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INTERIM TOPICAL REPORT *The Ohio River Valley CO₂ Storage Project*

Preliminary Assessment of Deep Saline Reservoirs and Coal Seams

Prepared by

Battelle Memorial Institute
505 King Avenue
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INTERIM TOPICAL REPORT

The Ohio River Valley CO₂ Storage Project
Background Geologic Assessment for CO₂ Storage
In Deep Saline Reservoirs and Coal Seams

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The contents of this report are subject to substantial modification based on the geologic conditions encountered in the borehole. The final geologic evaluation will be presented in the site characterization report to be prepared after the completion of the field effort.

ABSTRACT

This report describes the geologic setting for the Deep Saline Reservoirs and Coal Seams in the Ohio River Valley CO₂ Storage Project area. The object of the current project is to site and design a CO₂ injection facility. A location near New Haven, WV, has been selected for the project. To assess geologic storage reservoirs at the site, regional and site-specific geology were reviewed. Geologic reports, deep well logs, hydraulic tests, and geologic maps were reviewed for the area. Only one well within 25 miles of the site penetrates the deeper sedimentary rocks, so there is a large amount of uncertainty regarding the deep geology at the site.

New Haven is located along the Ohio River on the border of West Virginia and Ohio. Topography in the area is flat in the river valley but rugged away from the Ohio River floodplain. The Ohio River Valley incises 50-100 ft into bedrock in the area. The area of interest lies within the Appalachian Plateau, on the western edge of the Appalachian Mountain chain. Within the Appalachian Basin, sedimentary rocks are 3,000 to 20,000 ft deep and slope toward the southeast. The rock formations consist of alternating layers of shale, limestone, dolomite, and sandstone overlying dense metamorphic continental shield rocks. The Rome Trough is the major structural feature in the area, and there may be some faults associated with the trough in the Ohio-West Virginia Hinge Zone. The area has a low earthquake hazard with few historical earthquakes.

Target injection reservoirs include the basal sandstone/Lower Maryville and the Rose Run Sandstone. The basal sandstone is an informal name for sandstones that overlie metamorphic shield rock. Regional geology indicates that the unit is at a depth of approximately 9,100 ft below the surface at the project site and associated with the Maryville Formation. Overall thickness appears to be 50-100 ft. The Rose Run Sandstone is another potential reservoir. The unit is located approximately 1,100 ft above the basal sandstone and is 100-200 ft thick. The storage capacity estimates for a 20-mile radius from the injection well ranged from 39-78 million tons (Mt) for each formation. Several other oil and gas plays have hydraulic properties conducive for injection, but the formations are generally only 5-50 ft thick in the study area. Overlying the injection reservoirs are thick sequences of dense, impermeable dolomite, limestone, and shale. These layers provide containment above the potential injection reservoirs. In general, it appears that the containment layers are much thicker and extensive than the injection intervals.

Other physical parameters for the study area appear to be typical for the region. Anticipated pressures at maximum depths are approximately 4,100 psi based on a 0.45 psi/ft pressure gradient. Temperatures are likely to be 150°F. Groundwater flow is slow and complex in deep formations. Regional flow directions appear to be toward the west-northwest at less than 1 ft per year within the basal sandstone. Vertical gradients are downward in the study area.

A review of brine geochemistry indicates that formation fluids have high salinity and dissolved solids. Total dissolved solids ranges from 200,000-325,000 mg/L in the deep reservoirs. Brine chemistry is similar throughout the different formations, suggesting extensive mixing in a mature basin. Unconsolidated sediments in the Ohio River Valley are the primary source of drinking water in the study area.

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CONTENTS

ABSTRACT	iii
ACKNOWLEDGMENTS	iv
FIGURES	vi
TABLES	vii
ACRONYMS AND ABBREVIATIONS	viii
EXECUTIVE SUMMARY	ix
 1.0 INTRODUCTION	 1
1.1 Background.....	1
1.2 Objectives	4
 2.0 LOCATION/GEOGRAPHY	 5
 3.0 REGIONAL GEOLOGY	 9
3.1 Geologic Setting	9
3.2 Regional Stratigraphy	10
3.3 Geologic History.....	12
3.4 Regional Structure	14
3.5 Seismic Activity	16
3.6 Regional Mineralogy	17
3.7 Coalbed Methane Potential.....	21
 4.0 HYDROGEOLOGY	 30
4.1 Deep Hydrostratigraphic Units	30
4.2 Hydraulic Parameters	32
4.2.1 Primary Potential Injection Units	34
4.2.2 Secondary Potential Injection Units	37
4.2.3 Containment Units.....	38
4.2.4 Formation Pressures	40
4.2.5 Formation Fluid Temperatures	42
4.2.6 Rock Density And Compressibility	42
4.2.7 Formation Fluid Density and TDS	44
4.2.8 Diffusion and Dispersion.....	45
4.3 Groundwater Flow	46
4.4 Reservoir Capacity Estimates	48
 5.0 LOWERMOST UNDERGROUND SOURCE OF DRINKING WATER.....	 52
5.1 Surficial Geology.....	52
5.1.1 Unconsolidated Deposits	52
5.1.2 Bedrock.....	54
5.2 Hydrologic Conditions	54
5.3 Geochemistry of Underground Sources of Drinking Water	58
5.4 Determination of Lowermost Underground Source of Drinking Water	60
 6.0 GEOCHEMISTRY	 62
6.1 Regional Geochemistry	62
6.2 Site-Specific Geochemistry	62
6.3 Analysis Of Brine Chemistry Trends	64

7.0 CONCLUSIONS.....	69
7.1 Location/Topography	69
7.2 Geology	69
7.3 Groundwater Hydrogeology	71
7.4 Geochemistry	72
7.5 Recommendations	72
8.0 REFERENCES	74
Appendix A: Preliminary Assessment of Potential Injection Strata for Carbon Dioxide Sequestration at New Haven, West Virginia	

FIGURES

Figure ES-1. Rock Formation Lithology, Thickness, and Depth at the Study Area	xi
Figure 1. Conceptual Diagram of CO ₂ Injection System	2
Figure 2. Project Location Map	3
Figure 3. Topographic Map of Study Area	6
Figure 4. Digital Elevation Map of the Study Area	7
Figure 5. Regional Structure Around the Study Area	9
Figure 6. Bedrock Stratigraphy for the Study Area	11
Figure 7. Regional Structural Features	14
Figure 8. Regional Cross Section Through the Rome Trough	15
Figure 9. Earthquake Epicenters Near the Study Area	18
Figure 10. USGS National Earthquake Hazard Index Map	18
Figure 11. Extent of the Northern Appalachian Basin	22
Figure 12. Pennsylvanian Allegheny and Pottsville Groups Net Coal Thickness	23
Figure 13. Appalachian Basin Coalbed Methane Production	24
Figure 14. Map Showing Average Permeability in the Basal Sandstone in the Region	35
Figure 15. Histogram of Basal Sandstone Permeability Values from the Midwest Region	35
Figure 16. Permeability and Porosity at Depth as Measured in Basal Sandstone Cores at the Aristech Site	36
Figure 17. Formation Fluid Temperatures at Depth in the Midwest	43
Figure 18. Regional Fluid Density in the Basal Sandstone	46
Figure 19. Hydraulic Head Corrected for Brine Density in the Basal Sandstone	47
Figure 20. Equivalent Freshwater Heads and Groundwater Flow Direction in the Basal Sandstone	48
Figure 21. Estimated Injection Capacities for Expected Reservoir Thickness and Hydraulic Parameters	51
Figure 22. Mountaineer Site with Locations of Geologic Cross Sections	54
Figure 23. Lithologic Log for MW-1 at the Mountaineer Site	54
Figure 24. Geologic Cross Section A-A'	55
Figure 25. Geologic Cross Section B-B'	55
Figure 26. Geologic Cross Section C-C'	56
Figure 27. Geologic Cross Section D-D'	56
Figure 28. Monongahela Series Generalized Geologic Cross Section	57
Figure 29. Water Table Contour Map of Mountaineer Plant Site (December 1997)	59
Figure 30. Typical Bedrock Water Well Log in the Study Area	60
Figure 31. Fingerprint (Schoeller) Diagram of Brine Data	65
Figure 32. TDS at Different Formations	66

Figure 33. Brine Density at Different Formations.....	66
Figure 34. Piper Diagram Showing the Distribution of Major Ionic Species (Equivalent Basis) in the Different Formations of Ohio and Kentucky	67
Figure 35. Equivalent Concentrations of Chlorine at Different Formations	67
Figure 36. Equivalent Ion Ratios for Br/Cl (left) and Iodide Concentrations (meq/L) (right) at Different Formations.....	68
Figure 37. Relationship Between the Bromide and Divalent Metal Chlorides of Waters at Different Formations	68
Figure 38. Diagram of Rock Layers in the Study Area	70

TABLES

Table 1. Summary of Mountain-Building Events in the Appalachian Region	13
Table 2. Summary of Earthquakes within 60 Miles of Study Area	17
Table 3. Summary of Paleozoic Mineralogy at BP Chemicals Lima, OH Site	19
Table 4. Mineral Percentages in the Rome/Maryville Formation at the Aristech Site	20
Table 5. Mineral Percentages in the Conasauga/Nolichucky Shale at the Aristech Site	20
Table 6. Coal Shows in Pomeroy, Chester, Addison, and Cheshire quadrangles of Mason County, WV	26
Table 7. List of Wells with Coal Shows in Pomeroy, Chester, Addison, and Cheshire Quadrangles of Mason County, WV	27
Table 8. Potential Coal Horizons Detected in Pomeroy, Chester, Addison, and Cheshire Quadrangles of Mason County, WV	28
Table 9. List of Wells with Black Shale Shows in Pomeroy, Chester, Addison, and Cheshire Quadrangles of Mason County, WV	29
Table 10. Hydrostratigraphic Units in the Study Area	31
Table 11. Hydraulic Parameters for Hydrostratigraphic Units in the Study Area Including Potential Gas Plays	33
Table 12. Pressure Gradients for Various Rock Formations in West Virginia.....	41
Table 13. Pressure Gradients at the Aristech Site.....	42
Table 14. Estimated Bulk Density of Hydrostratigraphic Units	43
Table 15. Summary of Compressibilities for Various Materials	44
Table 16. Summary of TDS and Density of Formation Water Samples at the Aristech Site	45
Table 17. CO ₂ Storage Capacity for the Basal Sandstone in the United States.....	49
Table 18. Reservoir Capacity Estimates	50
Table 19. Summary of Monitoring Well Groundwater Quality Data in Alluvium Groundwater Wells at Mountaineer Plant	61
Table 20. Summary of Geochemistry at Aristech Site	63
Table 21. Concentrations of Dissolved Ionic Constituents Present in the Selected Brine Samples	65

ACRONYMS AND ABBREVIATIONS

AEP	American Electric Power
bgs	below ground surface
CO ₂	carbon dioxide
DOE	(United States) Department of Energy
DST	drill stem test
gpd	gallons per day
gpm	gallons per minute
Gt	gigatonnes
hsu	hydrostratigraphic unit
Mcf	million cubic feet
mD	milliDarcy
meq/L	milliequivalents per liter
msl	mean sea level
Mt	million tones
MYA	million years ago
N/A	not analyzed
NA	not available
ND	not detected (below detection limit)
NETL	National Energy Technology Laboratory
ODNR	Ohio Department of Natural Resources
ppm	parts per million
psi	pounds per square inch
SCADA	Supervisory Control and Data Acquisition System
Tcf	trillion cubic feet
TDS	total dissolved solids
USDW	Underground Source of Drinking Water
U.S. EPA	United States Environmental Protection Agency
USGS	United States Geological Survey

EXECUTIVE SUMMARY

This report describes the geologic setting for the Deep Saline Reservoirs and Coal Seams in the Ohio River Valley CO₂ Storage Project area. Concerns about global warming have spurred interest in mitigating carbon dioxide (CO₂) emissions from large point sources such as power plants or industrial facilities. One option is geologic sequestration in deep saline reservoirs. Once CO₂ has been captured and compressed into a liquid at the source, the liquid is injected into rock layers 2,500 ft or deeper below the surface. After injection, the liquid is isolated in the deep reservoirs by thick, dense layers of rock that overlie the injection reservoirs. Quite a bit of research has been performed on the topic of geologic sequestration of CO₂ emissions from the past 10 years. In addition, there is a substantial amount of research available on the topics of waste injection and enhanced oil recovery. However, no full-scale power plant CO₂ injection facility has been implemented. The object of the current project is to site and design a CO₂ injection facility.

A site near New Haven, West Virginia, has been selected for the project. The site is located along the Ohio River on the border of West Virginia and Ohio. Topography in the area is flat in the river valley but rugged away from the Ohio River flood plain. Routing a pipeline a significant distance from the power plant may involve some technical as well as public acceptance challenges. The Ohio River Valley incises 50-100 ft into bedrock in the area. Weather in the area is temperate with seasonal temperature swings. Several small towns exist in the area. Roads and infrastructure are moderately developed.

A major requirement of any injection site is suitable geology. An injection reservoir must have:

1. Sufficient **depth** (generally greater than about 2,500 ft) to maintain the injected fluid as a supercritical liquid,
2. Enough **thickness and lateral extent** to provide capacity for large injection volumes,
3. Sufficient **porosity and permeability** to accept injection fluids,
4. **Impermeable caprock** layers above the injection layer to provide containment,
5. A **structurally sound setting** free of faults and fractures, and
6. **Suitable chemistry** to prevent adverse interaction between the rock and injection fluid.

To assess these requirements, regional and site-specific geology were reviewed. Geologic reports, deep well logs, hydraulic tests, and geologic maps were reviewed for the site. Only one well within 25 miles of the site penetrates the deeper sedimentary rocks, so there is a large amount of uncertainty regarding the deep geology at the site.

The area of interest lies within the Appalachian Plateau, on the western edge of the Appalachian Mountain chain. The Appalachians are an ancient mountain system that reflects several hundred million years of tectonic events that have had a large effect on the nature of rock formations in the area. Within the Appalachian Basin, sedimentary rocks are 3,000 to 20,000 ft deep and slope toward the southeast. The rock formations consist of alternating layers of shale, limestone, dolomite, and sandstone overlying dense metamorphic continental shield rocks. The Rome Trough is the major structural feature in the area, and there may be more faults associated with the trough in the Ohio-West Virginia Hinge Zone. The area has a low earthquake hazard with few historical earthquakes.

Several potential injection reservoirs exist in the study area. These formations are sandstones with suitable porosity and permeability. The reservoirs are capable of accepting large volumes of injected fluids. Overlying the injection reservoirs are thick sequences of dense, impermeable dolomite, limestone, and shale. These layers provide containment above the potential injection reservoirs. In general, it

appears that the containment layers are much thicker and extensive than the injection intervals. Figure ES-1 summarizes the arrangement of rock layers in the study area.

Target injection reservoirs include the basal sandstone/Lower Maryville and the Rose Run Sandstone. The basal sandstone is a sandstone is an informal name for sandstones that overlie metamorphic shield rock. Regional geology indicates that the unit is at a depth of approximately 9,100 ft below the surface at the project site and associated with the Maryville Formation. The basal has been used for deep well injection of waste fluids in other areas of the Midwest outside of the Appalachian Basin where is also termed the Mt. Simon Sandstone. Unfortunately, few wells near the study area penetrate the basal sandstone, so the thickness of the rock layer is uncertain. Thickness appears to be 50-100 ft. Based on geophysical logging in nearby wells, only 25-40 ft of the unit may have porosity needed for injection. Porosity of the basal sandstone is likely 10-15%, and permeability is 10-50 millidarcys (mD). The Rose Run Sandstone is another potential reservoir. The unit is located approximately 1,100 ft above the basal sandstone and is 100-200 ft thick. Porosity is 5-15% and permeability is 10-86 mD. Geophysical logs suggest an effective thickness of up to 46 ft with enough porosity for injection. Several other oil and gas plays have hydraulic properties conducive for injection. These formations include the "Clinton," Oriskany, and Newburg. However, the formations are generally only 5-50 ft thick in the study area. Precambrian basement rocks are a speculative injection reservoir that will be evaluated in this study.

Other physical parameters for the study area appear to be typical for the region. Anticipated pressures at maximum depths are approximately 4,100 psi based on a 0.45 psi/ft pressure gradient. Temperatures are likely to be 150 °F. Groundwater flow is slow and complex in deep formations. Regional flow directions appear to be toward the west-northwest at less than 1 ft per year within the basal sandstone. Vertical gradients are downward in the study area.

In general, the basal sandstone and Rose Run Sandstone have hydraulic characteristics most suitable for injection. Storage capacity estimates were calculated for a ten-mile radius of the study site based on the general properties of the formations. The storage capacity estimates ranged from 39-78 million tons (Mt) for each formation. Combined capacity was 78-156 Mt. Variations in the nature of the rocks will affect storage capacity. Porosity, especially has a large effect on storage capacity. More capacity may be available further away from the study area, but geology would need to be further assessed at each location.

A review of brine geochemistry indicates that formation fluids have high salinity and dissolved solids. Total dissolved solids ranges from 200,000-325,000 milligrams per liter (mg/L) in the deep reservoirs. Brine chemistry is similar throughout the different formations, suggesting extensive mixing in a mature basin. Unconsolidated sediments in the Ohio River Valley are the primary source of drinking water in the study area. Sand and gravel layers form a productive aquifer with groundwater suitable for drinking. Pennsylvanian bedrock forms a marginal bedrock aquifer in the area below the river valley. The bedrock aquifer is not highly developed because it produces small amounts of poor quality water. However, the Pennsylvanian bedrock is considered the lowermost source of drinking water in the study area and is utilized in the upland areas for individual water supplies. Rock formations below this aquifer are concentrated brines that are not considered sources of drinking water.

Overall, the effective thickness of the injection reservoirs is the main uncertainty at the New Haven site. Otherwise, the potential reservoirs are more than deep enough with reasonable geologic, physical, and hydrologic properties. It does not appear that the geochemistry of the formation waters will adversely affect injection. The potential injection formations are separated from the lowermost source of drinking water by over 6,500 ft of dense, impermeable rock, offering excellent containment.

All depths and thicknesses approximate based on nearby deep well lithology.

Figure ES-1. Rock Formation Lithology, Thickness, and Depth at the Study Area

1.0 INTRODUCTION

1.1 Background

Concerns about global warming have prompted research into the mitigation of greenhouse gases through such methods as deep ocean disposal, geologic sequestration, and enhanced terrestrial uptake. Injection of carbon dioxide (CO₂) into deep rock formations is an attractive option because regional saline reservoirs with large storage capacities are present throughout the world. Based on the current state of understanding, geologic sequestration is ready to be tested in the field through a pilot-scale project focusing on locations in the Midwest and Ohio River Valley using nearby deep saline aquifers as potential host reservoirs. The current work is continuation of research funded under the United States Department of Energy (DOE) and several other research groups and agencies. The overall project work is aimed at providing an understanding of the viability of carbon capture and sequestration as a global warming countermeasure by laying the groundwork for an integrated demonstration of CO₂ capture and geologic sequestration at a meaningful scale. The work involves several tasks including a review of geology, a geophysical survey, a deep test boring, computer modeling, and risk assessment/stakeholder dialogue. The ultimate goal of the program is to provide a workable well capable of injecting CO₂ at meaningful rates to enhance knowledge and practicality of geologic sequestration of CO₂.

The concept of CO₂ disposal involves capture of emissions at a fossil fuel-fired power plant, separation of the emissions to isolate the CO₂, compression of the gas to a supercritical liquid, and dehydration of CO₂ to remove any moisture in the liquid. Once the gas is compressed to a liquid, it is injected into a deep underground rock zone that is porous and permeable. Dense, impermeable, confining layers overlying the injection layer prevent the injected fluid from migrating. Figure 1 summarizes the components of a CO₂ sequestration system.

The supercritical liquid will generally remain in a separate phase, but eventually a portion of the liquid will dissolve in formation fluids or transform to minerals in rock-water reactions. The reason that geologic sequestration appears feasible is that the practice of CO₂ injection has been used for enhanced oil recovery for many decades. In addition, many analogous cases in nature exist, where naturally occurring CO₂ has accumulated in underground reservoirs. Finally, deep well disposal of liquids that are often much more hazardous than CO₂ has been practiced throughout the United States for several decades and is an established practice.

The American Electric Power (AEP) Mountaineer Power Plant near New Haven, WV (Figure 2), has been proposed for the injection site. This facility is equipped with modern pollution control technology. The site lies in the Ohio River Valley, along the river and near many other coal power plants, and provides a research location for both Ohio and West Virginia. The area of review includes portions of West Virginia and a large portion of southeastern Ohio. One of the advantages of geologic sequestration is that it can often be accomplished without the need for expensive pipelines. The Ohio River Valley is a useful location, because its natural resources and nearby markets make it a popular location for power plants. As such, experience at the study site could be applied to other locations. It should be noted that the geology at the proposed site presents several challenges. However, if the program is successful in the study area, it could easily be implemented at locations that are more conducive to injection.

For the purpose of this study, it is assumed that a condensed stream of CO₂ is readily available at the source. As such, the program focuses on characterizing the geology and designing a successful injection program. Detailed geological characterization is a significant step to meeting permitting and regulatory requirements. This report is designed to provide the framework for addressing those regulatory permit requirements.

Figure 1. Conceptual Diagram of CO₂ Injection System

Figure 2. Project Location Map

1.2 Objectives

The main objective of this effort is to assess the geologic potential for CO₂ sequestration in deep saline reservoirs below the proposed Ohio River Valley site. Key aspects assessed in the report include geography, geomorphology, rock stratigraphy, geologic structures, mineralogy, hydrology, hydraulic parameters, seismic history, oil and gas plays, coalbed methane potential, geochemistry, and underground sources of drinking water. In general, each of these topics is discussed from a regional scale to a more site-specific scale, when possible. A major objective of the study is to find a suitable interval of rock for injection with the following properties:

1. Sufficient **depth** to maintain the injected fluid as a liquid,
2. Enough **thickness and lateral extent** to provide capacity for large injection volumes,
3. Sufficient **porosity and permeability** to accept injection fluids,
4. **Impermeable caprock** layers above the injection layer to provide containment,
5. A **structurally competent setting** free of faults and pervasive fractures, and
6. **Suitable chemistry** to prevent adverse interaction between the rock and injection fluid.

These requirements provide a general outline for investigating the geology of the study area. In addition, several other aspects of the site are related to the injection system, such as drinking water sources, coalbed methane, and surface physiography.

Information on the site area was gathered from available maps, historical records, and studies. Several environmental studies from the power plant were reviewed to obtain data on shallow site-specific details near the injection facility. Geology and stratigraphy were reviewed in a joint effort between Battelle and the Ohio Department of Natural Resources (ODNR) Ohio Geological Survey. The Ohio Geological Survey has experience in mapping, cataloguing, and describing natural resources in the Ohio region, and also has a library of geophysical well logs. The Survey was mainly responsible for outlining stratigraphy, mapping formation depths, assessing geologic structures, creating geologic cross-sections, and evaluating reservoirs in the area. In addition, they reviewed geophysical surveys for the region. Much of the Survey's expertise is in the area of oil and gas, and this knowledge was useful in assessing the extent of hydrocarbon reserves in the study area. Potentials for enhanced coalbed methane recovery in conjunction with CO₂ disposal were evaluated by Dr. Lloyd English of West Virginia University. Most of the information on hydraulic parameters for the potential formations was obtained from other injection facilities where extensive testing has been performed on reservoirs.

The report is aimed at providing a better understanding of the processes and characteristics of the injection system. The potential for injection is addressed as well as containment and fluid migration. Information gained from this report will be used as the basis for other tasks including a drilling work plan, risk assessment, and underground injection permitting. It should be noted that much of the information required to design an injection system is very site-specific and cannot be ascertained until a borehole is drilled at the study site and tests are performed. As such, the information in this report is meant as only a general guide for drilling and other tasks.

