation water, and found Total Dissolved Solids (TDS) to average 46,287 mg/L for three separate samples. This value is well above the threshold for classification as a USDW. Consequently, the St. Francois Aquifer beneath THEC would be considered appropriate for carbon sequestration with respect to water quality.

Geomechanical testing of core samples from the Thomas Hill borehole indicated that Young's Modulus is approximately 5x107 kilopascals (7x106 psi) for the Lamotte Sandstone and approximately 2x107 kilopascals (3x106 psi) for the Davis Formation. No pump-in tests were conducted at THEC to measure breakdown pressure directly, but the fracture gradient was determined using standard fracture gradient calculation methods. These calculations indicate a fracture gradient of 13.8 to 14.5 kPa/m (0.61 to 0.64 psi/foot) in the Lamotte Sandstone.

No reservoir simulation was conducted for the THEC site, and CMG reservoir simulation is required to adequately model CO2 injection and storage. However, some general observations can be drawn by comparing the THEC reservoir characteristics to those found at JTEC, which was modeled and simulated extensively. Reservoir porosity was similar in both boreholes, but THEC has significantly better permeability compared to JTEC (47 millidarcies vs. 2 millidarcies on average). The Thomas Hill borehole also has nearly 15.24 m (50 feet) of formation with an average permeability of 90 millidarcies. Assuming a linear scale, one could expect up to 4 times the injectivity which was modeled for the JTEC site.

Although porosity is similar, the Lamotte is thicker and slightly deeper at THEC, which would also provide an increase in storage capacity. Based on these estimates, an 800 m x 800 m reservoir, allowing for 5-spot water withdrawal and an injection rate of 60 m3 per day, could achieve a total CO2 storage capacity of 1.27 x 106 metric tons over 15.8 years.

The target formation at THEC does not appear to be quite deep enough to support supercritical injection of CO2, but would have to be confirmed by downhole testing. Carbon dioxide behaves as a supercritical fluid when it is held above its critical temperature (304.25 K) and critical pressure (7390 kPa or72.9 atm). Conversion to a supercritical fluid allows much more CO2 to be stored in a given reservoir volume than can be achieved in the gas phase. The reservoir depth at which formation pressures support supercritical injection of CO2 is generally assumed to be 760 m (2,500 feet). The St. Francois Aquifer at THEC occurs between a depth of 363 and 774 meters (2,087 feet and 2,540 feet).

3. Iatan Generating Station – Exploratory Borehole No. 3

Exploratory borehole # 3 was drilled at KCP&L's Iatan Generating Station (IGS). IGS is located in the Dissected Till Plains physiographic province, but lies within the floodplain of the Missouri River.

Structurally, the site is located within the Forest City Basin. The regional dip of the top of the Derby– Doerun Dolomite is approximately 2 m/km (11 feet per mile) to the northwest, toward the center of the Forest City Basin.

Elevation at the top of the surface casing for this borehole was 237.59 m (779.49 feet) msl. The borehole was advanced through the Missouri River alluvium and encountered bedrock at a depth of 28 m (93 feet). The borehole was advanced to a depth of 637.0 m (2,090 feet), but caving within the borehole made interpretation of strata from cuttings collected below 404 m (1,325 feet) impractical. Drilling at IGS was terminated before reaching the St. Francois Confining Unit, and the borehole was subsequently abandoned. Since no core was obtained from the borehole, no research was conducted by the MSU or Missouri S&T research teams for this site.

4. Sioux Power Plant – Exploratory Borehole No. 4

Since no drilling site was available within the Sioux Power Plant (SPP) site, proper, the SPP borehole was drilled at the former Bellfontaine Quarry approximately three miles southwest of the power plant site. This site is sometimes referred to herein as the Luecke Site. SPP is located in the Dissected Till Plains physiographic province adjacent to the Missouri River floodplain. The drilling site is located between two structural features; the Waterloo-Dupo anticline and the Cheltenham syncline. The axis of the Waterloo–Dupo anticline is located 1.2 km (0.75 mile) to the northeast of the site. This northwest-southeast trending anticline plunges to the southeast. The axis of the Cheltenham syncline is located 0.8 km (0.5 mile) to the southwest of the site and consists of a northwest–southeast trending syncline plunging to the southeast. Since the site is located between these two close structural features, the strata at the site are likely dipping to the southwest.

Elevation at the top of the surface casing for this borehole was 137.35 m (450.61 feet) msl. The St. Francois Confining Unit was encountered at a depth of 845.8 m (2,775 feet) and had a measured thickness of 87.2 (286 feet). The St. Francois Aquifer was encountered at a depth of 893.7 m (2,932 feet), and had a measured thickness of 172 m (563 feet) to the bottom of the borehole. The lowermost formation (Lamotte Sandstone) was only partially penetrated by the borehole and the actual aquifer thickness was not determined, since drilling was terminated at a depth of 1105 m (3,625 feet) due to the physical limitations of the coring rig. The depth of the St. Francois Aquifer at SPP was the greatest encountered in the three exploratory boreholes, and is considered deep enough to support supercritical injection of CO2.

The MSU research team conducted a 24-hour single-well pumping test at the Sioux site. The top of the target formation (Lamotte Sandstone) at this site is approximately 1061 m (3,480 feet) below ground surface. Unfortunately, the borehole packer installed for the pumping test could not be set below approximately 594.4 m (1,950 feet) depth, which was insufficient to isolate the Lamotte from all of the overlying permeable strata. Several carbonate beds with discrete fractures and solution- widened bedding planes are present within the interval between the packer and Lamotte, and these overlying zones inevitably contributed water during the pumping test. Nonetheless, an apparent transmissivity of 4.4E-6 m2/sec and apparent hydraulic conductivity of 1E-7 m/sec were calculated. The true transmissivity and hydraulic conductivity of the Lamotte Formation would be significantly less than these limiting values. Because no individual pressure testing was conducted at SPP, only a bulk analysis of permeability of the entire target formation can be developed. Therefore, no injection rate profile is available for this site based on our research.

The Missouri S&T research team performed laboratory testing of core samples to determine the porosity and permeability of the confining unit and target formation. Core analysis of the confining unit indicated a range of permeability from 2.9 microdarcies to 15 microdarcies. Most of the Davis Formation samples exhibited permeabilities so low they could not be measured. The DavisFormation was encountered between depths of 893 and 1013 m (2,930 feet and 3323 feet), and indicated an average porosity of 3%. The Davis Formation at SPP had less porosity and less permeability than the values measured at the other sites. Average core porosity for the target formation at SPP was found to be 12.3% with a range of 6% to over 21%. The porosity was high throughout the target formation, but especially around the 1096 m (3,596-foot) level. Average core permeability was approximately 10 md with a range of .02 millidarcy to 99 millidarcies. The highest permeability in the target formation occurred between depths of 1090 and 1091 meters (3,577 and 3,580 feet).

The Missouri S&T team also conducted water quality analysis of target formation water, and found Total Dissolved Solids (TDS) to average 42,055 mg/L for three separate samples. As with THEC, this value is well above the threshold for classification as a USDW, and SPP would also be considered appropriate for carbon sequestration with respect to water quality.

Geomechanical testing conducted by the Missouri S&T research team found Young's Modulus in the Derby-Doerun Formation and Davis Formation at SPP to be 7.157 x 107 and 8.494 x 107 kPa (10.38 x 106 psi and 12.32 x 106 psi), respectively. The average Young's Modulus value for the Bonneterre/Lamotte transition tests at SPP was 2.48 x 107 kPa (3.60 x 106 psi). Similarly, the average Young's modulus value for the Lamotte Formation at SPP was 5.87 x 107 kPa (8.52 x 106 psi). No pump-in tests were conducted at SPP to measure breakdown pressure directly, and the fracture gradient could not be calculated as logs were not run in the borehole. Lamotte Sandstone was found considerably deeper at SPP than at JTEC and THEC, which may increase CO2 storage capacity since the greater depth would likely support supercritical injection of CO2. Lamotte Sandstone porosity at SPP is similar to that found at both JTEC and THEC, although permeability is about five times better than at JTEC (2 md versus 10 md). Since the CMG simulation for JTEC was based on a Lamotte permeability of 20 md, the injectivity and storage capacity at SPP should be similar to that calculated for JTEC. Based on this estimate, and factoring in the greater depth and thickness of the target formation, the storage capacity at SPP, assuming an 800 m x 800 m reservoir, 5-spot water withdrawal, and an injection rate of 60 m3 per day, is projected to be 5.53 x 105 metric tons over 15.8 years. This estimate does not account for supercritical injection of CO2, so the actual storage capacity at SPP may be much greater.