2.0 LOCATION/GEOGRAPHY

The proposed study area is associated with the AEP Mountaineer Power Plant, located in Mason County, WV, on the banks of the Ohio River (Figure 2). Across the river is Meigs County of Ohio, and Jackson County, WV, is to the south. The site is within the Township of Graham. Route 33 runs along the Ohio River in West Virginia, and Route 7 runs along the Ohio River in Ohio. A railroad track also exists along the river in the area. The closest West Virginia town to the study area is New Haven, which is less than a mile upriver. The City of Racine, OH, is located across the river from the power plant. Other nearby towns include Syracuse, OH; Pomeroy, OH; Mason, WV; and Middleport, OH. The towns each have populations of less than 25,000 people. Mason County, WV has a population of approximately 26,000 people based on 2000 U.S. Census data. Huntington, WV, and Charleston, WV, are both located about 50 miles from the study area.

Infrastructure is fairly well-developed along the river, but less extensive away from the river valley. Land use along the river is a mixture of agricultural, industrial, and residential. Upland of the river valley, the hilly terrain makes large-scale farming or large industry less common. Several state parks and national forests exist in the area including the Shade River State Forest, Forked Run State Park, and Clifton F. McClintic State Wildlife Station.

Topography along the Ohio River in the study area consists of a flat river terrace surrounded by steep valleys eroded into Pennsylvanian and Permian rocks by streams, as shown in Figure 3. Vertical rock cliffs abut the river along many stretches. The elevation along the Ohio River valley is approximately 500 to 600 ft, and the surrounding areas are up to 900 ft in elevation as shown in Figure 4, a digital elevation model of the study area. The Ohio River travels a meandering route along the Ohio-West Virginia border and bends nearly 180 degrees in northern Mason County, WV. The Ohio River floodplain is a flat area along the river. The floodplain is approximately ½ to 1½ miles wide in the area and generally abuts the hills on one side; the other side has a wider floodplain, a typical configuration for a meandering river. The floodplain consists of unconsolidated clay, silt, sand, and gravel sediments that cut 50-100 ft into bedrock in the area.

Several small streams empty into the Ohio River off the surrounding highland areas on either side of the river. The landscape on either side of the flood plain consists of steep hills and valleys. The streams incise smaller stream valleys within the higher elevation terrain surrounding the area. Most valleys are sharply incised into the terrain, but other areas contain flatter valleys. The drainage pattern is dendritic with a drainage density of 8-16 miles/square mile. The drainage pattern reflects a mature basin with flat sedimentary rocks. The basin has been affected by periods of uplift related to the isostatic rebound in the Appalachian Province and reversal of streamflow caused by the last glacial advance. The largest river that merges with the Ohio in the area is the Kanawha, which flows from the southeast, through Charleston, and merges into the Ohio to the southwest of the study area (Figure 2). Flooding of the Ohio River in the study area is mostly caused by flow from other upstream tributaries. Significant floods occurred in the area in 1861, 1913, 1936, and 1937 (AEP, 1974). Subsequent upstream dams or other stream control measures, most notably a hydroelectric dam at Racine, have reduced the severity and frequency of floods. The 100-year flood plain level has been designated at 581 ft mean sea level (msl).

Soils in the area reflect silica based rock in the area and are moderately acidic. The soil is shallow to moderately deep, depending mostly on the topography. Rapid erosion of soils in the hilly areas is typical. Deep layers of brown, well-drained soil exist along the Ohio River and are suitable for farming. The soils are referred to as the Aston-Wheeling-Lakin Association in West Virginia (AEP, 1974).

Figure 3. Topographic Map of Study Area

Figure 4. Digital Elevation Map of the Study Area

Bedrock consists of alternating layers of sandstone, shale, coal, and limestone of the Permian Dunkard Group and the Pennsylvanian Monongahela Group. Permian rocks generally are exposed along ridges, whereas the older Pennsylvanian rocks are found in valleys. The rocks are exposed in many areas. Primary sedimentary features such as cross bedding and bioturbation can be seen in the rocks. In addition, secondary structures such as folds, faults, and fractures are visible in exposed rocks. The fractures are probably related to decompression of the rocks due to long-term erosion trends. The surface bedrock dips gently southeast toward the axis of the Parkersburg Syncline.

The area is in a temperate climatologic region of the country. Average monthly temperatures range from approximately 32°F in January to 75°F in July. Average yearly temperature is about 53°F. Predominant wind direction is from the west-southwest. The area receives approximately 43 inches of precipitation a year. Most precipitation occurs in the spring and summer. Flash-flooding occasionally occurs in small stream valleys. Mass wasting occurs in the form of small rockslides along the steep slopes of valleys.

Mixed mesophytic forest consisting of deciduous trees is found in the area (AEP, 1974). The forest type consists of a variable mixture of oak, maple, hemlock, pine, walnut, and hickory trees. The forest reflects second or third growth after various clear cutting or selective cutting measures over the past 100 years.

Most of the trees are fairly mature with diameters of more than 12 inches. Other small grasses, bushes, weeds, and ferns are also found in forested areas. Several areas have been modified for grazing and consist of grassy uplands. Along the Ohio River floodplain, the forest has been selectively cut and consists of a mixture of trees and grasses.

3.0 REGIONAL GEOLOGY

This section summarizes regional geology as it applies to the proposed CO₂ injection study site. Topics include general geologic setting, regional geologic structures, general stratigraphy, mineralogy, geologic history, and seismic activity. A more detailed investigation into deep rock layers is presented in Appendix A, which includes maps of target formations, detailed geologic cross sections, and deep well review for the study area.

3.1 Geologic Setting

Thick sequences of sedimentary rocks of Paleozoic age (250-570 million years old) form broad regional structures in the eastern and midwestern United States (Figure 5). The study area lies within the Appalachian Basin, an area from New York to Tennessee where rock formations slope toward the east. The basin is bound by the Adirondack Uplift to the north, the Blue Ridge Thrust Belt to the east, the Black Warrior Basin to the far south, and the Cincinnati and Findlay Arches to the west. Within the Appalachian Basin are several physiographic provinces that have similar landforms. The study area is located in the Appalachian Plateau Province. In this province, erosion has subdued uplifted landscape into hilly upland areas. To the southeast the Valley and Ridge Province exists where elongated ridges and valleys border the Blue Ridge Mountains. Flatter landforms of the central lowlands are located to the west of the Appalachian Plateau Province. The province extends considerably to the southwest and northeast of the study area.

Figure 5. Regional Structure Around the Study Area

In the region, sedimentary rocks ranging from 3,000 to 20,000 ft thick overlie Precambrian metamorphic and igneous rock. The Precambrian rock consists of gneiss and granite associated with ancient mountain-building in the area. This rock forms stable continental cratons that are the base of tectonic plates. Above the Precambrian rock, sedimentary rock consists of alternating layers of sandstone, limestone, dolomite, siltstone, and shale. These rocks reflect transgressive seas that existed in the area in Paleozoic times. Layers with similar properties are termed formations and can be traced throughout the region to outline geologic structures and physiographic provinces. In the Appalachians, several mountain-building events have gently folded the rock layers in the study area. The rock layers vary in thickness, and several formations are limited in extent. Toward the southeast of the study area, the rocks are more intensely folded and faulted along the Blue Ridge Thrust Belt.

3.2 Regional Stratigraphy

The stratigraphy of the sedimentary rocks in the study area have been categorized by drillers and geologists based on rocks encountered during drilling. With a column of nearly 10,000 ft of sedimentary rocks, numerous formations have been identified in the study area. Terminology for the rock formations varies with location and time, but the general stratigraphy can be traced throughout the region. Figure 6 summarizes the stratigraphy in the study area. In this research, the terminology of Ryder (1991, 1992a, and 1992b; Ryder et al., 1992, 1996, and 1997) was adopted. A more detailed examination of stratigraphy is presented in Appendix A.

Metamorphic and igneous Precambrian rock of the Grenville Province is found at depths of approximately 8,000-10,000 ft in the study area. These rocks form the base or craton of continental plates. At the base of the Paleozoic sedimentary sequence is the Mt. Simon Sandstone or basal sandstone in most of the Midwest. This formation was deposited as clastic sediment in a marine setting. Regionally, the rock has high porosity and permeability. It is used for underground waste disposal throughout the Midwest. Overlying the basal sandstone is the Maryville/Rome formation, which is dolomite with low porosity and permeability. The Maryville/Rome Formation subcrops in eastern Ohio (the Rome formation is present in eastern Ohio, and the Maryville is present mostly east of the Ohio river in the region). The Nolichucky formation is next, which is roughly equivalent to the Eau Claire formation in the region. The Nolichucky is overlain by the Maynardville Limestone, a dolomite termed the Copper Ridge, and the Rose Run, a sandstone unit that appears in eastern Ohio and extends into the eastern Appalachian Basin. The formation generally marks the youngest Cambrian rock in the area.

Lower Ordovician rocks include the Beekmantown, Wells Creek, Black River Group, Trenton, and Point Pleasant. These formations are mostly shale, limestone, and dolomite. Between the Beekmantown and the Wells Creek is a major unconformity, or erosional surface, marking a gap in the sedimentary record. This “Knox Unconformity” can be traced throughout the region and is a significant marker in geological investigations. The Copper Ridge, Rose Run, and Beekmantown are often referred to as the “Knox Group.” The Reedsville and Juniata formations form shale layers with a combined thickness of more than 1,000 ft in the upper Ordovician rock column. These shale layers correspond to the Cincinnati Series in other parts of the Midwest.

At the base of the Silurian are a series of sandstone and limestone units including the “Medina Sand,” “Clinton Sand,” and Dayton formation. The “Clinton Sand” is a significant gas reservoir in the region with more than sixty thousand gas wells. The overlying Dayton limestone is often referred to as the “Packer Shell” by drillers. The Rochester formation overlies the Dayton in the area. The Lockport, Salina, and Bass Islands formations are present in the upper Silurian. These formations are mostly limestone and dolomite sandstone. Within the Lockport is a high permeability sandstone termed the “Newburg.”

Figure 6. Bedrock Stratigraphy for the Study Area

Within the Lower Devonian is the Helderburg Formation and the Oriskany Sandstone. The Oriskany is a clean sandstone that subcrops in eastern Ohio. The Onondaga Limestone overlies the Oriskany unconformably. Several sandstone and limestone layers exist above the Onondaga, including the Hamilton, Sonyea, West Falls, and Java formations. A major shale formation often termed the Ohio Shale or Marcellus Shale marks the Upper Devonian in the study area.

A series of sandstone and shale units exist in the lower Mississippian interval. The Bedford Shale, Berea Sandstone, Sunbury Shale, Cuyahoga, and Logan formations are found within the lower Mississippian column. Pennsylvanian and early Permian rocks are generally the youngest bedrock formations found in the study area and may outcrop in the area. These rocks include the Pottsville, Allegheny, Connemaugh, Monongahela, and Dunkard. Coal plays are found in several of these formations. Unconsolidated sediments overlie bedrock in much of the study area. The sediments are a mixture of clay, silt, sand, and gravel associated with erosion and rivers.

3.3 Geologic History

An understanding of the mountain-building, erosion, and deposition events at the proposed injection site provides insight into the structures and rock formations that comprise the injection and containment intervals. Although a detailed investigation of sedimentary facies may be of interest in the future, this section presents a general overview of the geologic history as it relates to the injection site. The area of interest lies within the Appalachian Plateau, on the western edge of the Appalachian Mountain chain. The Appalachian range is an ancient mountain system that reflects several hundred million years of orogenic (mountain-building) events. Table 1 summarizes the geologic history for the area of interest.

The first major mountain-building event discernable in the Appalachian region was the Grenville Orogeny. Approximately 1 billion years ago, it is proposed that the ancient continents of Laurentia and Gondwanaland collided. The Grenville Front marks the deeply buried boundary between the two accreted landmasses that can be traced using geophysical methods through the western portions of Ohio and Kentucky. Following the Grenville Orogeny, Gondwanaland and Laurentia moved apart to form the Iapetus Ocean in the Cambrian period. This event signaled the beginning of a prolonged interval of deposition and erosion that resulted in the thick Paleozoic sedimentary rocks that are being considered for injection purposes. During the Cambrian period, clastic and marine sediments were deposited in shallow to deep marine settings. In the late Ordovician to Silurian periods, the Taconic Orogeny occurred when an island arc collided with Laurentia. Volcanic activity in portions of modern West Virginia is associated with the Taconic Orogeny but is not found in the study area. Additional deposition in shallow to deep marine environments resulted in thick limestone and shale rock layers.

The Silurian period saw the end of the Taconic orogeny and more deposition of clastics, carbonates, and shales in shallow to deep marine environments. During the Devonian period, the Acadian Orogeny occurred as tectonic plate movements resulted in the collision of Laurentia and Baltica continents. The orogeny resulted in uplift to the northeast of the study area and continued deposition of marine shales and limestones. Marine deposition continued in the early Carboniferous/Mississippian period. Limestone, shale, and sandstone formations continued to be deposited. Seas receded in later Carboniferous/Pennsylvanian periods as marsh conditions prevailed. During this time, coal formations and clastic sediments were deposited in the area.

The Alleghenian/Appalachian Orogeny occurred in the Permian period as Laurentia and Gondwanaland collided to form the ancient super-continent Pangaea. Much of the faulting and folding currently associated with the Appalachians occurred during this period. The study area was uplifted and eroded.

Table 1. Summary of Mountain-Building Events in the Appalachian Region

Era/Period	MYA	Orogeny	Tectonic Events	Depositional Environment	Comments
Cenozoic	0	Schooley, Somerville Erosion Surfaces	Intervals of secondary uplift and erosion to create current Appalachian provinces	Alluvial, fluvial	Continued erosion of uplifted mountains
Mesozoic	65		Initial rifting of Pangaea to form Atlantic Ocean	Alluvial, fluvial	Erosion of Appalachians to form continental shelf
Permian	245	Alleghenian Acadian Taconic	Collision of Laurentia with Gondwanaland to form Pangaea	Dry marine, upland	Evaporites, clastics
Carboniferous	286		Minor tectonic movement	Shallow marine to swamp	Marine carbonates to coalbeds
Devonian	360		Collision of Laurentia with Baltica	Shallow to deep marine	Sandstones, limestones, and shales
Silurian	408		Erosion, clastic, marine deposition	Shallow to deep marine	Marine carbonates and shales
Ordovician	435		Collision of Island Arc with Laurentia	Shallow to deep marine	Marine carbonates and shales
Cambrian	505		Rift of Gondwanaland and Laurentia to form Iapetus Ocean	Shallow to deep marine	Clastic and marine sediments
Precambrian	570		Collision of Gondwanaland with Laurentia Continent	Igneous intrusion, metamorphism	Folded gneiss and granites

MYA: million years ago.

Clastic rocks were deposited during this time that form the surficial rock formations in the study area. No significant sedimentary rocks were deposited after the Permian period in the Appalachian Basin. Over the Mesozoic Era, initial rifting of Pangea lead to the formation of the Atlantic Ocean and erosion of the Appalachians. Environments in the study area were alluvial and fluvial. The Cenozoic Era saw minor tectonic movement in North America. The uplifted mountains in the Appalachian region continued to be eroded. These intervals of secondary uplift formed the Schooley and Somerville erosion surfaces and the current Appalachian Provinces. Although glaciers did not advance into the study area, they did divert drainage from the northeast to the southwest into the Ohio River system. Unconsolidated alluvial and fluvial sediments are the youngest deposits in the area.

3.4 Regional Structure

Regional structures reflect the ancient mountain-building and tectonic events associated with the Appalachian Mountains. Figure 7 shows structural features near the study area. The study area lies within the Appalachian Basin, where rock layers slope toward the east-southeast at about 100 ft per mile. The predominant regional structures include the Ohio Platform to the immediate west, the Eastern Continental Rift Basin/Cincinnati Arch to the far west, and the Rome Trough to the east. Coogan and Peng (1993) note that these three features have a large effect on the structural and depositional setting for Ordovician and Cambrian rocks (Sauk Sequence) in the region.

Figure 7. Regional Structural Features

Several other structural features are of note. The Rome Trough is located approximately 25 miles to the southeast of the study area. The trough is a series of downdropped blocks (or grabens) of rock layers. The trough is oriented northeast/southwest and is bounded by steep normal faults. Within the trough, rock formations thicken and drop off more than 10,000 ft. Figure 8 shows a geologic cross-section through the Rome Trough. The trough is considered a failed Cambrian continental rift basin associated with the rift of Gondwanaland and Laurentia to form the Iapetus Ocean (Harris, 1978; Cable and Beardsley, 1984; Keller et al., 1983; Shumaker, 1996; Harris and Baranoski, 1997). As such, the faults related to the Rome Trough only penetrate into the lower Cambrian Mt. Simon and Rome formations, which thicken substantially within the trough. Shallower rock formations also thicken above the trough. Minor faulting within shallower rocks is not uncommon in the region and has been noted in regional seismic surveys (Shrake et al., 1990).

Figure 8. Regional Cross Section Through the Rome Trough

To the southeast of the trough, a series of thrust faults define the Valley and Ridge Province of the Blue Ridge Thrust Zone. To the northwest of the Rome Trough, the Ohio-West Virginia Hinge Zone has been proposed (Ryder et al., 1996). In this hinge zone, several normal faults have been suggested along the fringe of the Rome Trough, based on borehole correlations (Ryder et al., 1996). The faults generally

penetrate into the lower Cambrian formation and do not have a considerable offset like the Rome Trough. Shumaker (1996) identified the nearest normal faults along the Rome Trough as the Evans and Midway faults. The Kentucky River Fault Zone, a series of complex faults, exists approximately 75 miles south-east of the site. Other structures in the area include the Cambridge Fault to the northeast and the Starr Fault System (Brannock, 1993) to the north. The Waverly Arch occurs about a hundred miles to the west. Rocks slope gently upward in this area.

3.5 Seismic Activity

Deep well injection has the potential to trigger earthquakes, if the site is not carefully selected or if the injection pressures are too high. Areas with preexisting faults may be especially susceptible to induced seismicity (Healy et al., 1968; Raleigh et al., 1976; Wesson and Nicholson, 1987; Sminchak and Gupta, 2000). Geologic structures, fault lines, and seismic history are indicators of seismic suitability. Paleozoic rocks in the Midwest are generally uniform, flat-lying or gently-dipping, sedimentary rock layers with conformable contacts, and seismic activity is generally low throughout the Midwestern and Eastern United States. Most seismic events with epicenters in the region have magnitudes of less than 3.0 on the Richter scale.

Table 2 summarizes earthquake activity within 60 miles of the study area. Figure 9 shows the locations of the earthquakes. Notable earthquakes occurred in the immediate study area in 1926, 1974, 1975, and 2002. The 1926 earthquake epicenter was in Meigs County, OH, just across the Ohio River from New Haven. The United States Geological Survey (USGS) estimates the earthquake at a Richter scale of 3.8 and Modified Mercalli Scale intensity of VII-VIII, which means it caused a small amount of structural damage and was easily felt. More recently, earthquakes occurred in Vinton County, OH, in 1975 and in Wood County, WV, in 1974. Both of these seismic events had Modified Mercalli Scale intensities of IV to VI. The most recent earthquake in the area occurred in 2002 and had a Richter magnitude 2.8 with an epicenter in Meigs County. Earthquakes with magnitudes less than 3.0 are usually not felt by people. There is no discernable pattern to the earthquakes, and they do not appear to be related to any identifiable structure. Depths for the earthquakes are 13,000-36,000 ft (4-11 km), suggesting movement in Precambrian faults below the Paleozoic rock column. Several authors have suggested the presence of deep, inactive, Precambrian faults in the region. The nearest seismic monitoring stations are located in Athens, OH, and Portsmouth, OH. The nearest seismic monitoring station in West Virginia is located in Morgantown.

In terms of seismic hazards, the USGS classifies the study area as low risk. The USGS National Seismic Hazard Mapping project integrates seismic history, geology, and land type to represent the chances that a given location will have a damaging earthquake (Wesson et al., 1999). Figure 10 shows the seismic hazard map. The nearest location with a substantial risk of seismic activity is the Kentucky River Fault Zone, where a series of normal faults exists. In addition, the New Madrid Seismic zone has a history of damaging earthquake activity, but this location is well separated from the study in distance (over 400 miles) and geology. Overall, it appears that the site is not within a seismically active zone. There is little risk of an earthquake damaging the injection well, and the potential for induced seismicity in Paleozoic rocks is very low.

In summary, the study area lies within the Appalachian Basin where Paleozoic sedimentary rocks are 3,000 to 20,000 ft thick and dip toward the southeast. The rock formations consist of alternating layers of shale, limestone, dolomite, and sandstone. The Rome Trough is the major structural feature in the area, and there may be more faults associated with the trough in the Ohio-West Virginia Hinge Zone. The area has a low earthquake hazard with few historical earthquakes.

Table 2. Summary of Earthquakes within 60 Miles of Study Area

Year	Month	Day	State	County	Depth (km)	Magnitude (Richter)
1776	NA	NA	OH	Perry	NA	NA
1815	NA	NA	OH	Pike	NA	NA
1824	7	15	WV	Wood	NA	NA
1883	5	23	WV	Boyd	NA	NA
1886	5	3	OH	Athens	NA	3.4
1899	11	12	OH	Ross	NA	3.1
1901	5	17	OH	Vinton	NA	4.2
1902	6	14	OH	Pleasants	NA	NA
1926	11	5	OH	Meigs	NA	3.8
1952	6	20	OH	Perry	9	4.1
1953	5	7	OH	Perry	NA	2.7
1967	4	8	OH	Hocking	1	4.5
1970	8	11	WV	Cabell	10	2.8
1974	10	20	WV	Wood	4	3.8
1975	2	16	OH	Gallia	4	4.4
1979	11	9	WV	Greenup	1	3.6
1983	8	17	WV	Greenup	8	3.5
1988	5	28	OH	Noble	NA	3.4
1991	6	28	WV	Kanawha	5	3.2
1995	5	14	OH	Lawrence	NA	2.5
2002	5	6	OH	Meigs	5	2.8

Based on information from National Earthquake Information Center, Ohio Department of Natural Resources, and OhioSeis.
NA = not available.

3.6 Regional Mineralogy

The mineralogy of rock formations is important to understand the nature of the rocks, pore-scale hydraulics, and rock-water interactions. Overall, the mineral composition of Paleozoic rocks in the study area reflects sedimentary depositional environments. Primary mineralogy can be correlated to transgressive seas present in ancient times (Read, 1989). Secondary mineralization may be present as dolomite, calcite, or salt within fractures or pore spaces. Several waste disposal facilities in the region inject (or injected) waste into the basal sandstone. These wells provide a good deal of information on the deep rock geology due to the regulatory requirements for waste injection. Most oil and gas wells do not test deep rock formations beyond typical wireline logs because there are no economic targets.

Two injection well operations that provide valuable information for this report include the BP Chemicals and Aristech sites (see Figure 14). The BP site is located in Lima, OH and injects chemical byproducts into the basal sandstone. Although this facility is far from the proposed site, extensive testing was performed through the entire deep rock column. The BP Lima site offers one of the few comprehensive views of deep rock geology in the region. The Aristech site is approximately 50 miles from the study area in Haverhill, OH, and is the nearest deep well injection facility to the proposed site. Geology at the Aristech site is similar to the proposed site. Testing performed at the Aristech set is relevant to the proposed site. Table 3 shows a table of Paleozoic mineralogy as measured at the BP Lima site in north-western Ohio. Although this boring is quite a distance from the study area, it one of the few well-studied deep borings in the region and reflects the general mineralogy in the region.