5. Summary

Following is a table which summarizes the reservoir properties at each site. In each case, the properties apply to an 800 m x 800 m reservoir with 5-spot water withdrawal and 15.8-year injection period.

TABLE 6.1 – SUMMARY OF RESERVOIR PROPERTIES

SITE	John Twitty Energy Center	Thomas Hill Energy Center	Iatan Generating Station	Sioux Power Plant
INJECTION RATE (m^3 per day)	60	60	Undetermined	60
STORAGE CAPACITY (metric tons)	2.55×10^5	1.27×10^6	Undetermined	5.53×10^5
INJECTION PHASE	Gaseous	Borderline Supercritical	Undetermined	Supercritical
TDS CONCENTRATION (mg/L)	159 to 226	46,287	Undetermined	42,055

C. Lessons Learned from the Project

Following is a summary of lessons learned during the project which may prove helpful to future researchers:

- The Ozark Aquifer exhibits a great deal of karst development, particularly in the lower strata (Eminence and Potosi Dolomites). Although it is relatively easy to drill into the large solution cavities, as water well drillers typically do, advancing a borehole through the cavities to investigate deep strata requires careful attention and special techniques. The need for multiple casing strings should be anticipated, and the initial borehole and surface casing sized appropriately. Liberal use of lost circulation materials (LCMs), in conjunction with multiple-stage grouting, should be anticipated. In our communications with the FutureGen management team, we learn that similar problems were encountered with the same strata at the FutureGen drilling site near Jacksonville, Illinois. We also found that an articulated downhole camera was very useful in assessing the location, nature, and extent of solution cavities prior to grouting events.

- Solution cavities within the Ozark Aquifer also impacted our 3D seismic reflection survey at the JTEC site. The survey was conducted in an attempt to image the irregular Precambrian bedrock surface in hopes of siting the proposed injection well within a deep pocket which would have a thicker sequence of basal Lamotte Sandstone. The Ozark Aquifer cavities effectively masked the deeper Precambrian surface and prevented development of a useful Precambrian surface map.
- In hopes of obtaining equivalent data from each of the drilling sites, Exploratory Borehole #2 at THEC and Exploratory Borehole #4 at SPP were drilled and cored, and then capped for a period of time while Exploratory Borehole #3 was being drilled at IGS. Upon re-entering Exploratory Boreholes #2 and #4 in anticipation of pressure testing, it was found that each had experienced significant sloughing which precluded further testing. Correspondingly, it is highly advisable to finish all testing in a given borehole before proceeding to the next borehole.
- Sloughing problems were also encountered in the shallow Pennsylvanian-age shales within Exploratory Borehole #3, which resulted in the borehole being abandoned. The need for multiple casing strings should also be anticipated when drilling through these strata in northwestern Missouri.

D. Conclusions Based on Overall Results

Following are conclusions resulting from the state-wide assessment of carbon sequestration feasibility:

The St. Francois Confining Unit was found to be very consistent across the state. Thickness of the confining unit approached 60 meters (200 feet) in Exploratory Borehole # 1 and 90 meters (300 feet) in Exploratory Borehole # 2 and # 4. Permeability of the confining unit was extremely low in all three boreholes. The St. Francois Confining Unit is projected to be a suitable confining layer for carbon sequestration in Missouri, except in areas where it may be compromised by faulting.

The thickness of the St. Francois Aquifer generally increases across the state from west to east, ranging from 30 meters (100 feet) along the western border to more than 210 meters (700) feet along the eastern border (Figure 1.7). The aquifer exhibits a great deal of local variability, which would be expected since the basal sandstone was laid down on a very irregular Precambrian surface. Aquifer thickness ranged from 136 meters (446 feet) in Exploratory Borehole # 1 to 138 meters (453 feet) in Exploratory Borehole # 2 and more than 172 meters (563 feet) in Exploratory Borehole # 4. Although Exploratory Borehole # 3 could not be advanced to full depth, existing well data in the area suggests the St. Francois Aquifer is considerably thinner within the Forest City Basin.