Figure 9. Earthquake Epicenters Near the Study Area

Figure 10. USGS National Earthquake Hazard Index Map (Wesson et al., 1999)

Table 3. Summary of Paleozoic Mineralogy at BP Chemicals Lima, OH Site

Formation	#Samples	Quartz	Potassium Feldspar	Plagioclase Feldspar	Calcite	Dolomite	Clay
Lower Silurian	5	26%	0%	1.0%	3.2%	51.6%	18.2%
Cincinnatian	1	4%	0%	26%	7%	8%	20%
Trenton	4	0%	0%	0%	47.8%	50.5%	1.7%
Black River	5	1.2%	0%	0%	91.2%	7.6%	0%
Wells Creek	1	16%	9%	0%	21%	26%	28%
Knox/Rome	10	10.6%	8%	0.4%	0.5%	77.1%	3.4%
Eau Claire Conasauga	8	33.1%	34.6%	0%	9.5%	11.2%	9.5%
Mt. Simon/ Basal Sandstone	20	70.9%	24%	0%	0%	0.85%	4.7%
Middle Run	4	64.8%	23.8%	3.8%	0%	0.5%	7.2%

Based on various methods (BP, 1991).

Precambrian rocks are mostly gneiss and granite in the study area. Davis (1991) notes that the Precambrian rocks at the Aristech site were foliated gneiss to gneiss-granite that contained a large percentage of quartz, plagioclase, hornblende, and biotite mica. Some calcite, dolomite, and anhydrite were present in fractures, but decreased in abundance in deeper samples. More granitic rocks will likely contain a higher fraction of quartz as observed in western parts of the cratonic rocks. In general, all Precambrian rocks have a higher percentage of mafic minerals that give the rocks a higher density than the overlying sedimentary rocks. These rocks are almost void of pore space. Any pore space in the rocks is usually in the form of fractures.

The basal sandstone/Mt. Simon is a fine to medium grained sandstone composed of primarily quartz, potassium feldspar, clay, and dolomite. The basal sandstone/Mt. Simon reflects the deposition of clastic sands eroded off granitic mountains. Varying degrees of dolomitization are present in the rock pore space, possibly due to mineralization of formation fluids that migrated downward into the stratigraphic column. Green glauconite crystals are common in the rock and are useful as an indicator of the basal sandstone in certain areas. Potassium feldspar is common throughout the lower Cambrian strata, and is likely related to tectonic events resulting in erosion of igneous craton rocks.

The Rome/Maryville Formation is mostly dolomite in the study area (Table 4). Analysis of core samples from the Aristech site shows that the rock is primarily dolomite with lesser amounts of quartz and potassium feldspar. Little clay was present in the samples. Glauconite was present in some of the upper samples, but absent in the lower Rome so it may be a useful indicator of the basal sandstone/Mt. Simon. Otherwise, the lower Rome/Maryville formation appears to be similar to the basal sandstone in mineralogy and porosity.

The Conasauga Group is mostly shale with varying amounts of dolomite. In the study area, the lower Conasauga is largely dolomite, and shale is more prominent in the upper portions. Table 5 summarizes mineralogy encountered in this formation at the Aristech site. Mineralogy reflects the change in composition. Dolomite, feldspar, and quartz are the primary minerals in the lower section; clay, feldspar, and quartz are the principal minerals in the upper samples. The changes in mineralogy are gradational with no abrupt shift. Glauconite, pyrite, and mica are present throughout the formation.

Table 4. Mineral Percentages in the Rome/Maryville Formation at the Aristech Site

Sample Depth (ft)	5214-5215	5221-5222	5237-5238	5243-5244	5254-5255	5262-5263	5369-5270
Quartz	3.6%	16.9%	13.3%	3.0%	0.3%	5.3%	2.3%
Feldspar	2.0%	22.3%	1.3%	3.3%	2.0%	0.3%	2.7%
Mica	---	---	---	---	---	---	---
Dolomite	88.6%	54%	93%	93.7%	96.7%	93.0%	90.3%
Calcite	0.3%	0.3%	4%	---	---	---	3.7%
Clay	1.0%	0.6%	Tr	Tr	Tr	0.7%	Tr
Glauconite	3.3%	4.0%	---	---	---	---	---
Pyrite	0.6%	0.3%	---	---	1.0%	0.7%	---
Zircon	---	1.0%	---	---	---	---	---

Based on thin section point count (Davis, 1991).

Tr = trace direction.

Table 5. Mineral Percentages in the Conasauga Group at the Aristech Site

Sample Depth (ft)	5156-5157	5171-5172	5180-5181	5187-5188	5195-5196	5197-5198	5206-5207
Quartz	30.7%	11.1%	20.3%	9.3%	13.6%	7.6%	9.6%
Feldspar	26.9%	8.2%	16.3%	8.6%	10.0%	16.3%	4.6%
Mica	6.7%	4.6%	0.3%	2.3%	3.6%	2.6%	---
Dolomite	5.3%	39.3%	29.3%	64.3%	43.6%	60.6%	65.6%
Calcite	---	---	---	0.3%	---	---	---
Clay	23.6%	33.6%	27%	10%	23%	9.0%	0.3%
Glauconite	1.3%	0.3%	4.0%	1.0%	1.3%	2.0%	19%
Pyrite	3.6%	2.0%	2.6%	1.6%	4.6%	1.6%	0.6%
Zircon	---	---	---	---	---	---	---

Based on thin section point count (Davis, 1991).

The Copper Ridge Formation is predominantly dolomite in the study area. As such, dolomite is the main mineral present in the rock layer. Lesser amounts of quartz, potassium feldspar, and clay are found in the Copper Ridge. The formation is more variable to the west in Ohio where several formations merge into the Knox Dolomite. In Table 3, the Knox/Rome are likely similar to the Copper Ridge at the study area, because the Rome and Rose Run are not present at the BP Lima site.

The Rose Run Formation is a fine-grained sandstone. Major minerals in the formation include quartz, dolomite, and potassium feldspar. Glauconite and pyrite also are present in the formation. The sand grains in the Rose Run are well-rounded and well-sorted, preserving much of the primary sandstone in the rock. Dolomite and more calcareous limestone layers are interbedded within the formation.

The Beekmantown and Wells Creek formations are largely dolomite with varying amounts of calcite. In general, the Wells Creek is more calcareous and often classified as a limestone. These formations also include portions of potassium feldspar, quartz, and clay. The amount of clay may be significant in shaley layers of the formations as evidenced by the BP Lima Wells Creek mineralogy. Minor amounts of pyrite and glauconite also may be present.

The Black River and Trenton formations are mostly limestone. Calcite is the predominant mineral in the formations. Dolomite and quartz generally occupy less than 10% of the rock. Secondary porosity in the form of fractures provides enough porosity in the Trenton for it to be a (formerly) prolific reservoir for gas in the mid-eastern sections of Ohio.

The Reedsville and Juniata units are thick shale layers that correspond to the Cincinnati Series in the Midwest. These formations are composed of typical shale mineralogy with a large proportion of clay minerals and plagioclase feldspar. Dolomite, calcite, and quartz also are present to a much lesser extent. Plagioclase is the dominant feldspar in Upper Ordovician and younger rocks in the study area, likely due to long-term erosion trends.

A series of limestone and sandstone units exist in the Lower Silurian. These units are composed of mainly quartz, calcite, and dolomite with varying fractions of feldspar and clay. Another prominent shale, the Rochester, overlies the lower Silurian rocks. The shale unit contains clay minerals along with plagioclase feldspar, quartz, and calcite. Another series of mostly dolomite rocks is found in the Upper Silurian. The “Newburg” is present in the upper Silurian beneath the Salina. The Newburg is a fine grained quartz sandstone with varying degrees of dolomite. The formation has a good deal of primary porosity and readily supplies brine.

The Lower Devonian contains the Oriskany sandstone, a potential injection reservoir. The Oriskany is clean fine to medium grained sandstone with varying degrees of quartz or calcite cementation. Secondary minerals in the formation include plagioclase feldspar, clay, and pyrite. Patchen and Harper (1996) and Opritza (1996) suggest that the calcite cementation increases toward the western portion of the Oriskany where the formation thins out. This cementation decreases the porosity and permeability of the formation.

Overlying the Oriskany is a series of limestone, shale, and chert units in the middle Devonian. These units contain varying amounts of calcite, feldspar, and quartz. The Ohio Shale is a very thick and extensive unit that exists in the upper Devonian record in the study area. This formation contains clay, plagioclase feldspar, calcite, and quartz. The Ohio Shale represents the shallowest formation capable of retaining injected fluid in a supercritical state.

A series of sandstone plays is found at the base of the Mississippi. Quartz is the major mineral in the sandstones. Another shale, the Sunbury, is the next rock formation in the geologic record. This shale unit is comprised of clay, plagioclase feldspar, calcite, and quartz. Several series of sandstone, limestone, and shale units are found above the within upper Mississippian, Pennsylvanian, and Permian rocks. These formations are generally composed of variable mineralogy with mostly quartz, calcite, clay, and feldspar. Coalbeds are also found in several of the Pennsylvanian and Permian formations. The coalbeds are 2-10 ft thick.

3.7 Coalbed Methane Potential

Coalbed methane refers to natural gas that exists in coal deposits. The gas is produced by natural processes within coal and is sorbed onto the coal or retained in pore space. Although coalbed methane is a hazard in mining operations, it can be a valuable resource in extractable quantities. Coalbeds must generally be below 500 ft deep to maintain the gas at pressure. Some coalbed methane reservoirs readily produce gas when penetrated by a well, but many reservoirs require pumping of formation waters from the coalbed, which reduces reservoir pressure and allows the gas to escape. CO₂ also may be injected into a coal horizon to enhance natural gas production. In the process, CO₂ is preferably sorbed onto the coal and the methane is released, thereby sequestering the CO₂ while producing natural gas.

Total coalbed methane resources in the Appalachian Basin are estimated at 66 trillion cubic feet (Tcf) (GTI, 2001). Rice (1995) identified three main areas of coalbed methane resources in the Appalachian Plateau: the Northern Appalachian Basin Syncline Play, the Northern Appalachian Anticline Play, and the Central Appalachian Syncline Play (Figure 11). The New Haven site is nearest to the Northern Appalachian Syncline Play, which is estimated to have a 10.5 Tcf of recoverable coalbed methane (Ruppert and Rice 2000).

Figure 11. Extent of the Northern Appalachian Basin (Ruppert and Rice, 2000)

Coal deposits were evaluated for the area surrounding the project site to determine the potential for enhanced coalbed methane applications. The site lies in the Northern Appalachian Coalbed basin (Figure 11). Underground coal mining started in the region in the 1850s, and coal has been mined extensively in the basin. Much of the mining in the Northern Appalachian Basin is within the Pittsburgh and Pottsville groups, but the thickness of these groups is low in the New Haven area as shown in Figure 12 (Vinciguerra and Slucher, 2002). Mining activity in the study area occurs mainly in the seam identified as the Redstone in West Virginia and the Pomeroy in Ohio. This coal seam is fairly shallow in the area and dips to the east-southeast. Several abandoned sidewall mines or shallow surface mines access the Redstone/Pomeroy near New Haven on both sides of the Ohio River. Because of these abandoned mines

Figure 12. Pennsylvanian Allegheny and Pottsville Groups Net Coal Thickness
(Source: Vinciguerra and Slucher, 2002).

and the shallowness of the seam near New Haven, the coal seam is not capable of containing enough pressure so that CO₂ can be adsorbed onto the coal surfaces and then remain there in equilibrium.

Currently, coalbed methane is produced in the Northern Appalachian Basin mainly from the Pittsburgh coalbed in northern West Virginia about 60 miles from New Haven (Figure 13). Production in this area ranged from approximately 50 to 225 million cubic ft per year (Mcf/yr) with cumulative production of more than 1,000 MMcf. No coalbed methane recovery wells currently exist in the immediate area of New Haven.

Appalachian Basin CBM Production

Figure 13. Appalachian Basin Coalbed Methane Production (Source: Milici, 2002)

Because the shallow coal seams mined in the area were not suitable for coalbed methane application near the site, deeper coal deposits (over 300 ft) were investigated. All available drilling logs in Mason County, WV, were examined for a record of coal measures deeper than approximately 300 ft. Most logs offered little exploration information on coal at depth, because at the period in time when mines in the region were constructed, any coal at a substantial depth, even if very thick and of very high quality, was considered unminable. When coal companies performed exploratory drilling, they normally proceeded just to the depth of the coal that was already of interest.

Some knowledge of these deeper coals was obtained from the oil and gas wells developed in the area, many of which exceed 3,500 ft in depth. However, these logs do not provide as much information as wells drilled primarily for coal purposes, and frequently carry little dependable information on the

geologic zones of interest for coal definition. The oil and gas drillers were not interested in coal (except as marker beds for drilling guidance) and frequently neglected to note them. The information gained on coal horizons was not adequate to make estimates of uniformity, continuity, or total resource quantities. No useful information on the quality or grade of the coal or black shales was available from the logs. This study did not directly examine the geophysical logs from the local wells, since the tools were most commonly run through the upper strata at surveying speeds too fast to allow adequate resolution of the data to interpret coal horizons or other major features.

Of all the examined well logs in Mason County, 23 logs covering the West Virginia portion of the Pomeroy, Chester, Addison, and Chesire quadrangles mention either coal or a continuous black shale zone known to drillers of the day as “The Black,” which was used as a marker bed (Table 6). A total of 39 coal shows were detected in 23 wells. Multiple coal seams were noted in 11 of the wells (Table 7). Coal seams up to 10 ft thick were noted in the logs, and gas shows were recorded in several of the coal intervals. The average total thickness within the wells was 3.92 ft and average depth was 508 ft.

It was not possible to map the thickness or extent of the coal seams since most wells logs did not consider coal seams. Consequently, potential coal horizons were analyzed. Table 8 summarizes potential coal horizons in wells with coal shows. Overall, there were eight horizons with potential coal seams. Horizons at elevations of approximately 40 to 60, -1 to 20, -111 to -84, and -215 to -146 ft msl appear to have acceptable depth, thickness, and extent for coalbed methane applications and may merit further exploration.

Black shale horizons were also investigated. Organic black shale layers may be used for CO₂ sequestration and enhanced natural gas recovery. Considerable Devonian black shale deposits are present in Kentucky, but the black shales noted in the well logs of Mason County West Virginia that were analyzed appear to be associated with younger Mississippian formations. Table 9 summarizes black shale shows detected within the well logs examined from northern Mason County. Black shale was detected in 15 wells and had an average thickness of 8.2 ft. The shows were at a fairly consistent elevation of -1,012 to -962 ft msl. Depth to the shales ranged from approximately 1,500-1,600 ft bgs.

Overall, it appears that adequate information is not available to identify an individual coal horizon suitable for the production of methane or the sequestration of CO₂ in the area of the Mountaineer Power Plant. However, several coal horizons and a black shale interval appear to have potential for further exploration. Review of well logs and geological background information for the area suggests that a suitable horizon cannot be ruled out. Several coal shows were found at horizons over 300 ft deep in well logs for the area. In addition, a black shale with average thickness of 8.2 ft approximately 1,500-1,600 ft deep was detected in several wells in the northern portion of Mason County. Final determination on coalbed methane applications would have to be made with additional exploration activities specifically aimed at characterizing potential coal seams. Strata of adequate depth are more likely to be found on the West Virginia side and in regions eastward. The nearest active coalbed methane operation is approximately 60 miles north of the study site.

Table 6. Coal Shows in Pomeroy, Chester, Addison, and Cheshire quadrangles of Mason County, WV. Multiple Coal Showings Are Boxed with Blue. Black Shale Shows are Shaded Green.

Well I.D.	Dates Drilled	Elevation	Total Depth	Top	Foot	Thickness	Comment
25	7/38-7/38	606	2295	359	360	1	Log less detailed after 650' depth
		717.8	1755	604		5	coal
				675		2.5	Log doesn't show bottom coal, but it is listed in the coal section of cover
28				750		7	coal
31	4/43-7/43	725.5	3142	140	145	5	coal
				770	780	10	Slate and coal mix
9A	1925	608.7	610	604	610	6	Log lists a gas show in the center of the "Freeport" seam; hole
	1925	692.4	690	82	87	5	coal
				684	690	6	Log lists a gas show in the center of the "Freeport" seam; hole
118	unk, filed 5/73	591	1250	135	140	5	Incompletely filled form; coal blanks, drill dates ignored
				678	683	5	coal
				800	806	6	coal
10	Unk, permit 12/34	690.1	787	129	134	5	no proper form filled out
				771	774	3	coal
19	Unk, permit 7/35	688.7	558				mine opening listed 128 to 133
109	10/68/11/68	652	3387	417	421	4	coal & shale
384	12/84-12/84	557	1661	642	643	1	Note coal in this and adjacent 385 well
385	12/84-12/84	554	1675	235	237	2	coal
				1527	1534	7	just says "black", not "coal"
406	Permit 10/85	595	350	27	27.5	0.5	Shallow well
408	1/86-1/86	576	1680	514	516	2	More coal noted than in most nearby logs
				525	526	1	coal
				676	678	2	coal
				1552	1562		just says "black", not "coal"
407	1/86-1/86	595	1718	494	496	2	coal
				580	581	1	coal
				743	749	6	coal
				1594	1604	10	just says "black", not "coal"
409	1/86	652	1787	636	641	5	coal
				1644	1653	9	just says "black", not "coal"
410	1/86	593	1765	533	535	2	Listed in reporting form, but not in the log
411	1/86	594.5	1685	641	644	3	coal
				701	705	4	coal
				1551	1557	6	just says "black", not "coal"
412	12/86	599	1710	741	747	6	coal
				1582	1592	10	just says "black", not "coal"
413	12/86	613	1726	177	181	4	coal
				1590	1600		just says "black", not "coal"
414	12/86	567	1677	1537	1547	10	just says "black", not "coal"; note proximity to wells that do list coal
415	12/86	581.5	1685	282	284	2	coal
				1517	1527	10	just says "black", not "coal"
416	12/86	606	1695	330	333	3	coal
				772	774	2	coal
				1517	1527	10	just says "black", not "coal"
7A	Unk., aban. 1953	360	1630	437	443	6	Upper Freeport
				535	540	5	Middle Kittanning
364	11/84	559	1669.52	1526	1531	5	identifies the "Black" as a black shale
365	11/84	565	1660	1515	1523	8	identifies the "Black" as a black shale
366	11/84	565	1662.7	1525	1529	4	identifies the "Black" as a black shale
367	11/84	566	1660	1515	1523	8	identifies the "Black" as a black shale
368	11/84	549	1660	500	502	2	coal
				537	538	1	coal
				685	695	10	Note!!! Coal Handwritten, but read twice and checked
				1543	1549	6	"Black"

Table 7. List of Wells with Coal Shows in Pomeroy, Chester, Addison, and Cheshire Quadrangles of Mason County, WV

Well I. D.	Collar Elevation	Strata Top	Strata Foot	Strata Thickness	Strata Sea Level Elevation
10	690.19	129	134	5	556
10	690.19	771	774	3	-84
19	688.79	128	133	5	556
25	606	359	360	1	246
25	717.82	604	609	5	109
25	717.82	675	677.5	2.5	40
28	717.82	750	757	7	-39
31	725.5	140	145	5	581
31	725.5	770	780	10	-55
109	652	417	421	4	231
118	591	135	140	5	451
118	591	678	683	5	-92
118	591	800	806	6	-215
383	549	500	502	2	47
383	549	537	538	1	11
383	549	685	695	10	-146
384	557	642	643	1	-86
385	554	235	237	2	317
406	595	27	27.5	0.5	568
407	595	494	496	2	99
407	595	580	581	1	14
407	595	743	749	6	-154
408	576	514	516	2	60
408	576	525	526	1	50
408	576	676	678	2	-102
409	652	636	641	5	11
410	593	533	535	2	58
411	594.5	641	644	3	-50
411	594.5	701	705	4	-111
412	599	741	747	6	-148
413	613	177	181	4	432
415	581.5	282	284	2	298
416	606	330	333	3	273
416	606	772	774	2	-168
10A	692.4	82	87	5	605
10A	692.4	684	690	6	2
7A	560	437	443	6	117
7A	560	535	540	5	20
9A	608.7	604	610	6	-1

Wells: 23		Depth to	Strata	Strata Elev.
Coal Shows: 39		<u>Footwall</u>	<u>Thickness</u>	<u>Above Sea Level</u>
Wells w/1 show: 12	Average	508.26	3.92	110.30
Wells w/2 shows: 6	Std Dev	227.07	2.31	236.43
Wells w/3 shows: 5	Minimum	27.2	0.5	-215
	Maximum	806	10	605.4

**Table 8. Potential Coal Horizons Detected in Pomeroy, Chester, Addison, and Cheshire
Quadrangles of Mason County, WV**

Well I. D.	Collar Elevation	Strata Footwall	Strata Thickness	Strata Sea Level Elevation	
10A	692.4	87	5	605	
31	725.5	145	5	581	
406	595	27.5	0.5	568	
10	690.19	134	5	556	Potentially single strata of coal Probably the Redstone seam
19	688.79	133	5	56	
118	591	140	5	451	
413	613	181	4	432	
385	554	237	2	317	
415	581.5	284	2	298	
416	606	333	3	273	Potentially single strata of coal
25	606	360	1	246	
109	652	421	4	231	
7A	560	443	6	117	
25	717.82	609	5	109	Indeterminate signs of coal
407	595	496	2	99	
408	576	516	2	60	
410	593	535	2	58	
408	576	526	1	50	Potentially single strata of coal
383	549	502	2	47	
25	717.82	677.5	2.5	40	
7A	560	540	5	20	
407	595	581	1	14	Potentially single strata of coal
383	549	538	1	11	
409	652	641	5	11	
10A	692.4	690	6	2	
9A	608.7	610	6	-1	
28	717.82	757	7	-39	
411	594.5	644	3	-50	Indeterminate signs of coal
31	725.5	780	10	-55	
10	690.19	774	3	-84	
384	557	643	1	-86	
118	591	683	5	-92	Potentially single strata of coal
408	576	678	2	-102	
411	594.5	705	4	-111	
383	549	695	10	-146	
412	599	747	6	-148	
407	595	749	6	-154	Potentially single strata of coal
416	606	774	2	-168	
118	591	806	6	-215	

**Table 9. List of Wells with Black Shale Shows in Pomeroy, Chester, Addison, and Cheshire
Quadrangles of Mason County, WV**

Well I. D.	Collar Elevation	Strata Top	Strata Foot	Strata Thickness	Strata Sea Level Elevation
364	559	1526	1531	5	-972
365	565	1515	1523	8	-958
366	565	1525	1529	4	-964
367	566	1515	1523	8	-957
383	549	1543	1549	6	-1000
385	554	1527	1534	7	-980
407	595	1594	1604	10	-1009
408	576	1552	1562	10	-986
409	652	1644	1653	9	-1001
411	595	1551	1557	6	-962
412	599	1582	1592	10	-993
413	613	1590	1600	10	-987
414	567	1537	1547	10	-980
415	582	1517	1527	10	-945
416	606	1517	1527	10	-921

Summary:

15 wells		<u>Depth to Footwall</u>	<u>Strata Thickness</u>	<u>Strata Elev. Above Sea Level</u>
	Average	1557.20	8.20	-974.33
	Std Dev	37.23	2.04	22.83
	Minimum	1523	4	-1009
	Maximum	1653	10	-921

4.0 HYDROGEOLOGY

This section summarizes the hydrology of the rock formations at the study area. Topics covered in this chapter include hydrostratigraphy, hydraulic parameters, and groundwater flow. Information on deep formations comes from deep wells drilled to explore hydrocarbon resources and waste injection wells. Few wells penetrate deep formations, and many of the hydraulic tests were only performed in selected intervals. Consequently, data for deep formations were reviewed on a regional basis and then a more detailed examination of any site-specific information available was pursued. Overall, deep rock formations in the area are broad, layered, Paleozoic sedimentary rocks. The rocks are mainly thick sequences of shale, dolomite, limestone, and sandstone. The rock layers are laterally extensive and are similar in character throughout the region. As such, regional data are valuable to describe the general nature of the rocks.

Several potential injection reservoirs exist in the study area. These formations are sandstones with high porosity and permeability. The intervals are capable of accepting large volumes of injected waste. Overlying the injection reservoirs are thick sequences of dense, impermeable dolomite, limestone, and shale. These layers provide containment above the potential injection reservoirs. In general, it appears that the containment layers are much thicker and extensive than the injection intervals. In fact, natural gas reserves in the area hundreds of millions of years old attest to the containment capability of the rock formations. To simplify interpretation of geologic layers throughout the region, formations were divided into hydrostratigraphic units.

4.1 Deep Hydrostratigraphic Units

Hydrostratigraphic units have similar hydraulic and geologic properties. The hydrostratigraphic units are useful for tracking regional groundwater flow and predicting the impact of injection on hydrology of the system. Hydrostratigraphic units are especially useful at the New Haven site, as there are variations in the stratigraphic terminology in the area. Table 10 describes hydrostratigraphic units in the study area and the formations included in the units. In general, the hydrostratigraphic units correspond to similar formations throughout the region. Although these hydrostratigraphic units are adequate for describing formations on a regional scale, further characterization on a site-specific scale may be required to describe variations within units and the nature of the formations on a local scale.

Fluid injection and migration will be controlled by the nature of the hydrostratigraphic units. In general, the hydrostratigraphic units are laterally continuous layers throughout the region. The units are fairly flat-lying in the middle portion of Ohio into Kentucky within the Appalachian Plateau. Approaching the border of West Virginia and Ohio, the hydrostratigraphic units dip more steeply to the east-southeast. Many of the formations thin out significantly or subcrop toward this region as well. To the immediate east, several of the deeper hydrostratigraphic units downdrop dramatically within the Rome Trough, and shallower formations thicken across the Rome Trough. Some layers crop out in the subsurface toward western West Virginia and east-central Ohio, most notably the Rome, Rose Run, and Oriskany.

Target hydrostratigraphic units for injection include deep, thick sandstones that have high permeability and porosity. Several formations have the potential to accept large volumes of injected fluid. Primary potential injection reservoirs include the basal sandstone and the Rose Run Sandstone. These formations appear to have sufficient thickness for injection of large volumes. Gas plays of interest include the “Clinton Sand,” Newburg, and Oriskany. These formations appear to have acceptable hydraulic properties, but their extent and thickness are questionable. Each formation is somewhat variable in composition, but merits additional investigation. Other sandstone formations are generally too shallow for injection of CO₂.

Table 10. Hydrostratigraphic Units in the Study Area

Hydrostratigraphic Unit	General Description	Hydraulic Properties	Formations Included
Alluvium	Unconsolidated clay, silt, sand, and gravels	Very high permeability and porosity.	(Cenozoic)
Pottsville	Series of limestone, sandstone, shale, and coal units.	Low to medium permeability and porosity.	Pottsville, Allegheny, Connemaugh, Monongahela, Dunkard
Mississippian Series	Series of sandstone and shale units	Very low to high permeability and porosity.	Bedford, Berea, Sunbury, Cuyahoga, Logan
Ohio	Regional shale unit	Low to very low permeability and porosity.	Ohio
Onondaga	Shale, limestone, and dolomite units	Very low to low permeability and porosity.	Onondaga, Delaware, Hamilton, Sonyea, West Falls, Java
Salina	Limestone to sandstone	Med. Permeability and porosity	Salina, Bass Islands, Helderberg, Oriskany
Lockport	Dolomite	Med. Permeability and porosity	Lockport, "Newburg"
Rochester	Shale	Low to very low permeability and porosity.	Rochester, Dayton
Clinton	Sandstone, limestone	Med. Permeability and porosity.	"Clinton", Brassfield, Medina, Tuscarora
Reedsville	Regional shale unit	Low to very low permeability and porosity.	Reedsville, Juniata, (Cincinnati)
Black River	Mostly limestone	Med-low permeability and porosity.	Black River, Trenton, Lexington, Pt. Pleasant
Beekmantown	Dolomite, crops out in E. Ohio	Med-low permeability and porosity.	Beekmantown, Knox, Wells Creek
Rose Run	Sandstone, crops out in E. Ohio	Med-high permeability and porosity.	Rose Run Sandstone
Copper Ridge	Dolomite unit	Med-low permeability and porosity.	Copper Ridge, Gatesburg, Mayardsville
Conasauga	Regional shale unit.	Low to very low permeability and porosity.	Conasauga, Nolichucky
Rome/Maryville	Dense dolomite	Low permeability and porosity.	Rome, Maryville
Basal Sandstone	Regional sandstone unit.	Med-high permeability and porosity	Lower Rome/Maryville, Mt. Simon Sandstone
Precambrian	Precambrian rock formations.	Very dense, low permeability and porosity.	Metamorphic and igneous rocks.

Containment units.
Potential Injection unit.

In this report, the basal sandstone, Mt. Simon, and lower Rome/Marysville are grouped together as an informal designation the “basal sandstone.” In nearby wells, it was found that the lower Rome/Marysville was similar to the basal sandstone in composition and hydraulic parameters. As such, it is assumed that there is some degree of lateral continuity in the formations, and the zone is similar to the regional basal sandstone in character.

Shale, limestone, and dolomite layers form the major containment units to limit vertical migration of any injected CO₂. In general, the containment hydrostratigraphic units are thicker and more extensive than the injection hydrostratigraphic units in the study area. At the base of the Paleozoic rock formations, igneous and metamorphic rocks form a barrier to downward migration. These rocks may be fractured near the immediate contact with overlying sedimentary rocks, but are very dense and impermeable below this nonconformity. The nearest containment layers above the basal sandstone include the Rome/Marysville, Conasauga, and Copper Ridge. The Rome/Marysville is a dense dolomite, the Conasauga is a mixture dolomite and shale, and the Copper Ridge is a dense dolomite. Together, these formations provide more than 1,000 ft of containment above the basal sandstone. The Beekmantown, Black River, and Reedsville provide containment above the Rose Run Sandstone. The Beekmantown is a dense dolomite and the Black River is a limestone and dolomite mixture. The Reedsville is a uniform shale, which is considered an excellent confining layer. The unit is approximately 1,200 ft thick and primarily shale with very low permeability and porosity.

Several hydrostratigraphic units provide containment above the Reedsville. The Rochester Shale is a thick shale layer that overlies the “Clinton Sand,” and several shale layers are interspersed within the lower Silurian. The Ohio Shale represents a major containment layer in the region. The Ohio Shale is a regionally continuous and approximately 1,100 ft thick in the study area. The Ohio Shale exists at depths of approximately 2,200 to 3,300 ft bgs. As such, it is the last containment interval with enough depth to keep CO₂ at supercritical liquid pressure.

Supercritical CO₂ has a density of approximately 0.7, and formation fluids have a density of approximately 1.05 to 1.25. Consequently, the injected CO₂ is expected to move upward within the formations due to density-driven flow. Consequently, containment units above the potential injection interval are generally considered more important than underlying containment zones. In addition, the overlying containment units separate the injection intervals from any underground sources of drinking water (USDWs). Any detailed conclusions on the nature of flow would involve detailed computer simulations beyond the scope of this report. Most previous modeling indicates that the injected CO₂ will migrate upward to the immediate confining layer (Gupta et al., 1998; Gupta and Sminchak, 2000; Smith et al., 2001).

4.2 Hydraulic Parameters

Data on the regional hydraulic parameters for deep Paleozoic formations are available from drill stem tests, pressure falloff tests, pressure buildup tests, well interference tests, and geotechnical testing on core samples. These data represent average or geometric mean values from individual locations around the region and are presented to illustrate the general character of the rock layers. The main hydraulic parameters measured in formations are permeability and porosity (Table 11). A review of the data illustrates that the parameters are very site-specific. Permeability, especially, may vary over several orders of magnitude within a formation due to variations in the nature of the rock. Porosity is generally more consistent. The testing method also can have a large impact on results.

For permeability, there are two main categories of tests: in situ reservoir tests, and ex situ core tests. In situ reservoir tests consist of pressure fall-off, step rate, and interwell pressure interference tests. In the tests, an interval of the formation in a borehole is isolated with packers and pressure is monitored after

**Table 11. Hydraulic Parameters for Hydrostratigraphic Units in the Study Area
Including Potential Gas Plays**

Hydrostratigraphic Unit	Depth ^(a) (ft bgs)	Thickness ^(a) (ft)	Permeability (mD)		Porosity (%)	
			Regional ^(b)	Site ^(c)	Regional ^(b)	Site ^(c)
Alluvium	0	0-100	0.1-1,000s	0.1-1,000s	0.15-0.35	0.15-0.35
Pottsville	100	~1,300	Variable	Variable	2 – 25	2 – 25
Mississippian Series	1,400	~800	Variable	Variable	2 – 25	2 – 25
Ohio	2,100	1,100	1E-8 – 1E-9	1E-8 – 1E-9	1 – 5	1 – 5
Onondaga	3,200	500	<1.0	<1.0	2 – 10	2 – 10
Oriskany	3,700	5-15	0.1 – 30	NA	2 – 20	8.5
Salina	3,700	200	<1.0	<1.0	2 – 10	2 – 10
“Newburg”	3,900	5-15	0.8 – 133	7	5 – 20	11
Lockport	3,900	400	0.1 – 30	NA	2 – 10	8.5
Rochester	4,300	500	1E-6	1E-6	<3	<3
Clinton	4,800	200	<1.0	<1.0	2 – 10	2-10
“Clinton Sand”	4,800	5-50	0.1 – 111	0.36 – 6.2	2 – 23	8
Reedsville	5,000	1,200	1E-7 – 0.1	1E-6	<3	<3
Black River	6,200	750	<1.0	<1.0	<5	<5
Beekmantown	6,950	600	<1.0	<1.0	<5	2.5 – 13
Rose Run	7,550	100-150	0.01 – 198	13 – 86	2-25	8 – 14
Copper Ridge	7,700	700	0.1 – 100	28 – 135	2 – 8	5
Conasauga	8,400	200	<1E-6	2E-6 – 1.4E-4	<3	<3
Rome/Maryville	8,600	500	<0.1	2E-5 – 6.7	<5	<5
Basal Sandstone	9,100	50-100	0.01 – 500	20 – 60	4 – 25	12
Precambrian	~9,200	---	0-1.0	NA	0 – 10	<1

(a) Approximate values based on nearby deep wells.

(b) Approximate values based on regional summary data.

(c) Approximate values based on nearby deep wells or gas fields.

pressure is increased or fluid withdrawn. These tests reflect the overall permeability of the entire interval and result in a single value for permeability.

Ex situ testing involves analysis of individual core samples from the formations. A core sample is flooded with either gas or liquid and the permeability measured in a geotechnical laboratory. Values for horizontal and vertical permeability can be determined. Ex situ tests yield more variable results because they can be performed on numerous cores. Factors such as artificial fractures caused during core retrieval, overburden pressures, and precipitation of minerals (salts) due to sample drying can complicate core analysis. In this summary, both in situ and ex situ data on regional permeability and porosity are

presented. In situ tests are more applicable to injection purposes and are given more weight in drawing conclusions regarding the permeability of injection intervals.

Porosity values are usually measured from cores and geophysical logs. In situ geophysical logs are taken continuously by downhole instruments. Porosity scales in geophysical logs typically vary for the type of rock formation and can introduce some uncertainty. Ex situ core tests are performed by flooding and then drying the sample. It should be noted that shales and other low permeability formations may have high (15-40%) total porosity, but very low (0-3%) effective porosity. Effective porosity refers to the pore space in rocks that water can travel through. In terms of fluid migration and injectivity, effective porosity is the more useful parameter.

Relative permeability is a way to express the conductivity of a rock for mixtures of fluids with different densities. The parameter is usually expressed in a curve over the saturation amounts for each fluid. No substantial oil reserves have been found in most of the formations, so little if any relative permeability testing has been performed on cores from the formations.

4.2.1 Primary Potential Injection Units

BASAL SANDSTONE

The basal sandstone is an informal name that refers to sandstones encountered immediately above Precambrian bedrock. In the study area, the unit may be associated with portions of the lower Rome/Marysville and appears to be 50-100 ft thick. In general, regional permeability values for the basal sandstones range from less than 1 millidarcy (mD) to several hundred mD. Figure 14 shows average permeabilities from individual locations as measured within basal sandstones in the region. The regional data indicate an average permeability of approximately 86 mD, which is near the central tendency of the data as seen in histogram (Figure 15). The geometric mean value is 47 mD. Permeability varies with depth, location, and analysis method. As such, there is substantial variability in the parameter, indicated by a large standard deviation (104 mD) in the regional dataset. This is not unexpected, as permeability may vary by several orders of magnitude within a hydrostratigraphic unit. The ratios of horizontal to vertical permeability in the formation vary substantially from less than 1:1 to 1,200:1, but have a mean value of 25:1 and median value of 4:1 (Becker et al., 1978).

Regional data show few trends toward the study area. The nearest source for site-specific permeability data is the Aristech site. The basal sandstone was generally 70-80 ft thick in the wells but only the upper 35 ft of the formation had high enough porosity and permeability to be considered the injection zone. Reservoir tests performed in the basal sandstone suggested permeability of 20-60 mD. Short-term pressure falloff tests indicated permeability of 51-60 mD, whereas interference tests indicated a permeability of 20 mD (REC, 1991). Air permeability core analyses from the upper basal sandstone ranged from 0.1 to 94 mD and had an average permeability of 26.8 mD. Cores from the lower portion of the formation had an average permeability of 0.4 mD and many of the tests were below detection (Davis, 1991). When modeling the migration of injectate, a permeability value of 56 mD was used with acceptable results (REC, 1991). Figure 16 shows a graph of permeability and porosity with depth from cores at Aristech. Permeability shows more variation but generally stays within a range of 20-70 mD. Compared to other injection sites, the permeability values measured near the study area are well within the range expected for the basal sandstone and very comparable to other reservoir tests in the formation. Testing indicates layers of higher and lower permeability as seen in other wells. However, there are no tests with permeability at several hundred millidarcies as observed at many other sites.

Figure 14. Map Showing Average Permeability for Basal Sandstones in the Region

Figure 15. Histogram of Basal Sandstone Permeability Values from the Midwest Region

Figure 16. Permeability and Porosity at Depth as Measured in Basal Sandstone Cores at the Aristech Site (Davis, 1991)

A substantial amount of data is available on porosity for the basal sandstone formation, because the parameter can be measured from downhole logging as well as core analysis. A regional review of porosity ranges from 4% to 25% in the basal sandstone with an average of 12%. In the study area, porosity maps suggest a porosity of approximately 10-15%. Porosity in the basal sandstone appears to be primary intergranular space, which explains why it is such a favorable formation for injection.

At the Aristech site, porosity was estimated from core analysis and geophysical well logging. Based on core analysis from WDW#1, the upper basal sandstone had an average porosity of 11.9% and the lower portion had an average porosity of 3.9% (Davis, 1991). Porosity over most of the upper portion of the cores was consistent at 10-16%. Density-neutron porosity log measurements in WDW#1 suggest porosity of 5-22% in the upper basal sandstone and less than 10% porosity in the lower basal sandstone (Davis, 1991). Based on log analysis, the average porosity in the upper portion of the lower basal sandstone was 16.4% (Davis, 1991). Overall, porosity in the study area is similar to regional estimates and is suitable for injection.

ROSE RUN

The Rose Run is another hydrostratigraphic unit considered for injection, because it is a sandstone with relatively high permeability and porosity. The Rose Run total thickness in the study area appears to be greater than the basal sandstone. The Rose Run is better known for containing oil and gas reserves in portions of central Ohio, Tennessee, and Kentucky than for waste disposal, but the formation may be suitable for injection in the study area. The Rose Run consists of dolomitic sandstone approximately

100-150 ft thick in the study area. Regional porosity for the Rose Run equivalent ranges from approximately 2% to 25%, and permeability ranges from 0.01 mD to 198 mD (Baranoski et al., 1996). Cores from the Rose Run were collected from WDW#1 at the Aristech site and analyzed for porosity and permeability (Davis, 1991). Average core permeability for upper portion of Rose Run was below detection, and core porosity was 3.9%. However, core analysis from the lower Rose Run had a permeability of 33 mD and porosity of 10.4, which is similar to the lower basal sandstone. Air core permeability from the test/monitoring well at the site had a permeability of 86 mD. Reservoir tests in WDW#3 yielded a permeability of 22.7 mD in the Rose Run. Reservoir tests performed in WDW#1 in the Rose Run at the Aristech site suggested a permeability of 12.7 mD (REC, 1991). Density logs show porosity of 8-14%.

4.2.2 Secondary Potential Injection Units

“CLINTON”

The “Clinton” consists of a sandstone zone within the Lower Silurian. The layers vary substantially in properties and thickness throughout the region. The “Clinton” is one of the largest gas plays in the Midwest, with more than 60,000 gas wells completed in the unit. Gas plays in the Clinton have been penetrated in eastern Ohio, northwestern Pennsylvania, and southwestern New York. Regional porosity in the unit ranges from approximately 2% to 23% with an average of 6%-10% (McCormac et al., 1996). Average permeability within wells near the study area is approximately 8%. Regional permeability ranges from 0.1 mD to 111 mD (McCormac et al., 1996). Average permeability within fields near the study area ranges from 0.36 to 6.2 mD. There is some indication that the formation may be up to 46 ft thick in the study area (see Appendix A).

NEWBURG

At the top of the Lockport is a highly transmissive zone often termed the “Newburg Zone”. Drillers commonly refer to the layer as the “Big Water,” the “Second Water,” or the “Second Water in the Big Lime.” The interval is a prolific source of brine and often produces surface flows when penetrated. Production of hydrogen sulfide often is associated with the Newburg. The formation is comprised of a fine-grained quartz sandstone and dolomite. In western portions of the region, the “Newburg” may contain large open pore space or even cavernous zones within limestone and dolomite. However, in the study area, the formation is a fine-grained sandstone. Gas plays in the Newburg have been exploited in portions of Jackson County, WV, and Meigs County, OH. Porosity in the Newburg near the study site ranges from approximately 5 to 20% and averages 11% (Patchen, 1996). Permeability data were unavailable from the unit. Similar sandstones in the Lockport have an average permeability of 7 mD with a range of 0.8 to 133 mD (Noger et al., 1996). The formation thins in the study area and may not be present.

ORISKANY

The Oriskany is a well sorted quartz sandstone. The Oriskany contains gas plays to the east and north of the study area, where several hundred wells penetrate the unit. It is usually interbedded between two chert layers that make up an effective stratigraphic trap. The formation thins appreciably at its western extent near the study area, and porosity decreases. Consequently, the formation is not considered a viable gas reservoir in the area, with only scattered gas plays (Diecchio et al., 1984; Harper and Patchen 1996). Permeability in the Oriskany ranges from approximately 0.01 to 30 mD in the study area (Flaherty, 1996; Harper and Patchen, 1996; Patchen and Harper, 1996). Porosity in the formation ranges from 2-20% and generally averages 5-12%. Patchen and Harper (1996) note that the upper portion of the formation is

commonly more porous and permeable due to incomplete cementation. The Oriskany appears to be only 15 ft thick in the study area.

4.2.3 Containment Units. Many containment hydrostratigraphic units overlie the potential injection intervals. These containment intervals generally have low permeability and porosity, which makes upward migration of any injection liquids unlikely. Lateral migration of fluids is controlled by the extensiveness of the reservoir and structure. Containment units include the Rome Formation, the Conasauga, Copper Ridge, Beekmantown, Black River, Reedsville, Rochester, Salina, Onondaga, and Ohio Shale. The Reedsville, Rochester, and the Ohio Shale are all thick shale layers that are competent confining zones. Together, these layers form nearly 3,000 ft of containment above the basal sandstone and Rose Run. The fine-grained nature of the rocks inhibits fluid migration through the formations. The other hydrostratigraphic units are mostly sandstone and limestone that have lesser porosity and permeability than the injection formations. This section summarizes the hydraulic properties of the containment intervals.

ROME/MARYVILLE

The Rome/Maryville hydrostratigraphic unit is a dense dolomite that conformably overlies the basal sandstone interval. The Rome/Maryville appears in eastern Ohio and thickens toward the east where it downdrops into the Rome Trough. Geologic isopach maps indicate that the containment interval is several hundred feet thick in the study area. Few hydraulic testing data are available on the formation because it exists only in portions of the region and is not a source of oil and gas. Regional data generally suggest a permeability of less than 0.01 mD and porosity of 5% or less.

Site-specific hydraulic data from the Rome/Maryville were obtained at the Aristech site. Cores from the formation were tested for air permeability with a range of 0.06 to 6.7 mD. Brine permeability measured for four 1-ft intervals in the Rome had values of 2.3E-5 to 8.2E-5 mD. Geophysical logs, core samples, and thin sections all indicate porosity of less than 5%. Some fracturing was present in the cores, which may have influenced results. It is uncertain if the fractures were a byproduct of drilling or original.

CONASAUGA

The Conasauga is primarily shale with interbedded layers of dolomite. The formation is regionally pervasive and may be traced to the Eau Claire to the west of the study area. Regional data on the Conasauga and equivalent suggests a porosity of less than 3% and permeability of less than 1E-6 mD. At the Aristech site, no porosity was observed in core samples and reservoir testing yielded no fluid, suggesting a very tight, low permeability formation. Sixteen brine core permeability tests from the Conasauga ranged from 2.5E-6 to 1.4E-4 mD. One core was fractured, and had a suggested permeability of 705 mD.

COPPER RIDGE

The Copper Ridge is a dolomite formation that is about 700 ft thick in the study area and forms a regional layer that is equivalent to the Gatesburg. In general, the formation thickens and becomes more prominent to the east of Ohio into West Virginia. Regional testing suggests porosity in the range of 2-8% with typical values around 5%. Reservoir testing performed at the test/monitoring well at Aristech suggested a permeability of 28-135 mD. Given the low porosity in the formation, the relatively high permeability range is somewhat uncertain.

BEEKMANTOWN

The previous formations may be considered containment and/or buffer zones for the basal sandstone. The Rose Run overlies the Copper Ridge and is generally too permeable and porous to offer much containment. The Beekmantown and following formations are containment layers for the Rose Run and/or basal sandstone. The Beekmantown Formation consists of mainly dolomite and is approximately 500 ft thick in the study area. Regional porosity is generally less than 5% and permeability is generally less than 1 mD. At the Aristech site, a substantial amount of testing was performed in the Beekmantown in the test/monitoring well because the formation was designated the primary containment interval. Tests in the original disposal well showed permeability at less than detection and porosity of 2.5%. More extensive testing was performed in the test/monitoring well where the porosity averaged 2.2% and permeability was 0.1 mD. Porosity from geophysical well logs also was less than 3%. A closer look at the core testing shows that the porosity ranged from 0.3% to 8%. Permeability generally was less than 1.0 mD, but one sample had a porosity of 12% and permeability of 539 mD due to fracturing. In general, it appears that the Beekmantown is dense dolomite with low porosity and permeability. Sections with fractures may have substantially higher porosity and permeability.

BLACK RIVER

The Black River Group is mainly dense limestone and approximately 750 ft thick in the study area. Porosity is generally 0-5%, but zones of higher porosity were observed in the formation. The Trenton Limestone has similar properties to the Black River and is approximately 75 ft thick in the study area. The two units are included in the “Black River” hydrostratigraphic unit. The formation has a porosity generally less than 5% and permeability less than 1.0 mD. Geophysical logs for the Aristech WDW#1 show porosity at less than 5% with some sandstone intervals having porosity at 8-12%.

REEDSVILLE

The Reedsville marks a major shale containment hydrostratigraphic unit over the potential injection zones. In the New Haven area, the Reedsville and Juniata combine to form approximately 1,200 ft of mainly shale. Although geophysical logs often show shales with porosity up to 35%, effective porosity is usually on the order of 0-3%. Permeability is commonly below 1E-6 mD. Reservoir tests are generally unsuccessful in the shale layers because the formations do not yield water. Other core tests performed in similar shale formations in the Midwest yielded permeability values on the order of 1E-7 to 1E-1 mD within the formations. Fluid migration by traditional advective transport is usually insignificant across shale layers and mass movement is usually driven by diffusion processes in low permeability layers.