The depth of the St. Francois Aquifer generally increase with distance from the St. Francois Mountains, but the general trend can be altered substantially by geologic structure. The elevation of the top of the St. Francois Aquifer in Exploratory Borehole # 1 (approximately 225 kilometers west of the St. Francois Mountains) was measured to be -142 m (-465 feet) MSL. Based on Figure 1.6, the elevation of the top of the St. Francois Aquifer along the Missouri-Kansas border (approximately 320 kilometers west of the St. Francois Mountains) is projected to be – 230 m (-750 feet) msl. By comparison, the elevation of the top of the St. Francois Aquifer in Exploratory Borehole # 2 (approximately 260 kilometers northwest of the St. Francois Mountains) was measured to be -395.3 m (1,297 feet) msl and in Exploratory Borehole # 4 (approximately 100 kilometers north of the St. Francois Mountains) was measured to be – 756.2 m (-2,481 feet) msl.

The much greater depth of the St. Francois Aquifer at Exploratory Borehole # 4 is attributed to the steeper dip of strata on the northern flank of the St. Francois uplift and location of the borehole within an apparent structural syncline. The St. Francois Aquifer at Borehole # 4 is deep enough to support supercritical injection of CO_2. The St. Francois Aquifer at Borehole # 2 may also be deep enough to support supercritical injection, but would require additional site characterization for confirmation.

Based on TDS concentrations of groundwater in the St. Francois Aquifer, it appears the northern half of the state is generally suitable for carbon sequestration. The values measured in the exploratory boreholes are consistent with those shown in Figure 1.8.

E. Recommendations for Further Investigation

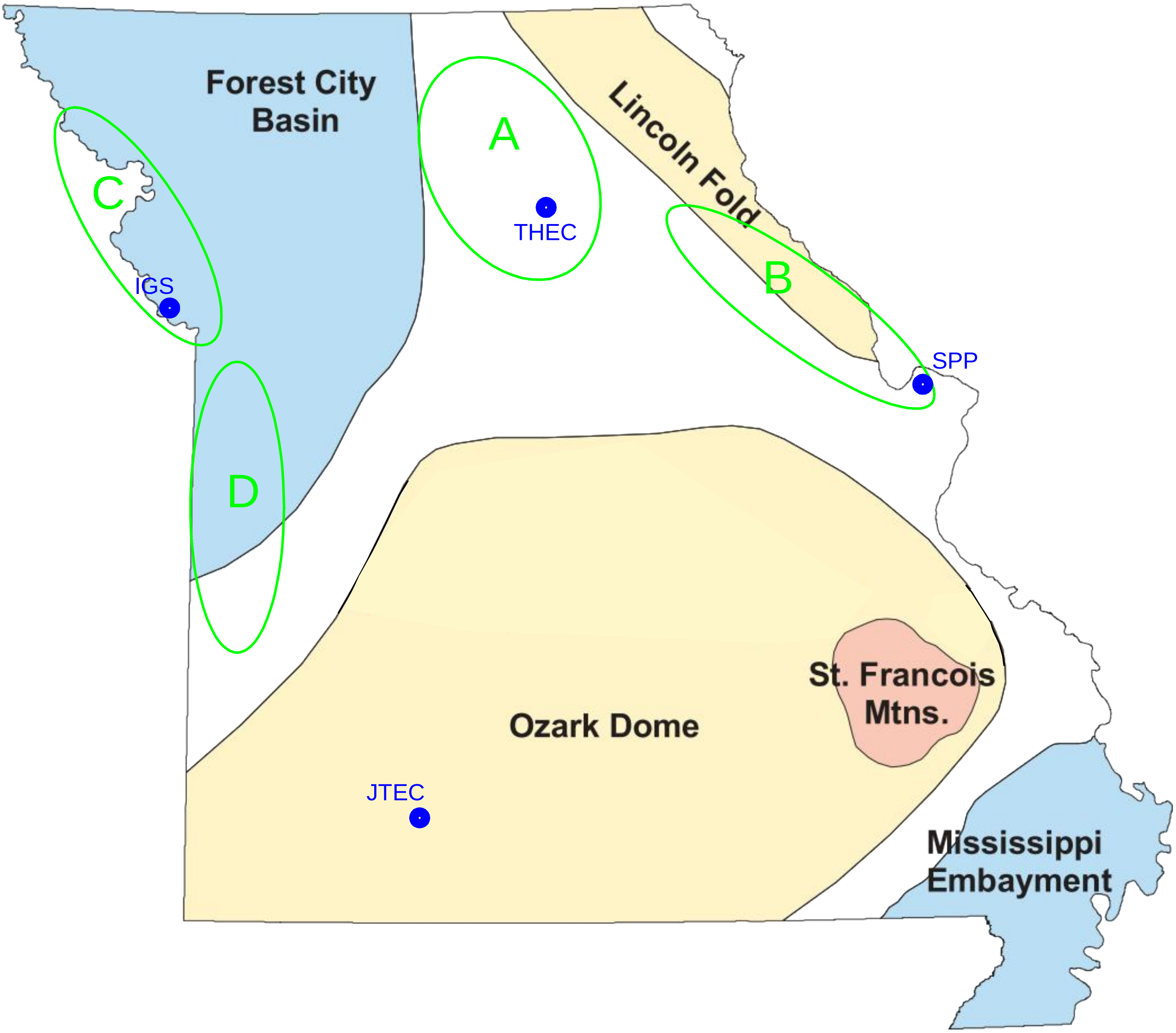
Areas that may warrant additional investigation are shown in Figure 6.2 and described below.