ROCHESTER

The Rochester is a containment hydrostratigraphic unit above the “Clinton.” The unit includes the Dayton Formation and the Rochester Shale. The Dayton is a dense limestone often referred to as the “Packer Shell” by drillers because it contained shell fossils and was used to pack off underlying “Clinton” gas wells. In the study area, the Rochester is approximately 500 ft thick, and continuous throughout the region. Few hydraulic tests in the formation have been performed because it is such a low permeability unit. Porosity in the formation is generally less than 3% and permeability is similar to other shales at less than 1E-6 mD.

SALINA

The Salina hydrostratigraphic unit consists of several limestone, dolomite, and shale units. In general, the formation has low porosity and permeability. Gas production is limited to the highly fractured and faulted areas in western New York. Regional porosity for the unit ranges from 2% to 10%. Few hydraulic tests have been performed in the unit, but permeability is likely to be less than 1 mD, similar to other limestone and dolomite units such as the Beekmantown.

ONONDAGA

The Onondaga includes several limestone, dolomite, and shale units that directly overlie the Oriskany potential injection reservoir. The formation has generally low porosity and permeability. Regional porosity ranges from 2-8% (Van Tyne, 1996), and permeability is generally less than 1 mD in non-producing intervals.

OHIO SHALE

The Ohio Shale represents a major confining layer in the region. In the study area, the Ohio Shale is approximately 1,100 ft thick, and the formation remains at least several hundred ft thick throughout the Midwest. Because the Ohio Shale extends to a depth of 3,300 ft near New Haven, it is the shallowest confining layer capable of keeping injected carbon dioxide in liquid form. Regional porosity of the formation is low at 1% to 5% and permeability is very low at 1E-8 to 1E-9 mD (Boswell, 1996). Lower portions of the units are often fractured, which may result in higher permeability and porosity.

SHALLOW DEVONIAN TO PERMIAN UNITS

Rock formations shallower than the Ohio Shale consist of a series of sandstones, limestone, and shale. In general, these formations have variable permeability and porosity based on rock type. These rocks are not considered containment intervals. Bedrock in the river valley at the study area usually consists of shale that does not produce useable quantities of water. Sandstone units in some upland areas produce enough groundwater for domestic uses. Underground sources of drinking water are discussed in Section 5.0.

4.2.4 Formation Pressures. In this section, the available data on formation pressures is summarized in order to understand site conditions. In fresh water deep wells, pressure increases with depth at approximately 0.40 psi/ft. However, brines with a density above 1.0 will have a higher pressure-gradient due to the brine being denser than fresh water. Consequently, the pressure gradient in deep saline reservoirs is typically 0.40-0.50 psi/ft. Variable density stratification may further complicate the issue. Russell (1972), Clifford (1973), and Bond (1970; 1972) summarize the methods and equations for determining water level observations in deep formations. To be comparable, pressures must be converted to equivalent freshwater heads based on brine density. Reservoirs are affected by other boreholes, which release pressure, so it is difficult to determine unaffected formation pressures in highly developed formations. In addition, some rocks have abnormally high reservoir pressures caused by rock compaction over millions of years. Other formations may have unusually low reservoir pressure due to erosion of overlying rocks.

Varied sources of formation pressures are available for the Paleozoic rocks in the Midwest. Generally, pressure gradients in the deep formations are approximately 0.44 to 0.48 psi/ft. However, the variable nature of geology in the Appalachian Basin results in a much wider range of pressure gradients. Table 12 summarizes pressure gradients as tabulated by Russell (1972) for rock formations in West Virginia. As

Table 12. Pressure Gradients for Various Rock Formations in West Virginia

Reservoir	Age	Mean Pressure Gradient (psi/ft)	Standard Error	Count
Big Injun Sandstone and Limestone	Lower and Middle Mississippian	0.242	0.016	12
All Mississippian Sandstones, excluding Big Injun	Mississippian	0.222	0.019	13
Upper Devonian Sandstones, exclusive of reservoirs in "Brown Shale"	Upper Devonian	0.358	0.021	16
"Brown Shale," Devonian	Devonian	0.152	0.016	19
Oriskany Sandstone and Huntersville Chert	Lower and Middle Devonian	0.418	0.020	28
Newburg Sandstone	Upper Silurian	0.412	0.019	6
Lower Silurian Sandstones ("Clinton"/Medina)	Lower Silurian	0.423	0.021	6

Source: Russell (1972).

shown, pressure gradients vary substantially in the Appalachian Basin. Shallower formations are low, whereas deeper rocks fall within the typical range.

The nearest site-specific formation pressure tests conducted in the deep formations was completed in 1967 at the Aristech Site in Haverhill, OH, about 50 miles from the proposed CO₂ injection site. Table 13 summarizes pressures observed in deep rock formations at the site. As shown, pressures fall within the expected range. The pressure gradient is usually lower in low permeability formations, which may be related to variety of factors (Russell, 1972). The pressure gradient in the basal sandstone was approximately 0.46-0.48 psi/ft. Based on this information, the basal sandstone pressure at the injection site would be approximately 3,995 psi at a depth of 8,500 ft. The pressure gradient was 0.43-0.46 psi/ft in the Rose Run and 0.48 psi/ft in the Newburg. No testing was performed in the Oriskany. Overall, pressures suggest an upward gradient from the basal sandstone to shallow depths. These results correspond to conceptual models on groundwater flow in the region, which suggest that deep basins are recharge areas.

Table 13. Pressure Gradients at the Aristech Site

Formation	Gauge Depth	Initial Pressure (psi)	Pressure Gradient (psi/ft)
Newburg	1,805	859	0.48
Rose Run	4,176	1901	0.46
Rose Run	4,230	1840	0.43
Basal Sandstone	5,511	2625	0.48
Basal Sandstone	5,557	2551	0.46
Basal Sandstone /Granite	5,613	2359	(0.42)

Sources: Davis (1991).

4.2.5 Formation Fluid Temperatures. Temperatures increase with depth as expressed by the geothermal gradient. In the Midwest, temperature increases with depth in a fairly predictable way at about 1°F/100 ft plus ambient. Thus, temperatures increase to around 105°F at 5,000 ft below the surface. Accordingly, temperatures in the basal sandstone (5,500 ft bgs) at the Aristech site were 122°F, suggesting that formations follow general geothermal trends are somewhat higher than geothermal trends. Based on the thermal trend, the temperature in the basal sandstone formation in the area of interest will be approximately 146°F at 9,100 ft. The temperature would be 126°F in the Rose Run (7,100 ft), and 94°F in the Newburg (3,900 ft). These temperatures should be considered during well design, as some cements are susceptible to degradation at high temperatures over prolonged durations. Temperatures may vary considerably, as shown in Figure 17.

Some variations in the geothermal gradient occur due to groundwater flow regime, tectonic action, measurement method, and other factors. Figure 17 illustrates formation temperatures for Paleozoic formations throughout the Midwest. No reliable measurements were available from depths expected at the study area. Although an increasing gradient is evident, significant variations are present, and there is some indication that temperatures may be higher in formations more than 5,000 ft below the surface. Groundwater temperature variations may lend insight into the nature of groundwater flow, where positive temperature variations from norms indicate groundwater discharge areas and negative deviations from norms indicate groundwater recharge areas (Vugrinovich, 1988).

4.2.6 Rock Density And Compressibility. The bulk density of rocks varies with rock type. Density may be measured from core samples or determined through downhole geophysical density logging. Paleozoic rocks in the region have a density in the range of 2.0 to 3.0. Shales and siltstones typically have a lower density than other rocks because they have higher total porosities. Higher-density rocks may have lower amounts of pore space and permeability. However, it is difficult to correlate density with hydraulic parameters due to the large influence that sediment size and orientation have on porosity and permeability. Table 14 summarizes the estimated bulk density for hydrostratigraphic units in the study area. The values were estimated from both geophysical logs and core samples from nearby deep wells. Downhole density graphs illustrate changes in lithology, but are subject to some interpretation so core analyses also were examined to verify values.

Figure 17. Formation Fluid Temperatures at Depth in the Midwest

Table 14. Estimated Bulk Density of Hydrostratigraphic Units

Formation	Density ^(a)	
	Range	Representative
Pottsville	2.0-2.8	2.6
Mississippian Series	2.2-2.8	2.6
Ohio	2.2-2.8	2.4
Onondaga	2.2-2.8	2.5
Oriskany	2.5-2.8	2.6
Salina	2.6-2.9	2.8
Lockport	2.6-2.8	2.7
Rochester	2.2-2.8	2.4
“Clinton”	2.5-2.8	2.6
Reedsville	2.2-2.8	2.4
Black River	2.6-2.8	2.7
Beekmantown	2.6-2.8	2.7
Rose Run	2.2-2.8	2.6
Copper Ridge	2.6-2.8	2.7
Conasauga	2.6-2.8	2.7
Rome	2.6-2.8	2.7
Basal Sandstone	2.2-2.8	2.6
Precambrian	2.7-3.5	3.0

(a) All values approximate based on density logs and core samples from nearby wells.

Compressibility describes the amount a rock formation will compact and expand under stress. When fluid pressure is reduced in a reservoir, the reservoir matrix will compress as the overlying stress is transferred from the water in the pore space to the reservoir matrix. Conversely, the reservoir matrix will expand as liquid pressure in the reservoir is increased due to fluid injection. When fluid is injected, the water in the interstitial pore space assumes the overlying pressure, allowing the rock formation to decompress and pore space increases. In this way, a reservoir can store more fluid than pore space would indicate. In addition, water itself is compressible. When water is withdrawn from a deep reservoir, it may come partly from storage due to the decompression of the water and compression of the rock matrix. On the other hand, a reservoir may be able to accept more water as the reservoir matrix expands and water in the pore space compresses. The compressibility of consolidated rock formations is typically low compared to unconsolidated materials (Table 15). Rocks with a higher compressibility will be able to accommodate more fluid through storage. Although compressibility of rock formations is small, the compressibility of rocks becomes more important in evaluating storage capacities over large areas and thicknesses.

Table 15. Summary of Compressibilities for Various Materials

Material	Compressibility (1/psi)	Source
Stiff clay	1.8E-3	Dominico and Mifflin, 1965
Dense sand	1.4E-4	Dominico and Mifflin, 1965
Rock, fissured	6.9E-5	Dominico and Mifflin, 1965
Rock, sound	2.1E-6	Dominico and Mifflin, 1965
Mt. Simon	7.0E-6	BP Chemicals, 1991
Eau Claire Shale	6.0E-6	BP Chemicals, 1991
CO ₂ (liquid)	5.0E-4 @ 1,450 psi	Nieto, 1989
Water	3.3E-6	Dominico and Mifflin, 1965

4.2.7 Formation Fluid Density and TDS. The presence of brines in deep reservoirs may be due to original formation fluids, evaporite deposits, and/or membrane filtration (Domenico and Schwartz, 1990). The density of the formation fluid in the injection interval will affect several aspects of the injection process. Because supercritical CO₂ has a density of approximately 0.7 g/cm³, it will create a density contrast with formation waters, which are on the order of 1.05-1.25 g/cm³ in deep formations. Information on fluid density in the basal sandstone is available from drill stem tests and other sampling methods, but it should be noted that data is subject to limitations related to sampling error. Fluid density may be used to infer total dissolved solids (TDS). In dilute brines (<20,000 mg/L), the density is approximately equal to TDS in parts per million by weight (ppm). For more concentrated brines, TDS is generally greater than the density would indicate. TDS are usually higher than density would indicate, so it is reasonable to assume that formation fluid with a density over 1.01 have TDS of 10,000 mg/L or greater.

Virtually all bedrock in the study area contains groundwater with TDS above the underground source of drinking water criteria of 10,000 mg/L. In fact, even shallow bedrock wells produce water with TDS of well over 20,000 mg/L. Consequently, the bedrock aquifers are not used as a source of drinking water in the area. TDS continues to increase with depth, Table 16 summarizes TDS and density from formation water samples obtained at the Aristech site. As shown, TDS increases rapidly with depth from 42,500 mg/L in the Logan to 266,000-327,000 mg/L in the Newburg. Brine density remains at high levels in deeper formations but shows little trend with depth.

Table 16. Summary of TDS and Density of Formation Water Samples at the Aristech Site

Formation	Depth (ft bgs)	Well	Recovery (gal)	Date	Density	TDS (mg/L)
Logan	164-262	Test	619	1991	1.035	42,500
Berea	679-733	Test	231	1991	1.095	135,000
Niagara/Lockport	1,497-1,567	WDW#3	3,667	1989	1.170	277,000
Newburg	1,757-1,835	Test	905	1991	1.193	290,000
Newburg	1,773-1,834	WDW#3	3,935	1989	1.200	327,000
Newburg	1,795-1,835	WDW#1	905	1968	1.193	266,000
Beekmantown	4,010-4036	Test	1,426	1991	1.218	313,000
Rose Run	4,183-4,271	WDW#3	7,896	1989	1.190	287,000
Rose Run	4,181-4,225	Test	3,389	1991	1.215	309,000
Rose Run	4,220-4,265	WDW#1	160	1968	1.199	278,000
Copper Ridge	4,447-4,480	Test	5,834	1991	1.200	293,000
Mt. Simon	5,520-5,565	WDW#1	1,895	1968	1.225	316,000

Source: Davis, 1991; REC, 1992.

A map of water densities in basal sandstone formations across the Midwest is shown in Figure 18. The basal sandstone is considered a source of fresh water only in northern Illinois and Indiana. In the study area, the regional map indicates that the fluid density in the basal sandstone is approximately 1.2. Basal sandstone drill stem test (DST) brine from the Aristech site had an original density of 1.22 and a TDS of 316,000 mg/L (Davis, 1991). An additional disposal well installed at the site in 1989 (after 20 years of waste injection) about 2,000 ft from the original well had a specific gravity of 1.05 and TDS of 48,400 mg/L, which illustrates that injection can strongly affect the chemistry of a formation.

4.2.8 Diffusion and Dispersion. Diffusion refers to mass transport from areas of high concentration to areas of low concentrations. Diffusion can be a significant process in deep reservoirs over geologic time periods. In general, diffusion acts to equilibrate concentrations of dissolved species. In saline reservoirs, the most evident sign of diffusion is an increase in salinity with depth. Reservoirs where salinity is constant may indicate a mature basin where salinity has equilibrated. Variable salinity may reflect an immature basin, the presence of evaporates, freshwater intrusion, or isolated rock formations. Based on the nearby Aristech well, TDS increases relatively rapidly with depth in the study area. Salinity reaches the 275,000-325,000 mg/L range less than 1,500 ft below the surface. This suggests a mature basin where diffusion has resulted in extensive mixing of formation waters. The geochemistry of the formations may show similar trends.

As groundwater moves through porous media, it spreads due to variations in pore space that cause variations in flow velocity. This process is termed dispersion. Dispersion is a physical process that is generally considered scale-dependant and driven by advection. The process can be expressed on a scale from centimeters (due to microscopic irregularities in pore space) to kilometers (due to heterogeneity in rock formations). The amount of dispersion is quantified by the dispersion coefficient, which is a somewhat empirical value that is related to the scale of the problem being addressed. Modeling performed for the basal sandstone at the nearby Aristech deep well injection site suggested a dispersivity of 5 ft, with an upper limit of 20 ft (REC, 1991). Similarly, a conservative dispersivity value of 20 ft was used for simulating waste migration in the basal sandstone at the BP Lima injection site (BP, 1991).

Figure 18. Regional Fluid Density in the Basal Sandstone

4.3 Groundwater Flow

Several authors have examined the nature of groundwater flow in deep Paleozoic formations in the Midwest (Bond, 1972; Clifford, 1973; Warner, 1988; Gupta, 1993). Many factors make it difficult to reach a definitive conclusion on the nature of flow in deep saline aquifers:

- Limited data coverage due to expense of deep wells,
- Variable density of saline waters requiring conversion to freshwater pressures,
- Artificial influences on formation pressures from injection/extraction wells,
- Lack of data from low permeability layers due to low-flow conditions,
- Complex and heterogeneous geology,
- Imprecise data from large time periods, and
- High formation pressures.

Several theories exist seeking to explain the potentiometric surface of the basal sandstone in the Midwest. A general theory is that the gradients move from deep recharge areas to shallow discharge areas. Clifford (1973) examined potentiometric values in the basal sandstone corrected for density and concluded that gradients followed this pattern with gradient directions from deep basins toward shallow arches (Figure 19). Warner (1988) and a study funded by the United States Environmental Protection Agency (U.S. EPA) Underground Injection Practices Council in 1989 arrived at similar conclusions with potentiometric gradients higher in deep basins and lower in shallow arches (Figure 20). Gradients were typically 3-7 ft per mile. Based on these studies, the gradient in the study area would be west-northwest at about 6 ft per mile. Using a typical range of permeability and porosity found in the basal sandstone, Clifford concluded that groundwater flow velocity in the basal sandstone would be less than 1 ft/year. Gupta (1993) agreed that flow velocities in the basal sandstone are less than 1 ft/year. However, his research indicated that groundwater flow directions were controlled by variable density flow.

Figure 19. Hydraulic Head Corrected for Brine Density in the Basal Sandstone (based on Clifford, 1973)

Overall, it appears that groundwater flow in the basal sandstone is fairly complex and slow, so that no resolute conclusion on flow dynamics has been reached. Based on the available research, flow in the study area would be toward the west/northwest toward the Cincinnati/Findlay Arch at less than 1 ft/yr. Flow velocities in other target intervals would likely be even lower as they generally are less permeable and porous across the region. Given the low flow velocities, groundwater flow will have a negligible impact when compared with the influence caused by the injection wells. Flow directions are toward the west-northwest, and are likely controlled to some extent by regional structures. Research indicates that the area of interest is in a recharge zone. Discharge zones are over 100 miles to the west and northwest along the Cincinnati and Findlay Arches where the basal sandstone is shallowest. In these areas, the basal sandstone is overlain by several hundred feet of the Eau Claire. The Rose Run and Oriskany both subcrop in eastern Ohio, forming a conceptual trap for flow. The Newburg, on the other hand, is a

Figure 20. Equivalent Freshwater Heads and Groundwater Flow Direction in the Basal Sandstone (based on Warner, 1988)

prolific source of drinking water for portions of central and western Ohio, where the formation is much shallower.

Vertical gradients in deep Paleozoic formations in the Midwest also have been examined (Bond, 1970 and 1972; Vugrinovich, 1988; Gupta, 1993). Most conceptual models on vertical flow in deep aquifers suggest downward flow in topographic high areas. However, drill stem test data from deep wells tends to complicate the issue. Bond (1972) notes that extended pumping in overlying aquifers may induce an upward gradient from the basal sandstone as has been observed in northern Illinois. In general, vertical flow rates across formations are low, but significant when considered over a large area and time span. Flow across low permeability shale layers is vertical due to refraction of flow directions. Drill stem tests performed at the Aristech disposal wells suggest a downward gradient throughout the Ordovician and Cambrian rock formations in the area (Davis, 1991).

4.4 Reservoir Capacity Estimates

Estimates on reservoir capacity were calculated to provide some guidance on the amount of fluid that may be injected in the target formations. These capacities are approximate involving many assumptions, and more detailed modeling is required to assess injection capacities. However, the methods are suitable for initial investigations. Only one deep well within 25 miles of the proposed site penetrates comparable geology, and the effective thickness of the target reservoirs is uncertain. Consequently, reservoir volumes were based on a thickness range. The estimates were based on a ten-mile radius around the injection site, because geology changes rapidly at the Rome Trough beyond this distance.

The estimates of the amount of CO₂ that may be injected into the target reservoirs at the area of interest were calculated using the equation proposed by van der Straten (1996) in the Joule II report:

$$Q = V_p h_{st} \rho_{CO_2} \quad (4-3)$$

where,

V_p	=	$V_b(\text{Net:Gross})\phi$,
V_b	=	bulk aquifer volume (km ³),
Net:Gross	=	percentage of porous, permeable rock,
ϕ	=	formation porosity (%),
h_{st}	=	storage efficiency (i.e., fraction of pore volume that can be filled with CO ₂ [%]),
ρ_{CO_2}	=	density of CO ₂ (700 kg/m ³) and,
Q	=	storage capacity (Mt).

This equation is not a simple pore volume calculation, as it accounts for reservoir heterogeneity and inefficiencies in storage. It does assume that the injection formation is a homogeneous, “open” aquifer in which the entire volume is available for the injected CO₂. In the equation, storage capacity is a function of the bulk aquifer volume, the formation porosity, the percentage of the formation that is permeable rock, the storage efficiency of the formation, and the density of CO₂. Porosity and volume may be determined from nearby wells and isopach maps. Density of CO₂ is 700 kg/m³. The ratio of net to gross permeable rock accounts for heterogeneity in the rock formation that may reduce its effective thickness. Similarly, storage efficiency accounts for the fraction of pore space available for injection.

For comparison, Table 17 summarizes CO₂ storage capacity for the basal sandstone unit in the Midwest United States (Gupta and Sminchak, 2000; Smith et al., 2001). As shown, capacities are on the order of 270 Gt in the Midwest. Much of this capacity exists in Illinois and Indiana where the basal sandstone is thick. Ohio has a respectable capacity of 15 Gt. Estimates for West Virginia were not calculated because the basal sandstone is not well mapped east of the Rome Trough. It should be noted that these estimates are for the basal sandstone only, and other formations with suitable characteristics exist in the region. The Oriskany Sandstone has good capacity in other portions of West Virginia. It appears that the Rose Run is also an appealing reservoir at the proposed site.

Table 17. CO₂ Storage Capacity for the Basal Sandstone in the United States

Location	Capacity ^(a) (Gt)
Midwest US	270
Illinois	82
Indiana	70
Ohio	15

(a) Sources: Gupta and Sminchak, 2000; Smith et al., 2001.

Table 18 summarizes the storage capacities within a 10-mile radius of the study site. Several of the input parameters such as storage efficiency are variable. Consequently, storage capacities are presented for several of these parameters. The ratio of permeable to impermeable rocks was assumed to be 75% for the base case. Low ratio was estimated at 50% and high ratio was estimated at 95%. Porosity for the base case was estimated at 10% for both the units, which agrees with nearby core samples and regional trends. High porosity was considered 15%, and low porosity was considered 5%. Storage efficiency was assumed at 6% of available porosity.

Table 18. Reservoir Capacity Estimates

Thickness = 50 ft	V (ft³)	V (km³)	Net:Gross	Porosity	V_p (km³)	Q (Mt)
Base	4.37E+11	12.4	75%	10.0%	0.9	39
Low Net:Gross	4.37E+11	12.4	50%	10.0%	0.6	26
High Net:Gross	4.37E+11	12.4	95%	10.0%	1.2	49
Low Porosity	4.37E+11	12.4	75%	5.0%	0.5	19
High Porosity	4.37E+11	12.4	75%	15.0%	1.4	58
Thickness = 75 ft	V (ft³)	V (km³)	Net:Gross	Porosity	V_p (km³)	Q (Mt)
Base	6.56E+11	18.6	75%	10.0%	1.39	58
Low Net:Gross	6.56E+11	18.6	50%	10.0%	0.93	39
High Net:Gross	6.56E+11	18.6	95%	10.0%	1.76	74
Low Porosity	6.56E+11	18.6	75%	5.0%	0.70	29
High Porosity	6.56E+11	18.6	75%	15.0%	2.09	88
Thickness = 100 ft	V (ft³)	V (km³)	Net:Gross	Porosity	V_p (km³)	Q (Mt)
Base	8.75E+11	24.8	75%	10.0%	1.86	78
Low Net:Gross	8.75E+11	24.8	50%	10.0%	1.24	52
High Net:Gross	8.75E+11	24.8	95%	10.0%	2.35	99
Low Porosity	8.75E+11	24.8	75%	5.0%	0.93	39
High Porosity	8.75E+11	24.8	75%	15.0%	2.79	117
Thickness = 150 ft	V (ft³)	V (km³)	Net:Gross	Porosity	V_p (km³)	Q (Mt)
Base	1.31E+12	37.1	75%	10.0%	2.78	117
Low Net:Gross	1.31E+12	37.1	50%	10.0%	1.85	78
High Net:Gross	1.31E+12	37.1	95%	10.0%	3.52	148
Low Porosity	1.31E+12	37.1	75%	5.0%	1.39	58
High Porosity	1.31E+12	37.1	75%	15.0%	4.17	175
Thickness = 200 ft	V (ft³)	V (km³)	Net:Gross	Porosity	V_p (km³)	Q (Mt)
Base	1.75E+12	49.5	75%	10.0%	3.71	156
Low Net:Gross	1.75E+12	49.5	50%	10.0%	2.48	104
High Net:Gross	1.75E+12	49.5	95%	10.0%	4.71	198
Low Porosity	1.75E+12	49.5	75%	5.0%	1.86	78
High Porosity	1.75E+12	49.5	75%	15.0%	5.57	234

Based on equation by vad der Straten, 1996, Joule II Report.

Based on the baseline parameters, the storage capacity in a 50-ft-thick reservoir would be 39 Mt, whereas a 200 ft thick reservoir would have 156 Mt of capacity. The basal sandstone appears to be 50-100 ft thick at the study site, so its capacity would be 39 to 78 Mt. The effective thickness of the Rose Run also appears to be 50-100-ft-thick (see Appendix A), and its capacity would be 39 to 78 Mt. Combined, the reservoirs could accommodate approximately 80 to 150 Mt of CO₂. Figure 21 illustrates the effect of

porosity and the ratio of permeable to impermeable rocks. As shown, porosity has the largest effect on reservoir capacity and is a key hydraulic parameter of the injection reservoir. Low permeable layers within the reservoir not appear to have quite as much of an effect as evidenced by the net:gross results.

Based on these calculations, the reservoirs have a combined capacity for up to approximately 150 million tones of injected fluid. The reservoir capacities are most directly dependant on porosity and thickness. Neither reservoir has the capacity associated with thicker formations in other parts of the region. Long-term injection of larger amounts of fluids (5-7 Mt/yr) would approach the combined capacity of the reservoirs in 20 years or less. More capacity may be found in areas beyond the 10-mile radius considered in these calculations, but the geology would require more characterization in structurally significant zones (i.e., Rome Trough).

Figure 21. Estimated Injection Capacities for Expected Reservoir Thickness and Hydraulic Parameters for a 25-mile Radius of the Injection Site

5.0 LOWERMOST UNDERGROUND SOURCE OF DRINKING WATER

The U.S. EPA considers an aquifer to be an USDW when the aquifer may yield water with less than 10,000 ppm TDS. Regulation on underground injection requires designation of the lowermost USDW to prevent contamination of any drinking water by injection. The Mountaineer Power Plant site is located on an alluvial valley underlain by a thick sequence of Paleozoic rocks. The unconsolidated alluvium deposits are less than 100 ft thick and contain the main drinkable water at the Mountaineer site. In the bedrock aquifers, the upper formations which are Pennsylvanian and Mississippian age limestones, sandstones, and shales contain briny water and have relatively low groundwater yields.

5.1 Surficial Geology

The Mountaineer Power Plant site is located on the Ohio River alluvial plain. Figure 22 shows the layout of the Mountaineer Plant site. The width of the Ohio River Valley in the area ranges from 0.5 - 0.7 mile at the site. Locally, the maximum width occurs southeast of the Mountaineer Power Plant site as a result of the confluence of Yellowbush Creek across the river from the site. Along the northern boundary of the Mountaineer site is Little Broad Run, a tributary of the Ohio River.

5.1.1 Unconsolidated Deposits. The Ohio River Valley is underlain by alluvium that is thin or absent near the valley walls and marginally extends into the valleys of tributary streams. The alluvium coarsens downward and consists of clay and silt floodplain deposits overlying coarse sand and gravel. Three generalized zones can be identified with the alluvium – clay, sand, and gravel. A geologic log of one of the monitoring wells at the Mountaineer site shows the three generalized zones (Figure 23). The alluvium is generally at elevation 580 ft msl. Based on boring data from the plant site, the alluvium ranges from 80-100 ft in thickness (EPRI, 1999).

The upper layer of the alluvium consists of silty clay. The clay layer ranges in depth from 0-47 ft. The clay zone is discontinuous, but it is thickest near the river along the northern half of the plant site (EPRI, 1999).

At the Mountaineer site, the overall thickness of the coarse-grained zones together ranges from 35-100 ft. The sand zone, which underlies the clay zone, ranges from 0-50 ft. The sand zone is underlain by 0-70 ft of silty-sandy gravel. The sand zone has a range of sand content from about 50-90%, with increasing gravel content and decreasing silt and clay content with depth. The gravel zone is poorly sorted and the gravel content ranges up to 35%. The sand and gravel units grade together laterally, typical of river depositional environments, and there are no sharp contacts between them (EPRI, 1999).

Fill also is present at the Mountaineer site. This fill is found primarily near the Ohio River. The fill was likely generated from on-site excavations and consists primarily of silty clay with silty to gravelly sand. The typical depth of the fill is approximately 15-25 ft. The fill is thicker in the former channel of Little Broad Run Creek, which was rerouted north during plant construction (EPRI, 1999).

During the environmental investigations looking at the groundwater quality at the Philip Sporn and Mountaineer Power Plants, four geologic cross-sections of the alluvial deposits were constructed based on the borehole data (Figure 22). Sections A-A' (Figure 24) and B-B' (Figure 25) are oriented perpendicular to the groundwater flow and parallel to the river. Sections C-C' (Figure 26) and D-D' (Figure 27) are oriented parallel to the groundwater flow (EPRI, 1999).

Figure 22. Mountaineer Site with Locations of Geologic Cross Sections

Figure 23. Lithologic Log for MW-1 at the Mountaineer Site

5.1.2 Bedrock. The site is underlain primarily by the Monongahela, Conemaugh, Alleghany, and Pottsville series of the Pennsylvania Age. These strata are composed primarily of sandstone, limestone, shale, and numerous coal seams. The Monongahela Series lies directly underneath the alluvium. A generalized geologic cross section is shown in Figure 28 (AEP, 1974).

The regional strike of the Pennsylvania strata is generally north-northeast, dipping to the east-southeast an average of 36 ft to the mile. The bedrock surface elevation is fairly consistent adjacent to the river at an elevation of 505 ft msl (AEP, 1974). Well logs indicate that bedrock in the study area is primarily shale, limestone, sandstone, and coal.

In the upland areas adjacent to the site, bedrock may be developed for individual water supplies.

5.2 Hydrologic Conditions

The Ohio River is a major influence in the hydrologic conditions of the Mountaineer site. The stage of the Ohio River is regulated by a series of locks and dams. In the general area of the Mountaineer site, the normal operating stage is 538 ft msl. Groundwater generally flows toward the river from the edges of the valley, with an average seasonal fluctuation of several feet. A water table contour map from

Figure 24. Geologic Cross Section A-A'

Figure 25. Geologic Cross Section B-B'

Figure 26. Geologic Cross Section C-C'

Figure 27. Geologic Cross Section D-D'

Figure 28. Monongahela Series Generalized Geologic Cross Section

December 1997 at the Mountaineer site is shown in Figure 29 (EPRI, 1999). Recharge to the alluvium results from leakage from tributary streams crossing the floodplain and from precipitation. The silt and clay materials typically have low hydraulic conductivity, which limits the recharge from precipitation.

In Mason County, the majority of the population depends on the alluvial groundwater to meet its domestic needs, pumping more than 4 million gallons per day (gpd). At the Mountaineer site, the alluvium of the Ohio River Valley yields most of the alluvial groundwater used. The principal source of groundwater is the coarse sand and gravel alluvium along the Ohio River. Most communities in Mason County draw their public water supplies from the alluvial groundwater. Though there is abundance of surface water, the groundwater is superior in quality. In rural areas, residences and farms, not supplied by the public water supply system, are supplied with groundwater by drilled wells, dug wells, driven wells, and springs (AEP, 1974). Few dug wells have been constructed in Mason County in recent years. Driven wells tapping the unconsolidated alluvium are the most common source of non-public domestic water supply in the Ohio River Valley. These wells are used when water supply requirements are small. The average depth of the drilled well is 85 ft; of driven wells, 73 ft; and of dug wells, 34 ft (AEP, 1974).

Alluvium in the Ohio River Valley is the principal source of industrial, municipal, and rural supplies. The standard well yields 20 to 675 gallons per minute (gpm). The industrial and public supply wells yield an average of 200 gpm. The major industrial and commercial users of groundwater in Mason County include cooling condensing, fire protection and sanitation. Substantial amounts also are used for boilers and as process water (AEP, 1974).

Review of well logs in the area shows that some bedrock wells are in the area. Most of the wells were drilled in 1950-1975 before municipal water supplies were available, or are removed from alluvial deposits. The well logs indicate that the wells are less than 250 ft deep and completed in Pennsylvanian sandstone, limestone, and shale formations. Figure 30 shows a typical water well log for the area. Most of the bedrock wells were completed as open holes in sandstone. Well yields are generally poor at less than 10 gpm, but some wells were more productive. Many of the wells yielded less than 1 gpm of water and were abandoned. In general, it appears that the Pennsylvanian bedrock forms a marginal aquifer in the area.

5.3 Geochemistry of Underground Sources of Drinking Water

The groundwater that comes from the alluvium is usually bicarbonate type, hard, alkaline, and low in chloride and of variable iron content. The concentration of total dissolved solids varies with depth, but is generally less than 3,000 mg/L. Table 19 summarizes twenty-eight alluvium groundwater-monitoring wells sampled in the study area for site environmental investigations. The wells had a minimum TDS of 380 mg/L and maximum of 3,000 mg/L. Other major constituents detected included calcium, chloride, iron, magnesium, sodium, and sulfate. Overall, the alluvial aquifer has good groundwater quality typical of many river valleys in the region.

Little water quality information is reported for the Pennsylvanian bedrock units underlying the alluvium at this site. The groundwater from these units is considered to be briny and have low yields, which makes the bedrock aquifers an undesirable source of drinking water. Bedrock at higher elevations may have a lower TDS due to infiltration of surface water. Bedrock at lower elevations may be more saline and related to deep basin hydrology. Below Pennsylvanian formations, TDS appears to increase rapidly with depth to over 100,000 mg/L at depths over 1,000 ft below the surface (see Section 4.2.7). The bedrock unit has historically been used for drinking water, so it is assumed that portions of the formation have TDS below 10,000 mg/L.

Reference: EPRI, June 1999

Figure 29. Water Table Contour Map of Mountaineer Plant Site (December 1997)

WELL LOG AND DRILLING REPORT		
Well Log Number: 180207		
ORIGINAL OWNER AND LOCATION		
Original Owner Name: -----	Lot Number:	
County: MEIGS	Township: SUTTON	Section Number: 10
Address: ST RT 124	City:	
State: OH	Zip Code:	
Location Number:	Location Map Year: 1981	Location Area:
CONSTRUCTION DETAILS		
Borehole Diameter:	Total Depth: 96 ft.	Depth to Bedrock:
Casing Diameter: 5.63 in.	Casing Thickness:	Casing Length: 68 ft.
Well Use:	Screen Length:	Date of Completion: 2/26/56
Aquifer Type: ROCK	Driller's Name:	
WELL TEST DETAILS		
Static Water Level: 25 ft.	Test Rate: 2 gpm	<u>Associated Reports</u>
Drawdown: 40 ft.	Test Duration: 1 hrs.	NONE
WELL LOG		
<u>Formations</u>	<u>From</u>	<u>To</u>
CLAY	0	- 10
QUICKSAND	10	- 40
BLU ROCK	40	- 50
RED ROCK	50	- 59
BLU ROCK	59	- 76
RED ROCK	76	- 80
BLU ROCK	80	- 85
RED ROCK	85	- 96

Source: ODNR Water Well Database.

Figure 30. Typical Bedrock Water Well Log in the Study Area

5.4 Determination of Lowermost Underground Source of Drinking Water

The primary underground source of drinking water at the Mountaineer Power Plant is located at the base of the alluvial aquifer, approximately 100 ft bgs. Some bedrock units have also produced enough water that the units have been used on a limited basis for drinking water. This bedrock aquifer includes Pennsylvanian sandstone, limestone, and shale less than 250 ft deep. The bedrock aquifers have marginal groundwater yields and quality. Water quality degrades rapidly with depth below Pennsylvanian rock. TDS concentrations typically are more than 100,000 mg/L at depths over 1,000 ft in the area. Based on review of geology in the area, Pennsylvanian bedrock units are the lowermost source of drinking water in the study area. Selection of this bedrock unit is conservative, as the rock formation is a marginal aquifer. The main underground source of drinking water in the area is unconsolidated sediments in the Ohio River Valley.

**Table 19. Summary of Monitoring Well Groundwater
Quality Data in Alluvium Groundwater Wells at
Mountaineer Plant**

Parameter (mg/L)	Minimum	Median	Maximum
pH	3.28	5.06	7.31
TDS	380	740	3,000
Alkalinity	ND	ND	690
Barium	ND	ND	45
Calcium	32	110	430
Chloride	12	34	53
Fluoride	0.08	0.48	0.95
Iron	ND	14.2	330
Magnesium	7.5	23.5	120
Nickel	ND	74.5	490
Nitrate/Nitrite	ND	ND	0.63
Potassium	0.64	3.9	12
Sodium	6.6	30	58
Sulfate	5	320	1,800

Source: EPRI, 1999.

ND: below detection limit.

6.0 GEOCHEMISTRY

6.1 Regional Geochemistry

Several resources were consulted to characterize formation fluid geochemistry in the region (Stout et al., 1932; Hoskins, 1947; Stith, et al., 1979; Kentucky Geological Survey, 1980; Breen et al., 1985; Knapp and Stith, 1989; Sanders, 1991; Musgrove and Banner, 1993). Abundant brine chemistry data exist for formations that yield oil and gas like the Trenton, Berea, Salina, and Clinton. However, these reservoirs are not a primary objective of the research. In addition, many of these formations are highly affected by oil and gas activities. Consequently, investigation into brine geochemistry focused on the target injection formations and containment intervals immediately over the injection reservoirs. These formations included the basal sandstone, Rome/Maryville, Rose Run, and the Beekmantown. Where appropriate, some shallower formations also were included in the analysis for comparison purposes.

Several general trends in geochemistry of deep Paleozoic rock formations are present in the region. Formation fluids in deep rock layers are brines with high TDS levels. In fact, salt was made from wells throughout the region during settlement. The dominant species in fluids are usually chloride, calcium, sodium, magnesium, and potassium. Aluminum, barium, bromide, iron, and sulfate also are present in concentrations generally less than 1,000 mg/L. Density of fluids ranges from 1.010 to 1.250. TDS generally increases with depth to over 300,000 mg/L.

6.2 Site-Specific Geochemistry

Formation fluids recovered from drill-stem tests in Aristech WDW#1 were analyzed for chemistry in 1968 when the well was installed (Davis, 1991). Samples from the basal sandstone/Mt. Simon, Rose Run, and Lockport/Newberg were analyzed. A drill stem test in the Berea yielded only drilling mud and no formation fluids. Chemical data from the other WDW#3 and the Test/Monitoring Well were collected in 1989 and 1991. Samples from these wells from the deeper Paleozoic intervals show significant dilution from injection activities. For example, TDS from the basal sandstone/Mt. Simon in the original Aristech disposal well was 316,000 mg/L, whereas TDS from the basal sandstone/Mt. Simon measured in WDW#3 in 1989 was 48,400 mg/L. Consequently, geochemical analyses from the deeper formations do not reflect unaffected conditions. However, analyses from shallower formations appear to be more reliable and are similar to original samples.

Table 20 summarizes geochemical conditions as measured at the Aristech site. This data set is the most thorough set that is available from deep formations near the study area. It should be noted that formations are 1,000 to 5,000 ft deeper in the study area than at the Aristech site. As such, the geochemistry will differ to some extent. However, the Aristech site offers the best available picture of geochemical conditions in the general area. Formation waters in the study area are likely to have higher overall concentrations than the Aristech samples.

Only one unaffected sample was retrieved from the basal sandstone/Mt. Simon. This sample had a density of 1.22 and TDS of 316,000 mg/L. The pH of the sample was 5.5. Calcium was fairly high at 50,600 mg/L, which may reflect dolomitic rock in the formation. Hydrogen sulfide and dissolved oxygen were not detected in the sample.

The Copper Ridge sample represents a containment interval between the Mt. Simon and the Rose Run. A sample from the Test/Monitoring well at the Aristech site had a density of 1.2 and TDS of 293,000 mg/L. Overall, the sample was similar to the basal sandstone, mainly differing in the amount of

Table 20. Summary of Geochemistry at Aristech Site

Formation	Logan	Berea	Niagaran	Lockport/ Newburg	Lockport/ Newburg	Lockport/ Newburg	Beekm- antown	Rose Run	Rose Run	Rose Run	Copper Ridge	Mt. Simon
Depth (ft bgs)	164- 262	679- 733	1,497- 1,567	1,757- 1,835	1,773- 1,834	1,795- 1,835	4,010- 4,036	4,183- 4,271	4,181- 4,225	4,220- 4,265	4,447- 4,480	5,520- 5,565
Well	Test	Test	WDW#3	Test	WDW#3	WDW#1	Test	WDW#3	Test	WDW#1	Test	WDW#1
Date	1991	1991	1989	1991	1989	1968	1991	1989	1991	1968	1991	1968
Recovery (gal)	619	231	3,667	905	3,935	905	1,426	7,896	3,389	160	5,834	1,895
Density	1.035	1.095	1.17	1.193	1.2	1.193	1.218	1.19	1.215	1.199	1.2	1.225
pH	N/A	N/A	N/A	N/A	N/A	5.4	N/A	N/A	N/A	6.7	N/A	5.5
Alkalinity	138	8	N/A	ND	N/A	32	268	N/A	100	60	56	28
Calcium	2,670	9,790	36,400	33,540	38,700	39,600	38,500	38,500	37,000	39,800	35,000	50,600
Magnesium	648	2,960	8,970	7,875	9,150	9,470	7,430	6,070	7,010	7,610	6,190	7,080
Sodium	34,300	ND	N/A	32,900	N/A	46,900	9,330	44,600	25,500	54,100	48,200	58,300
Barium	40.7	141	1.1	0.86	1.0	ND	3.05	1.8	4.7j	ND	3.8	ND
Sulfate	4.95	ND	180	64.3	130	80	51.8	330	ND	74	229	140
Chloride	26,200	82,500	139,000	164,000	179,000	170,000	251,000	170,000	218,000	176,000	208,000	200,000
Silica	36.8	5.2	N/A	1.57	N/A	3.0	17.3	N/A	7.3	2.0	10.8	2
Total Iron	52.5	188	122	90.4	64	39	999	60.8	171	35	409	39
Aluminum	10.6	0.19	12.9	0.19	5.4	0.5	2.23	ND	ND	0.5	1.3	.5
Potassium	3,750	1,243	1,210	260	1,430	N/A	89.7	3,330	3,810	N/A	3,610	N/A
Iodide	N/A	N/A	N/A	N/A	N/A	2.7	N/A	N/A	N/A	1.3	N/A	1.3
Bromide	150	564	N/A	1,680	N/A	1,820	2,260	1,630	2,200	1,950	2,090	2,160
Carbon Dioxide	N/A	N/A	N/A	N/A	N/A	280	N/A	N/A	N/A	350	N/A	240
TDS	42,500	135,000	277,000	290,000	327,000	266,000	313,000	287,000	309,000	278,000	293,000	316,000

*All results reported as milligrams per liter unless otherwise noted.

N/A: not analyzed.

ND: not detected.

Hydrogen sulfide and dissolved oxygen were below detection in the Mt. Simon, Rose Run, and Newburg samples from WDW#1.

total iron. The Copper Ridge had 409 mg/L total iron, whereas the basal sandstone had total iron of 39 mg/L.

Several samples were analyzed from the Rose Run Formation. Density was approximately 1.2 for all the samples and TDS was 278,000-309,000 mg/L. Concentrations of species were generally similar across the three different samples. Hydrogen sulfide and dissolved oxygen were not detected in the sample from WDW#1.

The Beekmantown was sampled in the Test/Monitoring well in 1991. The formation overlies the Rose Run. The sample had a specific gravity of 1.2 and TDS of 313,000 mg/L. Sodium concentration was only 9,330 mg/L. Iron levels were higher, similar to the Copper Ridge. Otherwise the sample was similar to the Rose Run and basal sandstone samples.

Three samples were analyzed from the Lockport/Newburg Formation. The Newburg is a productive sandstone. As such, one may expect the chemistry to be different from the other zones which are less dynamic. Overall, the samples have a density of 1.19-1.20 and TDS of 266,000-327,000 mg/L. Magnesium levels are slightly higher than in the deeper formations, whereas chloride levels were lower than in the lower formations. Hydrogen sulfide and dissolved oxygen were not detected in the sample from WDW#1.

One sample was obtained from the Niagaran/Dayton Formation. The Niagaran is a shaley dolomite above the Clinton sandstone. Density was 1.17 and TDS was 277,000 mg/L, which are high levels for such a shallow formation (1,497-1,567 ft bgs).

The sample collected from the Berea Formation had a density of 1.095 and TDS of 135,000 mg/L. Overall, concentrations of species were much lower than in the deeper formation and the Berea is the first formation sampled that shows a distinct contrast to the deeper formations. The formation fluids are still brines with TDS well above the 10,000 mg/L drinking water criteria.

A sample was obtained from the Logan Formation in the Test/Monitoring well. The Logan is the shallowest bedrock formation at the Aristech site. The sample had a density of 1.035 and TDS of 42,500 mg/L. As may be expected, concentrations of species are much lower in the Logan when compared to deeper formations. However, the formation is still considered a brine.

6.3 Analysis Of Brine Chemistry Trends

This section analyzes the formation brine chemical constituents and constituent ratios that may be used as source-formation indicators or geochemical tracers in the deep well injection of CO₂. Data were obtained from regional brine investigations. Analysis focused on the target injection formations (basal sandstone/Mt. Simon and Rose Run) and overlying formations (Rome and Newburg). Data were screened for quality, and representative samples were included in analyses.

Composition of formation water is controlled by their origin and subsequent chemical evolution. In some formations, the original seawater may be residual brine from an evaporite environment. The formation water also may originate as meteoric water, which infiltrates into sediments and moves into the basin through subsurface flow, or may originate as water produced during diagenesis or metamorphic dehydration reactions.

The concentrations of dissolved ionic constituents present in the brines are generally categorized in Table 21. Concentrations of the dissolved constituents are reported as milliequivalents per liter (meq/L). The constituents selected for the analysis represent the alkali metals, alkaline earth metals, group III elements, halide anions, sulfur and carbon anions, transition metals, silica, and hydrogen ion (pH). A Schoeller diagram (Figure 31) shows relative concentrations and salinities of the major cations and anions.

The density and TDS concentration of basal sandstone/Mt. Simon, Knox Equivalent, Rose Run, and Newburg brines at different depths are shown in Figures 32 and 33. The density and TDS increase as the depth of the selected brine samples increases. Brines are known to have increasing salinity with increasing depth. TDS concentration increases from less than 50,000 mg/L to over 325,000 mg/L, and density increases from 1.01 to 1.25. The variations in TDS and density with depth are likely due to dilution of brine sources with meteoric water infiltrating from shallow depths.