Area A - Thomas Hill Energy Center and Northern Till Plains

Given the favorable results from Exploratory Borehole No. 2, the size of the tract of land owned by AECI, and its central Missouri location, Thomas Hill Energy Center is a good candidate for development as a regional carbon sequestration site. The THEC site would appear suitable for installation of an injection well field. The till plains to the north and northwest of THEC may also be favorable for carbon sequestration. TDS concentrations to the north and northwest would be expected to remain well above the USDW threshold. Moreover, the St. Francois aquifer would be expected to deepen to the north and thicken to the east. Assuming that a depth of 760 m (2,500 feet) is sufficient to support supercritical injection of CO_2 and a regional northwesterly dip of 11 feet per mile, suitable St. Francois Aquifer depths should be encountered approximately 65 kilometers to the northwest of Exploratory Borehole No. 2. Area A extends from U.S. Highway 24 on the south to U.S. Highway 136 on the north, and from U.S. Highway 65 on the west to State Highway 15 on the east.

Area B - Sioux Power Plant and Area to the West of the Lincoln Fold

Given the great depth and thickness of the St. Francois Aquifer at Exploratory Borehole # 4, the suitability of the confining layer, and the favorable permeability of the target formation, the area around Sioux Power Plant warrants further investigation to determine its suitability for development as a regional carbon sequestration site. The great depth of the St. Francois Aquifer at Exploratory Borehole # 4 is attributed to its location near the axis of the Cheltenham syncline. Additional site investigation should be conducted to better define the nature and extent of the Cheltenham syncline and any associated synclinal structures on the western flank of the Lincoln Fold. Area B extends generally from Exploratory Borehole No. 4 on the south to U.S. Highway 36 on the north, and from U.S. Highway 61 on the west to the Mississippi River on the east.



Principal tectonic features of Missouri

LEGEND:

○ Area of Investigation

● Power Plant Location

Notes:
1. The locations of all features shown are approximate.
2. This drawing is for information purposes. It is intended to assist in showing features discussed in an attached document. GeoEngineers, Inc. can not guarantee the accuracy and content of electronic files. The master file is stored by GeoEngineers, Inc. and will serve as the official record of this communication.

Recommendations for Additional Investigation

Shallow Carbon Sequestration Demonstration Project

GeoEngineers

Figure 6.2

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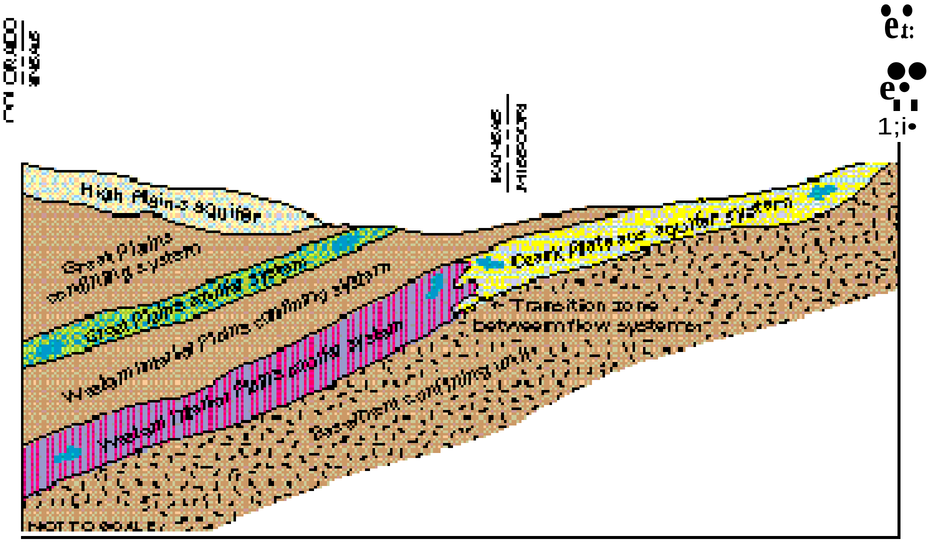
Area C – Iatan Generating Station and Forest City Basin

Although Exploratory Borehole # 3 was not completed and the feasibility of carbon sequestration at the site was not assessed, existing well data in the area of the Forest City Basin suggests the St. Francois Aquifer lies deep enough to support supercritical injection of CO_2. Further, the shallow formations in the basin consist of Pennsylvanian-age unmineable coal seams, which may be suitable for Enhanced Coal Bed Methane (ECBM) projects. Area C extends generally from State Highway 92 on the south to U.S. Highway 159 on the north, and from the Missouri River on the west to Interstate Highway 29 on the east.

Area D – Western Interior Plains Aquifer

Although the Shallow Carbon Sequestration Demonstration Project focused on the St. Francois Aquifer and St. Francois Confining Unit, one additional hydrogeological unit which may warrant assessment is the Western Interior Plains Aquifer in western Missouri. The rock units of the Western Interior Plains Aquifer are equivalent to those of the Ozark Plateaus Aquifer System, but contain saline water or brine. The Western Interior Plains Confining Unit consists primarily of Mississippian- and Devonian-age shale beds. Regional groundwater movement within the Western Interior Plains Aquifer is to the east and southeast; merging with the Ozark Plateaus Aquifer System along a transition zone which extends generally from Jasper County northeasterly to Saline County, and then westerly to Jackson County. A hydrogeological section depicting the transition between Western Interior Plains Aquifer and the Ozark Plateaus Aquifer is provided in Figure 6.3. The areal extent of the Western Interior Plains Aquifer is depicted in Figure 6.4. Thickness of the Western Interior Plains Aquifer in Missouri ranges from 150 meters to 600 meters (500 feet to 2,000 feet). Total Dissolved Solids concentrations within the Western Interior Plains Aquifer appear to be above the 10,000 mg/L USDW threshold for much of the aquifer's extent in Missouri. Area D extends generally from U.S. Highway 54 on the south to U.S. Highway 50 on the north, centered along the route of U.S. Highway 71.



i. **EXPLANATION**

- - **Din!ICl:ion of ground- waler molemenl:**

Modified from Jorgensen, D.G., Helgesen, J .0., and Imes, J.L., 1993, Regional aquifersh I<ansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexic o, Oklahoma, South Dakota, Texas, and Wyoming-Geohydrologic framework: U.S. Geologie&I Survey Pre.fessional Paper 1414-B, 72 p.

Figure 91. This idealized hydrogeologic section in central Kansas anci southern Missouri shows that the predaminantly lateral movement of water in the Ozark Plateaus and the Western hterior Plains

ii. **aquifer systems changes to vertical upward movement in the transition zone between the two** aquifer systems. The water eventu:ally disch:arges to shallower aquifers art o surface streams.