Table 21. Concentrations of Dissolved Ionic Constituents Present in the Selected Brine Samples

Descriptive Term	Constituent	Concentration Range (meq/L)
Dominant	Ca, Na, Cl	≥1,000
Major	Mg	≥100 to <1,000
Minor	SO ₄ , HCO ₃	≥10 to <100
Trace	Zn, Al, Fe, Br, I, SiO ₂	<10

Figure 31. Fingerprint (Schoeller) Diagram of Brine Data

Figure 32. TDS at Different Formations

Figure 33. Brine Density at Different Formations

The relative concentrations of ions across Ohio and Kentucky geologic formations represented using a Piper diagram in Figure 34. In a Piper diagram, ion concentrations are converted to charge equivalents, and then each type of ion is expressed as a fraction of the total equivalents of either cations or anions. The Piper diagram is composed of two ternary plots that show the proportions of major cations (Na, Ca, and Mg) and major anions (Cl, bicarbonate, and sulfate). The diamond shape figure in the upper portion of the diagram is a projection of the two ternary plots. The main features of the brine data represented in the Piper diagram are the following:

- Sodium and calcium are the dominant cation in all of the brines investigated. Except Rose Run, the charge equivalencies of Na and Ca are approximately equal.
- The proportion of Mg ions is fairly constant in most of the brine samples.
- Chloride is the predominant anion in all brine samples. However, sulfate makes up several percent of the total anion charge in a few of the samples. Bicarbonate (HCO_3^-) levels remain very low in relative abundance, primarily due to low pH of the brines, which restricts the molecular form of inorganic carbon to dissolved CO_2 [$\text{CO}_{2(\text{aq})}$] and carbonic acid (H_2CO_3). Both species have limited solubilities in water. In contrast, bicarbonate as well as carbonate (CO_3^{2-}) ions can have high solubilities in water, providing the pH is sufficiently elevated and a source of inorganic carbon is present.

Additional features concerning ionic concentrations and ionic ratios can be illustrated with other types of plots. Sodium (Na), calcium (Ca) and chloride (Cl) are the dominant ions contributing to the observed levels of total dissolved solids. Chloride concentration has a range nearly twice that of sodium. The Na:Cl ratios are consistently less than 1, and have a median of 0.5, except Rose Run brine samples from Grayson and Metcalfe, KY. Linear relationships between Ca and Cl and Na and Cl are shown in Figure 35. For reference, the properties of seawater are shown in different figures.

Figure 34. Piper Diagram Showing the Distribution of Major Ionic Species (Equivalent Basis) in the Different Formations of Ohio and Kentucky

Figure 35. Equivalent Concentrations of Chlorine at Different Formations

Bromide in the brine is contributed by evaporation of seawater or formation water, dissolution of halite, release by clays, and organic sources. Bromide substitutes for chlorine in solid solution in halite. As formation water percolates through evaporite beds, it may become enriched in bromide through dissolution of halite. Through the range of normal halite precipitation from evaporating seawater, the ratio

($1,000 \times \text{Br/Cl}$) ranges from 0.1 to 0.4 in most of the brine samples, the variation in this ratio (0.4 to 0.6) in Mt. Simon and Newburg formations reflects the fact that more bromide is available to substitute into the solid phase (see Figure 36a, left). Certain marine organisms biologically concentrate bromide as well as iodide. If the brines were biogenically enriched in bromide, they also should be enriched in iodide. However, the bromide and iodide in basal sandstone/Mt. Simon and Newburg brines were not biogenically enriched, as distinct variations in iodide concentrations were not observed (see Figure 36b, right).

The relation between bromide and divalent metal chlorides, MCl_2 is shown in Figure 37. The brine samples from all formations are above the 1:1 ratio line, and it indicates that brines are enriched in MCl_2 or depleted in bromide.

Figure 36. Equivalent Ion Ratios for Br/Cl (left) and Iodide Concentrations (meq/L) (right) at Different Formations

Figure 37. Relationship Between the Bromide and Divalent Metal Chlorides of Waters at Different Formations

7.0 CONCLUSIONS

7.1 Location/Topography

The proposed study area of the CO₂ sequestration project is located near New Haven, WV, along the Ohio River. Several small towns exist along the river near the site. Topography varies from a flat floodplain along the river to steep hilly areas on either side of the river. Weather conditions are temperate with an average yearly temperature of approximately 53°F. Several roads exist along the river, but access to more remote areas is limited. Overall, it appears that the site is suitably located. The topography presents some challenges, as any operations away from the floodplain will require additional efforts to accommodate the terrain.

7.2 Geology

Thick sequences of Paleozoic sedimentary rocks form broad basins and arches in the region. The study area is located within the Appalachian Basin, where rocks slope toward the southeast. A review of deep wells and geophysical logs in the region indicates that the sedimentary rocks are 8,500-10,000 ft thick in the study area. The sedimentary rocks overlie dense, metamorphic basement rocks. The Paleozoic rocks are layered arrangements of shale, siltstone, limestone, dolomite, and sandstone. Figure 38 summarizes the arrangement of rock layers in the study area. In general, the rock formations are laterally continuous and can be traced throughout the region. Sandstone formations comprise potential injection reservoirs. Dolomite, shale, and limestone layers provide containment above the primary injection intervals. Only one well within 25 miles of the site penetrates the entire sedimentary column. Consequently, there is a fair amount of uncertainty concerning deep geology near the study area.

Rocks dip to the east-southeast in the study area at about 100 ft per mile. The major geologic structure in the area is the Rome Trough, a failed rift valley that runs southwest-northeast about 25 miles to the south of the study area. In this feature, a series of normal faults results in downdropped blocks of rocks leading into the Rome Trough, where Cambrian rock formations deepen substantially. The faulting appears to be located along the northwest border of the Rome Trough, and it is uncertain whether these faults are present in the study area. Earthquake activity in the area is low, and the site is classified as low risk by the USGS Seismic Hazards Mapping Project.

Several potential injection reservoirs are present. Primary targets include the basal sandstone/lower Maryville and Rose Run sandstone. The basal sandstone is an informal name for sandstone units commonly found above Precambrian rocks in the region. At the study site, it appears the basal sandstone is associated with the lower Maryville Formation. The basal sandstone is typically a well sorted sandstone and similar to the Mt. Simon Sandstone in the region. The Rose Run is another potential reservoir. This formation is another fine-grained sandstone. Several other gas plays are found in the study area including the "Clinton," Oriskany, and Newburg. Nearby wells indicate that these formations are only 0-40 ft thick in the study area and consequently are considered secondary injection targets. However, the gas reservoirs do demonstrate the capability of the deep formations to retain fluids for long periods of time. Precambrian basement rocks are a speculative injection reservoir.

In general, confining intervals are much thicker and numerous than the injection formations. Consequently, containment at the site is likely to be excellent. Containment layers consist of shale, siltstone, dolomite, and limestone layers. Major confining units above the Basal Sandstone include the Rome formation, a dense dolomite. Above the Rome is a dolomite and shale formation termed the Conasauga and a dolomite termed the Copper Ridge.

All depths and thicknesses approximate based on nearby deep well lithology.

Figure 38. Diagram of Rock Layers in the Study Area

Overlying the Rose Run is the Beekmantown, another dense dolomite unit. The Wells Creek, Black River, Trenton, and Pt. Pleasant are dolomite and limestone formations offering additional containment above the Beekmantown. The Reedsville and Juniata are thick shale layers that form a competent containment layer as well. Shallow layers provide additional containment.

7.3 Groundwater Hydrogeology

Rock formations may be classified into hydrostratigraphic units that have similar hydraulic and geologic properties. Potential injection reservoirs have sufficient thickness, porosity, lateral extent, and porosity to accept large volumes of injected fluid. Containment intervals are dense rocks with low effective porosity and permeability that will inhibit any migration of fluids. The main injection intervals are the basal sandstone and Rose Run Sandstone. Containment layers include dense dolomite, limestone, and shale layers that overlie the injection targets.

The basal sandstone is a well-sorted fine grained sandstone equivalent to the Mt. Simon sandstone in the region. The formation typically has a high porosity of 10-15% with a permeability up to several hundred mD. Geologic maps indicate that the unit is 50-100 ft thick at the proposed site. The Rose Run is also a fine-grained sandstone located about 1,500 ft shallower than the basal sandstone in the study area. The unit subcrops in eastern Ohio and thickens toward the east. Maps indicate that it is 100-150 ft thick in the study area. The unit has variable permeability and porosity. Nearby wells indicate porosity of 5-15% and permeability of 10-86 mD. Several other potential reservoirs exist in shallower zones. These gas plays generally have marginal thicknesses of 0-40 ft.

Several containment units overlie the basal sandstone. The Rome/Maryville, Conasauga, and Copper Ridge are primarily dense dolomite and shale. Porosity in the formations is generally less than 5% and permeability less than 1 mD. These formations have a combined thickness of more than 1,500 ft. Overlying the Rose Run are a series of dolomite and limestone units including the Beekmantown, Wells Creek, Black River, and Trenton units. These rocks are mostly dolomite and limestone with low porosity and permeability, with a combined thickness of 1,400 ft. Another 1,200 ft of Reedsville and Juniata shale overlies these rocks. The shale formations have very low effective porosity of <1% and permeability is often below 1E-6 mD. In general, containment units appear to be present above the target injection layers that are more than adequate to prevent any upward migration of CO₂.

Groundwater flow in deep saline aquifers is complex due to the variable density of formation waters. Maps of equivalent freshwater head in the basal sandstone suggest regional flow from deep basins to shallow arches. Other studies suggest variable density has a larger effect on groundwater flow. Research agrees that groundwater flow in the basal sandstone is less than 1 ft per year. Vertical gradients in the area are not conclusive but suggest a downward gradient in the study area.

Initial estimates on reservoir capacity were calculated for the basal sandstone and the Rose Run Sandstone. The estimates were made for a 10-mile radius of the proposed site based on expected hydraulic parameters for the site. Calculations for the basal sandstone indicate a capacity of 39-78 Mt. The Rose Run Sandstone has the same capacity of 39-78 Mt due to its limited effective thickness. Based on these calculations, combined reservoir capacity is approximately 200 Mt. More capacity may be obtained beyond the 10-mile radius used in the calculations, but the geology changes rapidly in these areas.

7.4 Geochemistry

Groundwater analyses suggest that nearly all bedrock groundwater in the study area is brine, with TDS of more than 30,000 mg/L. Water becomes more concentrated with depth, with TDS of 200,000 to 325,000 mg/L found in formations less than 1,000 ft deep. Major dissolved ionic constituents are sodium, chloride, magnesium, and calcium. Minor ions are barium, sulfate, silica, iron, aluminum, potassium, and bromide. Major geochemical trends include increasing concentrations with depth and linear relationships between Ca and Cl and Na and Cl. Overall, groundwater chemistry appears to reflect a mature basin where formation fluids have mixed over several thousand years.

7.5 Recommendations

Review of geologic information available for the study area indicates that the proposed site has potential for injection. Only one well penetrates deep rocks within 25 miles of the site, so most conclusions on deep geology are based on regional trends. Primary targets for injection reservoirs are the basal sandstone and the Rose Run sandstone. Containment intervals appear to be more than sufficient in the study area.

It is recommended that several issues should be considered in any further investigations:

- Topography may present minor challenges to installing additional injection wells in upland areas away from the Ohio River flood plain. Steep terrain also may make pipeline construction more costly.
- The thickness of the potential injection reservoirs is a major uncertainty in the study area. Thick sandstone formations that are present in much of the region thin appreciably toward the study area. Although the presence and extent of target reservoirs is not in question, their effective thicknesses are uncertain because few deep wells exist nearby. Reservoir thickness will have a large influence on injection capacity and system design. Substantial injection is possible in thinner formations, but would require more injection wells spaced further apart.
- Porosity and permeability of the injection reservoirs needs to be verified. Regional data on potential injection reservoirs indicates that acceptable porosity and permeability exist in the rock formations. However, the properties of rock formations change relatively rapidly toward the Rome Trough. Also, few reservoir tests are known in the study area. Consequently, reservoir tests at the site would provide essential information on the targeted injection reservoirs.
- Faulting does not appear to be present in the study area, but faults leading to the Rome Trough are a possibility. Seismic surveys are the best method to detecting any faults in the study area. Most faults in the region penetrate from Precambrian rocks into lower Cambrian formations, and are not susceptible to upward migration of injected fluids.
- Multiple containment intervals are present in the study area, so upward migration through several containment zones is very unlikely. There is little evidence of fracturing in the containment interval, but extensive fracturing could result in the rapid transmission of fluids from the injection zone into the overlying formations. In addition, high injection pressure could reopen previously closed fractures. Detection of pervasive fractures in containment intervals should be an objective of any site-specific investigations.

- The influence of geologic structures in the area is important to understanding the nature of the deep reservoirs in the area. Features in the Precambrian basement rock may have some control on the thickness of Paleozoic rocks.
- Physical conditions that should be accounted for in system design include temperatures at approximately 90-150°F, TDS content of 300,000 mg/L or more, and high pressures on the order of 4,100 psi. These conditions are fairly typical for deep saline reservoirs but should be noted when selecting well construction materials.
- Baseline seismic monitoring should be performed at the site to help detect any induced seismic activity. The site is in a low-risk area for earthquakes, but seismic activity has occurred in the region, and baseline monitoring will be invaluable to differentiating natural quakes from induced ones. Seismic monitoring also may be used to monitor hydraulic fracturing and other processes.
- The lowermost USDW appears to be the Pennsylvanian bedrock although most drinking water is obtained from shallow alluvial sediments in the area. The quality and capacity of the bedrock formations is marginal. A more thorough analysis of groundwater from the bedrock aquifer would aid in describing the lowermost USDW.

Review of the geologic information for the New Haven site revealed several opportunities for additional research into the field of greenhouse gas sequestration in deep saline reservoirs:

- Further investigation into the potential for injection into fractured rock formations may be pursued. Fractured rock formations may offer increased injection capacities. Injection in fractured rock would also open up more opportunities to apply CO₂ sequestration at other locations.
- Additional monitoring methods should be considered beyond typical underground injection control. Tracking the injection front is of particular interest given the density contrast between the injected supercritical CO₂ and saline formation waters.
- Research into the long-term behavior of CO₂ in geologically complex settings may be of interest. The low density of CO₂ suggests that variable density flow will have a large impact on the movement of injected fluid in the subsurface. Geologic structures such as folds, arches, and basins may have a large control on the long-term migration of injected fluids. Fluid movement may be higher in steeply dipping formations.
- Wells in oil and gas reservoirs may merit further investigation given the large number borings available for monitoring and/or injection. Abandoned gas wells may be especially useful for monitoring and site characterization. The practical value of these wells versus their limitations needs to be considered.
- Design optimization of injection systems may be of interest to enhance injection. Application of technology such as horizontal wells, hydrofracturing, and formation treatment may be employed to maximize injection efficiency.

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Appendix A

Preliminary Assessment of Potential Injection Strata for Carbon Dioxide Sequestration at New Haven, West Virginia

**PRELIMINARY ASSESSMENT OF POTENTIAL INJECTION STRATA FOR CARBON
DIOXIDE SEQUESTRATION AT NEW HAVEN, WEST VIRGINIA**

PREPARED FOR BATTELLE

COLUMBUS, OHIO

OCTOBER 1, 2002

REVISIONS MADE AND RESUBMITTED

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TABLE OF CONTENTS

Introduction	1
Objectives	1
Methods	1
Previous Work	2
Regional Structural Geologic Setting	
Precambrian Structure	3
Paleozoic Structure	4
Paleozoic Stratigraphy	4
Review Of Oil And Gas Plays	
Introduction	9
Cambrian Conasauga Group	9
Cambrian-Ordovician Knox Group and St. Peter sandstone	9
Middle Ordovician Lexington/Trenton carbonates	10
Lower Silurian “Clinton-Medina”/Tuscarora Sandstone	10
Lower Devonian Oriskany Sandstone and Upper Silurian	
Newburg Sandstone and Lockport Dolomite	10
Upper Devonian Black Shales	11
Upper Mississippian and Lower Devonian Berea Sandstone	11
Upper and Lower Mississippian Limestones and Sandstones	11
Lower and Middle Pennsylvanian Allegheny and Pottsville Group.	12
Seismic Reflection Data	12
Seismicity	12
Structural Geology Near The New Haven Site	13
Potential Injection Zones, Isopach, Net Sandstone (Density Cutoff) Mapping	
Cambrian Maryville Formation	13
Cambrian Maryville Formation “lower unit”	14
Cambrian-Ordovician Rose Run sandstone	15
Speculative deep-injection zones	17
Shallow potential injection intervals	17
Confining Units For Potential Injection Intervals	
Cambrian Maryville “lower unit”	18
Cambrian-Ordovician Rose Run sandstone	18
Summary	18
Bibliography	21
Tables	26
Figures	30

FIGURES

1. Map of the New Haven AOR (Area of Review) showing location of oil and gas wells used in the study, cores, and lines of cross sections. Formations at total depth for oil and gas wells are indicated by color. Also shown are the mapped area and the location of the New Haven site.
2. Stratigraphic correlation chart for the AOR showing the Cambrian and lower part of the Ordovician.
3. Map showing structure on unconformity Precambrian surface in Ohio and surrounding region and location of the New Haven site.

4. Map showing Precambrian Provinces and location of the New Haven site.
5. Map showing major Cambrian structures and location of the New Haven site (modified from Baranoski, 2002).
6. Map showing regional extent of the Rome Trough, major Cambrian structures and location of the New Haven site (modified from Harris and Baranoski, 1996).
7. Stratigraphic cross section from Sandusky County, Ohio, to Pendleton County, West Virginia, showing Cambrian and Ordovician sequences (modified from Ryder and others, 1998).
8. Map showing major post-Cambrian structures and location of the New Haven site (modified from Baranoski, 2002).
9. Stratigraphic column for the AOR and potential injection zones.
10. Stratigraphic cross section (Knox unconformity to Precambrian unconformity interval) Dip D1-D1' deep
11. Stratigraphic cross section (Knox unconformity to Precambrian unconformity interval) Dip D2-D2' deep
12. Stratigraphic cross section (Knox unconformity to Precambrian unconformity interval) Strike S1-S1' deep
13. Stratigraphic cross section (Knox unconformity to Precambrian unconformity interval) Strike S2-S2' deep
14. Map showing isopach of the Maryville Formation within AOR and location of the New Haven site.
15. Maryville Formation core interval 5205.5 to 5214.5, #4 Aristech well (APINO 3414560141, Scioto County).
16. Map showing isopach of the Maryville Formation "lower unit" within AOR and location of the New Haven site.
17. "Lower unit" of the Maryville Formation core interval 5558.8 to 5572.3, #1 Aristech well (APINO 3414520212, Scioto County).
18. Map showing isopach of the Rose Run within AOR and location of the New Haven site.
19. Stratigraphic cross section (Shallow geologic units to Knox unconformity interval) Dip D1-D1' shallow
20. Stratigraphic cross section (Shallow geologic units to Knox unconformity interval) Dip D3-D3' shallow
21. Stratigraphic cross section (Shallow geologic units to Knox unconformity interval) Strike S1-S1' shallow
22. Stratigraphic cross section (Shallow geologic units to Knox unconformity interval) Strike S2-S2' shallow
23. Map showing the Cambrian-Ordovician Knox Dolomite and St. Peter sandstone oil and gas fields and location of the New Haven site.
24. Map showing the Middle Ordovician Lexington/Trenton and Black River Group carbonates, and Utica shale oil and gas fields in Ohio, and location of the New Haven site. Also shown are wells permitted to the Trenton in West Virginia.
25. Map showing the Lower Silurian "Clinton-Medina"/Tuscarora sandstone oil and gas fields and location of the New Haven site.
26. Map showing the Lower Devonian Oriskany Sandstone and Upper Silurian Newburg Sandstone and Lockport Dolomite oil and gas fields and location of the New Haven site.

27. Stratigraphic cross section showing the Devonian Oriskany to Ordovician interval Dip D4-D4'.
28. Map showing the Upper Devonian Black Shales oil and gas fields and location of the New Haven site.
29. Map showing the Upper Mississippian and Lower Devonian Berea Sandstone oil and gas fields and location of the New Haven site.
30. Map showing the Upper and Lower Mississippian limestones and sandstones oil and gas fields and location of the New Haven site.
31. Map showing the Lower and Middle Pennsylvanian Allegheny and Pottsville Group oil and gas fields and location of the New Haven site.
32. Structure map on the top of the Precambrian unconformity surface in the AOR.
33. Structure map on the top of the Maryville Formation in the AOR.
34. Structure map on the top of the Rose Run Sandstone in the AOR.
35. Type density log showing arbitrary net RHOB from the #1 Aristech well (APINO 3414520212, Scioto County).
36. Type density log showing arbitrary net RHOB from the #1 Trepanier well (APINO 3407920102, Jackson County).
37. Maryville "lower unit" net RHOB at ≤ 2.68 (porosity equivalence $\geq 0\%$) cutoff and location of the New Haven site.
38. Maryville "lower unit" net RHOB at ≤ 2.55 (porosity equivalence $\geq 6\%$) cutoff and location of the New Haven site.
39. Maryville "lower unit" net RHOB at ≤ 2.40 (porosity equivalence $\geq 15\%$) cutoff and location of the New Haven site.
40. Rose Run net RHOB at ≤ 2.68 (porosity equivalence $\geq 0\%$) cutoff and location of the New Haven site.
41. Rose Run net RHOB at ≤ 2.55 (porosity equivalence $\geq 6\%$) cutoff and location of the New Haven site.
42. Rose Run net RHOB at ≤ 2.40 (porosity equivalence $\geq 15\%$) cutoff and location of the New Haven site.
43. Map showing average bulk density for Rose Run Sandstone and location of the New Haven site.

TABLES

Table 1. List of data types/fields in ACCESS database.

Table 2. List of wells in the AOR with preKnox oil and gas production and shows.

Table 3. List of wells in the AOR with thickness calculations and RHOB calculations for injection intervals

APPENDICES

A. Core descriptions

Conasauga Group #1 Aristech well (APINO 3414520212, Scioto County), #4 Aristech well (APINO 3414560141, Scioto County), and #1 Powers Oil Company well (APINO 4710700351, Wood County)

- B. Miscellaneous test and analyses
 - #1-A Cambria Clay well (APINO 3408720219, Lawrence County) completion and DST data Knox dolomite
 - #1 Arrington well (APINO 4705300069, Mason County) DST results Maryville Formation (no pressures) brine analyses (Overbey, 1961).
- C. List of wells in the AOR with RHOB, porosity and permeability calculations for injection intervals
- D. Additional references
- E. Tests and analyses from Aristech Class 1 well site, Scioto County, Ohio

DISCLAIMER

The information contained herein has not been technically reviewed for accuracy and conformity with present Ohio Division of Geological Survey standards for published or open-file materials. The Ohio Division of Geological Survey does not guarantee this information to be free from errors, omissions, or inaccuracies and disclaims any responsibility or liability for interpretations or decisions based thereon.

INTRODUCTION

The Ohio Department of Natural Resources, Division of Geological Survey (DGS) was contracted by Battelle (Columbus, Ohio) to provide subsurface geologic information in support of Battelle's carbon dioxide sequestration project at New Haven, West Virginia. The area of review (AOR) is a 7,300 mile² area (about 83 miles by 88 miles) approximately centered on New Haven, and includes portions of West Virginia and southeastern Ohio (Figure1). The primary area of interest is the Ohio River corridor near the proposed site.

OBJECTIVES

The objective of this investigation is to prepare a subsurface geologic assessment of the AOR to include: literature review/bibliography, all pertinent data (digital where possible), geologic cross sections, and structure and isopach maps of important and potential injection horizons with emphasis on the deep Cambrian geologic units. This information will be used as the basis for other tasks to be completed by Battelle including a field-work plan (well design), monitoring plan, risk assessment, and application for underground injection permit. General subsurface data targeted for review include: oil and gas plays, deep wells to the Cambrian, and public-domain seismic reflection data.

METHODS

Standard procedures and geologic mapping techniques were used to compile and represent existing geologic information. Data collected included: formation depths, formation thickness, well-construction details, formation pressure, permeability, porosity, location and availability of core samples, location and availability of brine/formation fluid samples, and mineralogy for potential injection zones. Digital data were assembled from sources at the DGS and West Virginia Geological and Economic Survey (WVGES) into Microsoft® Access and Geographix Explorer computer software. Table 1 lists digital data types and fields. Wells in the text and figures are referred to by both lease name and APINO. The APINO is a national standardized method for assigning unique identifiers to oil and gas wells. It is expressed as a 10-digit number with the first 2 digits representing the state code, the next 3 numbers representing the county code, and the next 5 numbers representing the permit number. No wells have been drilled to the Precambrian basement complex within 25 miles of the New Haven site, therefore interpretation of Cambrian geology in the AOR is based on data from wells located at distances more than 25 miles from the site (Figure 1).