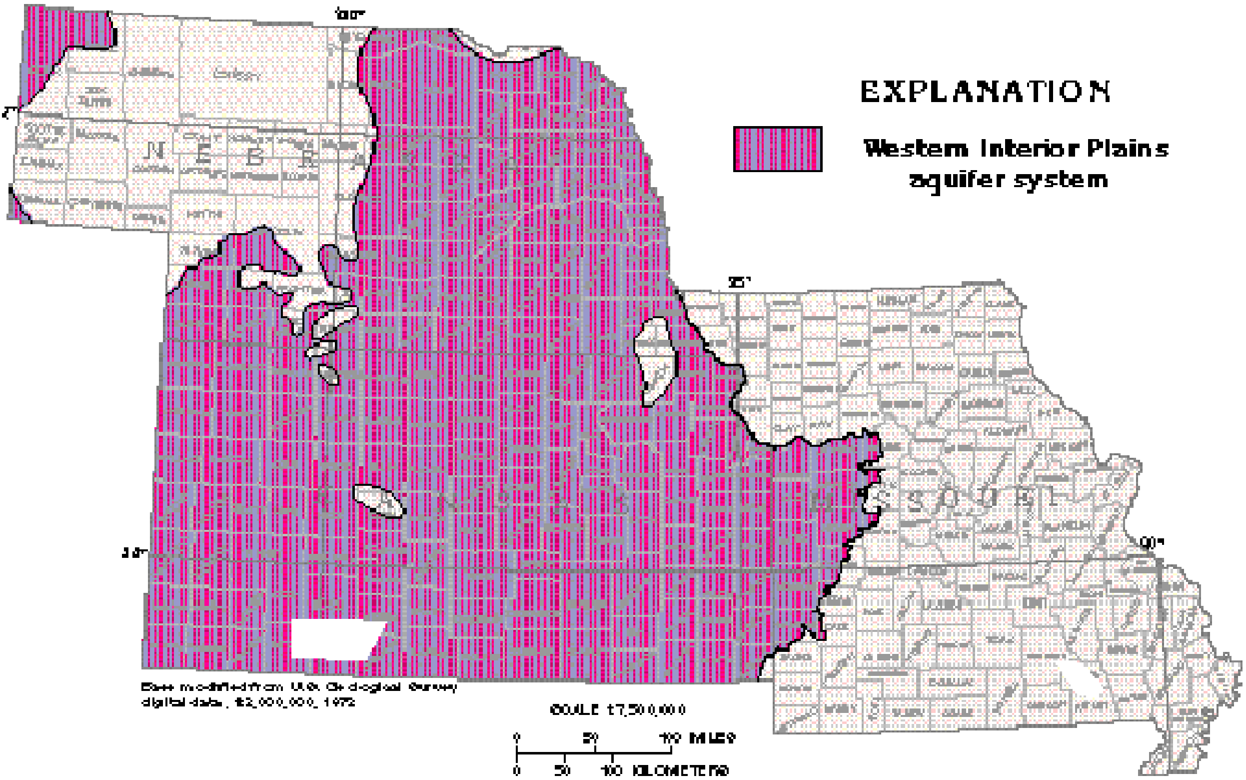
Notes:
1. The locations of all features shown are approximate.
2. This drawing is for information purposes. It is intended to assist in showing features discussed in an attached document. GeoEngineers, Inc. can not guarantee the accuracy and content of electronic files. The master file is stored by GeoEngineers, Inc. and will serve as the official record of this communication.

Western Interior Plains Aquifer Hydrogeologic Section

Shallow Carbon Sequestration Demonstration Project

GEOENGINEERS

Figure 6.3



Modified from Jorgensen, D.G., Helgesen, J.O., and Imes, J.L., 1993, Regional aquifers in Kansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Geohydrologic framework: U.S. Geological Survey Professional Paper 1414-B, 72 p.

Figure 118. The Western Interior Plains aquifer system extends over large parts of Kansas and Nebraska and a small part of Missouri.

Notes:
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Areal Extent of Western Interior Plains Aquifer

Shallow Carbon Sequestration Demonstration Project

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Figure 6.4

JGP : RBM

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