Correct and consistent usage of stratigraphic nomenclature has been an ongoing difficulty for investigators conducting regional stratigraphic studies across state boundaries (Janssens, 1973; Riley and others, 1993). A stratigraphic framework for subsurface Cambrian and Ordovician geologic units in eastern Ohio has been established from previous (Janssens, 1973; Riley and others, 1993; Ryder, 1992; Ryder and others, 1996) and ongoing work at the DGS. The Middle Cambrian in particular has been problematic in the past because of sparse deep-well data and a lack of continuous core. Another difficulty has been a lack of Cambrian paleontological studies to adequately constrain lithostratigraphic correlations (Babcock, 1994). Recent investigations of continuous core, and lithostratigraphic correlation of that core to available

geophysical logs from deep wells, have resulted in an updated Cambrian nomenclature and stratigraphy from that used by Janssens (1973). Figure 2 shows a preliminary stratigraphic chart for the Cambrian and lower part of the Ordovician, which compares Janssens (1973) nomenclature with the nomenclature used for this report. The Cambrian stratigraphy and nomenclature as used in this report is an ongoing project at the DGS and has not been finalized.

A network of three-dip and two-strike cross sections were constructed within the AOR using Geographix software (Figure 1). The cross sections illustrate the regional stratigraphy of the potential injection zones and confining units within the AOR. Two sets of cross sections were used for correlation (shallow and deep sections), with stratigraphic datums on the top of the Onondaga Limestone and Maryville Formation, respectively.

Computer mapping was done in Geographix Explorer software using minimum curvature algorithms. Structure maps were made on the top of the Cambrian Rose Run sandstone, and Maryville Formation. A digital structure map on the Precambrian unconformity surface (Baranoski, 2002) was utilized for the evaluation (Figure 3). Isopach maps were made of the Cambrian Rose Run sandstone, Maryville Formation, and “lower unit” of the Maryville Formation.

Computer mapping of bulk-density (RHOB) measurements from digital geophysical density logs was also performed for potential injection zones in the Cambrian Rose Run sandstone and the “lower unit” of the Maryville Formation. Multiple log suites (sonic, neutron, photo electric) from deep wells in the AOR were not available to calculate lithology models of the potential injection zones. As a result, RHOB was chosen as the best quantifiable rock-property measurement of potential injection zones within the AOR. The RHOB values were taken directly from the raw digital well-log data (Log ASCII Standard-LAS format) and were used to generate computer-contoured net footage maps for three bulk density cutoffs.

The RHOB values used for this report cannot be utilized for engineering calculations/estimations. Converting RHOB values into statistically accurate porosity values must take into account many engineering and geological variables that are not available for most wells in this study area: bore hole condition (rugosity, wash-out zones, mud cake buildup, etc.), drilling fluids, drilling muds, formation fluid density, formation fluid temperature, formation temperature, geophysical wireline logging tool calibration, geophysical wireline logging tool variations, etc. For example the single variable, formation temperature changes significantly across the AOR, thus affecting accurate modeling of RHOB across the AOR. Taking into account the numerous other variables, both geologic and engineering, yields an extremely complex relationship needed to model the porosity distribution across the AOR with a very incomplete data set. In addition, this report discusses the complex depositional, diagenetic and cementation history that affected the porosity and permeability of both the Rose Run Sandstone and Maryville Formation. These factors add significant heterogeneity to these units, which further complicates models using the RHOB data to calculate porosity across the AOR. Another difficulty with quantifying the RHOB data as porosity across the AOR is a lack of appropriate well logs available. To accurately model the potential injection intervals at the New Haven site, a stratigraphic test core should be acquired and calibrated to multiple modern geophysical wireline log suites (e. g. Density, Neutron, Photoelectric, Nuclear Magnetic Resonance, etc.).

Arbitrary RHOB cutoffs of 2.68, 2.55 and 2.40 grams per cubic centimeter (g/cc) were chosen in this investigation to illustrate an estimated net footage at different RHOB ranges. A porosity equivalency to each RHOB cutoff is assigned and shown in the legend for each of the net RHOB maps. These porosity equivalencies are derived from a RHOB versus porosity graph (Asquith, 1982) for a pure quartz sandstone. It is important to note that these porosity equivalencies assume the subject interval is of a uniform lithology (pure quartz arenite sandstone), which they are not. The complex depositional and diagenetic history of the Rose Run sandstone and Maryville Formation, which is based on deep wells more than 25 miles away, emphasize that arbitrary RHOB cutoffs can not be accurately assigned porosity and porosity-feet values. To accurately model the potential injection intervals at the New Haven site a stratigraphic test core must be acquired and calibrated to multiple modern geophysical wireline log suites (such as Density, Neutron, Photoelectric, etc.). Table 3 lists the RHOB and porosity equivalency values calculated for deep wells evaluated.

PREVIOUS WORK

Aside from regional mapping investigations that included the AOR, no detailed deep-subsurface investigations of the Cambrian strata have been conducted for the New Haven area. Subsurface studies of shallow strata in the area were done for the U.S. Department of Energy and Gas Research Institute Gas Shales projects (Negus-de Wys and Shumaker, 1978; Gray and others, 1982; Ohio Division of Geological Survey, 1988). See Ohio Division of Geological Survey (1988) for an additional listing of shallow studies in Meigs County, Ohio and adjacent West Virginia. Seismic reflection investigations were done in the Cottageville oil and gas field 10 miles SE of the New Haven site (Sundheimer, 1979). References to previous work related directly to the objectives of this investigation can be found in the appropriate sections of this report. Indirectly related references are listed in Appendix D.

REGIONAL STRUCTURAL GEOLOGIC SETTING

Precambrian Structure

The Precambrian Era basement complex is the foundation for overlying Paleozoic Era (and younger) rocks of eastern North America. In general terms, the Precambrian complex of the region includes all rocks older than 600 million years, and Paleozoic rocks include rocks less than 600 million years old. A thorough understanding of the geologic structure, character, and history of the underlying Precambrian complex is necessary in order to understand the geologic framework of the Paleozoic strata. However, the paucity of physical rock samples and cores from the deep subsurface of the AOR prevents a thorough characterization of the basement complex. Therefore, a very general description is provided based on our interpretation of the limited data.

The Precambrian basement complex of the region consists of portions of the Grenville Province, East Continent Rift System and the Eastern Granite-Rhyolite Province (Figure 4). On magnetic anomaly maps, Grenville Province metamorphic and igneous rocks of high magnetic susceptibility east of the Grenville Front show pronounced positive anomalies against less magnetic rocks of the Eastern Granite-Rhyolite Province west of the Grenville Front (Bass, 1960;

Lucius and von Frese, 1988). U/Pb age dates have not been determined for the Eastern Granite-Rhyolite Province or Grenville Province in Ohio. However, regional geochronological investigations outside Ohio indicate the Eastern Granite-Rhyolite Province is approximately 1.3 to 1.4 GA (Van Schmus et al., 1996), and the Grenville Province is approximately 1.0 to 1.2 GA (Culshaw and Dostal, 2002). The Eastern Granite-Rhyolite Province was down faulted and structurally deformed by continental rifting during the development of the East Continent Rift System. The rift is filled, in part, with Precambrian clastic sediments named the Middle Run Formation (Shrake, 1991; Shrake and others, 1990) and extends from northwest Ohio to central Kentucky and westward across Indiana. It is thought to be part of the Midcontinent Rift System (Drahovzal and others, 1992) (Figure 4).

The Grenville Province is an extension of the Grenville metamorphic and igneous terrane exposed in southern Canada, and consists of regionally metamorphosed igneous and sedimentary rocks formed during the Grenville Orogeny. Within two deep wells outside the AOR, the Grenville Province consists of meta-gabbro, orthogneiss, granite, and amphibolite ((#1 Aristech (APINO 3414520212, Scioto County) and #1 Power Oil Company (APINO 4710700351, Wood County)). The Grenville Province underlies eastern Ohio and adjacent West Virginia and forms the underpinning structure beneath Paleozoic sedimentary cover. Seismic reflection data suggests localized Precambrian sedimentary units beneath the Paleozoic in eastern Ohio and adjacent West Virginia, however the presence of these units has not been confirmed by drilling.

Paleozoic Structure

During the Paleozoic Era, periodic structural adjustment occurred along pre-existing Precambrian faults and associated zones of weakness. This adjustment affected faulting, sedimentation and depositional patterns during the Paleozoic (Beardsley and Cable, 1983; Riley and others, 1993).

Two regional structural features developed on the eastern Laurentian craton, which was the deeply eroded Grenville Province: the Rome Trough (McGuire and Howell, 1963) and the Appalachian Basin (Figure 5). The Rome Trough, which was first described by Woodward (1961) as a “Cambrian coastal declivity,” is considered an Early to Middle Cambrian age failed interior rift (Harris, 1978). The Rome Trough is a regional NE trending structure extending from southwestern Pennsylvania, where it is termed the Olin Basin (Wagner, 1976), to northern Tennessee (Figure 6) and is very prominent on magnetic intensity maps (King and Zietz, 1978). Sparse deep-well data and seismic reflection data correlate to this magnetic trend and indicate the Rome Trough is an asymmetric failed-rift zone with the deepest portion on the NW side (Ryder and others, 1998; Gao and others, 2000). A thick accumulation of carbonate and clastic rocks in excess of 10,000 feet (Ryder, 1995) infilled the Rome Trough. Figure 7 is a simplified cross section of the Rome Trough from Ohio to West Virginia with datum on the Ordovician Gull River limestone.

The Appalachian Basin did not begin to take on its present configuration until after Middle Cambrian time following the major movement of the Rome Trough. Major structural features in the region that were active along basement faults during the Late Cambrian subsidence of the Appalachian Basin include: the Waverly Arch, the Cambridge Cross-Strike-Structural-

Discontinuity, and the Burning Springs Cross-Strike-Structural-Discontinuity (Figure 5). The subsidence of the Appalachian Basin culminated with the Alleghenian Orogeny and development of the Appalachian structural front and lastly the Burning Springs Anticline and Cambridge Arch features (Figure 8). As the Appalachian Basin subsided, monoclinial flexures developed parallel to NNE strike, affecting localized structures throughout the region.

PALEOZOIC STRATIGRAPHY

Regional and localized areas of recurrent crustal movement of the Precambrian basement and later regional uplifts, subsidence, and compressional forces affected the distribution, character and thickness of Paleozoic rock units. Thickness of Paleozoic Appalachian Basin rock units in the region ranges from approximately 3,000 feet in central Ohio to an estimated 45,000 feet in central Pennsylvania (Milici, 1996). The Paleozoic stratigraphic column in the Appalachian Basin ranges in age from Lower Cambrian to Early Permian (Figure 9). A range of sedimentary units (carbonates, evaporites, shale, sandstone, siltstone, k-bentonites, chert, etc) are present throughout the region. Major unconformities mark the Middle Cambrian, Middle Ordovician, Lower Silurian, Middle Devonian, and Upper Mississippian. Pennsylvanian and Permian rock units are largely clastic rocks with minor carbonate units.

The emphasis of this report is an evaluation of potential injection zones within the Lower Ordovician-Cambrian rock sequence of NW West Virginia and adjacent SE Ohio. This interval is bounded at the bottom (base of the Maryville Formation/basal arkose) and top (top of the Beekmantown dolomite) by major unconformities (Figure 2). Sloss and others (1949) used the informal term Sauk sequence for this interval for facies analysis in the upper Mississippi Valley and regional subsurface correlation. Janssens (1973) recognized the importance of regional stratigraphic relationships to the Sauk Sequence in Ohio. His detailed regional study documented significant stratigraphic changes within the Cambrian that show variations from western Ohio, eastward into the Appalachian Basin. In a pre-Knox study of the Appalachian Basin, Harris and Baranoski (1997) divided the region into three sequences: stable cratonic sequence, Rome Trough sequence, and eastern basin sequence (Figure 6). The stable cratonic sequence is stratigraphically much thinner than the Rome Trough sequence, and both fall within the AOR. These terms will be used for the remaining discussion.

It should be noted that the stratigraphy and nomenclature presented in this report is preliminary and has not yet been published. Work in progress at the DGS indicates that significant changes from Janssens (1973) work are present in the Middle Cambrian (Figure 2). Specifically, the Mount Simon Sandstone pinches out in extreme southeastern Ohio, the Rome Formation is not present in southeastern Ohio, and the Conasauga Formation (Janssens, 1973) has been redefined to the Conasauga Group (Ryder, 1992; and Ryder and others, 1996). The Conasauga Group includes the Maryville Formation (including the "lower unit"), the Nolichucky Shale, and the Maynardville Limestone. The Pumpkin Valley Shale, Rutledge Limestone and Rodgersville Shale (Ryder, 1992; and Ryder and others, 1996), which form the lower portion of the Conasauga Group, are confined to the Rome Trough east of New Haven, based on present well control. Appendix A and B lists detailed core descriptions used in the evaluation.

The earliest record of sedimentation within the region is found within the Rome Trough sequence of rocks in West Virginia and Kentucky. Deposition of this sequence began with the lowermost Paleozoic basal sandstone (arkose) in the Latest Precambrian-Early Cambrian time. Rifting of the eastern Laurentian continent resulted in the opening of the Iapetus Ocean (Harris, 1978; Scotese, and McKerrow, 1991). Subsidence of the Rome Trough continued with deposition of the Shady Dolomite and Rome Formation during the Lower Cambrian and continued through Middle Cambrian with deposition of the Conasauga Group. The pre-Knox section of the Rome Trough is older and greatly thickened when compared to the same intervals of the stable cratonic sequence. As much as 10,000 feet of pre-Knox sediments accumulated in the Rome Trough (Webb, 1980; Ryder, 1992; Ryder and others, 1996). Dip sections D1-D1' deep (Figure 10) and D2-D2' deep (Figure 11) illustrate the variation in thickness of the Lower and Middle Cambrian units into the Rome Trough fault system. This is best illustrated between the #1 Arrington well (APINO 4705300069, Mason County) and the #1 Jividen well (APINO 4705300297, Mason County) (Figure 10). Regional cross sections S1-S1' deep (Figure 12) and S2-S2' deep (fig, 13) illustrate the stratigraphic changes along depositional strike for these units.

The basal arkosic sandstone is the lowermost unit within the Rome Trough sequence. The basal sandstone was deposited on the Precambrian unconformity surface and ranges in thickness from 20 to 650 feet (McGuire and Howell, 1963; Webb, 1980). Ryder shows thickness of approximately 150 feet for the basal sandstone in the Rome Trough in West Virginia (Ryder, 1992; Ryder and others, 1995). The Shady Dolomite, which is confined to the Rome Trough area, is a carbonate unit that directly overlies the basal sandstone. Cross sections by Ryder (1992) and Ryder and others (1995) show thickness of the Shady Dolomite at approximately 250 feet in the Rome Trough. The Rome Formation consists of sandstone, siltstone, shale, limestone, and dolomite and ranges in thickness from 1,000 to 2,900 feet (Ryder, 1992; Ryder and others, 1996). Depositional environments for the Rome and overlying Conasauga Group are interpreted as tidal-flat, tidal-channel, and shallow subtidal environments based on core (Donaldson and others, 1975, 1988). The Conasauga Group also consists of sandstone, siltstone, shale, limestone, and dolomite and ranges in thickness from 2,400 to 5,500 feet, which are subdivided into the Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Maryville Formation, Nolichucky Shale, and Maynardville Limestone (Ryder, 1992; Ryder and others, 1996). Figures 7, 10, and 11 show dramatic thickness increase in Cambrian rock units and generalized stratigraphic relationships from Ohio into West Virginia.

Throughout latest Precambrian to most of Middle Cambrian time, eastern Ohio remained an emergent area as a stable cratonic platform. During this time the erosion of the exposed Grenville basement complex in Ohio and northwestern West Virginia supplied clastic sediment to the Rome Trough while carbonates dominated the eastern side of the structure. Seismic reflection data in southeastern Ohio indicates local areas of Cambrian sediments older than the Maryville Formation "lower unit" in structurally low areas following incised channels, which drained into the Rome Trough. Near the end of the Middle Cambrian, seas had completely transgressed the exposed Precambrian basement complex in Ohio resulting in near shore to marginal marine deposition of Mount Simon Sandstone in western Ohio to marginal marine and marine deposition of Maryville Formation (Conasauga Group) in eastern Ohio. The Mount Simon Sandstone, which is a 200 to 300 feet-thick, highly permeable, porous quartz sandstone in western Ohio, pinches out and/or is in facies transition with the lowermost part of the Maryville Formation in the western portion of

the AOR. The Mount Simon had previously been considered a region-wide, areally extensive unit in Ohio (Janssens, 1973). The DGS is presently updating Janssens (1973) work using core and additional geophysical logs. This ongoing study indicates that the Mount Simon disappears eastward either at a pinch-out above the Precambrian unconformity surface or in facies transition from sandstone to dolomite with the lower-most portion of the Maryville “lower unit”. The implication is that the Mount Simon Sandstone is not recognized as a regional stratigraphic “blanket” of sandstone.

The Maryville Formation consists dominantly of dolomite to feldspathic quartz dolomite and ranges in thickness within the AOR from 373 to 2,800 feet (Figure 14). The upper portion is light to medium gray, cryptocrystalline to fine and medium crystalline, laminated to irregular, massive bedded, slightly arenaceous dolomite. Glauconite, anhydrite-filled vugs, rip-up clasts, stylolites, shaley discontinuity surfaces, scour surfaces, and bioturbation are locally common (Figure 15). Depositional environments range from shallow subtidal to shallow marine and continental slope (appendix A). The “lower unit” of the Maryville is feldspathic quartz dolomite to feldspathic quartz sandstone, and ranges in thickness within the AOR from 100 to more than 650 feet (Figure 16). The “lower unit” is light pink to white and light brown, fine and medium grained, poorly to well sorted, rounded to subrounded, laminated to irregular, massive bedded, feldspathic dolomitic quartz arenite (Figure 17). Trough cross-bedding, fining upwards sequences, anhydrite replacement clasts, shaley discontinuity surfaces, scour surfaces, bioturbation, vertical burrows, trace fossils, and intraformational breccia are locally common. Depositional environments range from near shore and shallow subtidal to shallow marine environments (appendix A). The quartz sandstone content and geophysical log porosity of the “lower unit” increases in the western portion of the AOR. Dip sections D1-D1’ deep (Figure 10) and D2-D2’ deep (Figure 11) illustrate the variation in thickness of the Maryville from Ohio into West Virginia. The most notable aspect is the rapid increase in thickness across the Rome Trough fault system from the #1 Arrington well (APINO 4705300069, Mason County) to the #1 Jividen well (APINO 4705300297, Mason County). Also notable is the decrease in Maryville thickness in the #1 Arrington well, which may indicate a higher shelf area on the immediate NW footwall to the Rome Trough. The Maryville Formation grades upward into the overlying Nolichucky Shale. Appendix A describes the Maryville sedimentary lithofacies from core. Figure 17 is a photo of core from the Maryville “lower unit” showing quartz arenite beds from the #1 Aristech well (APINO 3414520212, Scioto County).

Deposition of the Conasauga Group continued into the Upper Cambrian with a minor marine regression represented by the Nolichucky Shale clastics and carbonates, followed by a transgression with deposition of the Maynardville Limestone. Open marine conditions continued with deposition of the Knox Dolomite. As used in this report, the Knox Dolomite is subdivided in ascending order into the Copper Ridge dolomite, the Rose Run sandstone, and the Beekmantown dolomite (figs. 2 and 9). Minor regressions took place with input of clastics in the “B-zone”, and to a greater degree, the Rose Run sandstone.

The Rose Run sandstone occurs within a thick sequence of predominantly shallow-water carbonates that comprise the Knox Dolomite. This sequence has been interpreted to consist of the vertical stacking of various peritidal facies resulting from cyclical sea-level changes on a broad carbonate shelf (Read, 1989; Osleger and Read, 1991; Riley and others, 1993). The Rose Run

sands represent low-stand deposits, related to both third-order sea-level falls and short-term sea-level cycles (Read, 1989). Thin-section petrography indicates that the Rose Run sandstone has a continental block provenance with a source in the craton interior to the north and northwest of the project area (Riley and others, 1993). Thus, siliciclastic deposition in the Rose Run decreases to the south and southeast away from the stable craton.

The Rose Run sandstone is present throughout the entire AOR and can be correlated in the subsurface to where it subcrops in the extreme western portion of the mapped area (Figure 18). The gross thickness of the Rose Run sandstone ranges from 74 feet in Hocking County, Ohio, to over 195 feet in Jackson County, West Virginia (fig 18). In the mapped area, the average gross thickness is approximately 100 feet. At the proposed project site, the mapped Rose Run gross thickness is estimated to be approximately 125 feet. Generally speaking, the Rose Run gross interval thickens to the east and southeast down dip towards the basin center. Regional thickening of this interval also is illustrated on the northwest-southeast trending stratigraphic cross sections (figs. 10 and 11). It is important to note that while the gross interval thickens to the southeast, the amount of siliciclastics or potential injection zone in this interval decreases in this direction. This supports previous ideas on Rose Run provenance work that the sandstone-to-carbonate ratio decreases to the east and southeast away from the depositional source (Riley and others, 1993; Baranoski and others, 1996). The nearest logged well with a complete Rose Run section is about 25 miles SE, #1 Arrington (APINO 4705300069, Mason County) (Figure 10). The neutron log indicates poor sandstone development in the Rose Run interval. Sample cuttings were not recovered from the upper 100 feet of this interval, which may indicate a washed out zone (Overby, 1961). The interval with a high neutron curve above the Rose Run in this well occurs within a cherty dolomite (Overby, 1961), and may represent a drilling-induced fracture zone (Schlumberger, personal communication). The geophysical log notes that the calibration was changed above this anomalous interval.

A major regression took place during the Middle Ordovician with the onset of the regional Knox unconformity. An extensive erosional surface developed on the emergent Knox carbonate platform (Riley and others, 1993). Paleotopography reached a maximum of 150 feet on the karstic terrain of the Knox Dolomite (Janssens, 1973). Tropical seas returned to the Ohio region and inundated the subsiding Knox platform in the Middle Ordovician. The St. Peter sandstone and Wells Creek Formation represent the next major marine transgression; these units were deposited on the regional Knox unconformity. The St. Peter is a very fine grained, well-sorted, quartz arenite that forms the basal part (where the unit is present) of the Wells Creek Formation. The St. Peter increases in thickness from stable craton into the Rome Trough (Humphreys and Watson, 1996). The Wells Creek Formation is a sandy, dolomitic shale that locally contains beds of limestone. Shallow marine sedimentation continued through the Middle and Upper Ordovician with deposition of the Black River Group, Trenton Limestone, and Cincinnati Series undifferentiated. The clastic sediments of the Cincinnati Group were associated with the Taconic Orogeny of eastern North America.

Marine sedimentation in the region temporarily ceased during Late Ordovician-Early Silurian time as another major regression began and a regional unconformity develops on top of the Cincinnati Series undifferentiated. By the end of the Ordovician the western margin of the Appalachian Basin was delineated by the Indiana-Ohio Platform, and the Cincinnati and Findlay

Arches. As Silurian time progressed, repeated fluctuations of sea level flooded and retreated from the coastal lowlands on the western flank of the Appalachian Basin. Silurian-age Tuscarora Sandstone and other clastic equivalents were deposited in near shore to marginal marine deposition on this unconformity surface at the onset another marine transgression. A mixture of clastics and carbonates followed with deposition of the Rose Hill Formation and its equivalents, and the overlying Lockport Dolomite, Newburg sandstone, Salina Group, Bass Islands Dolomite and Helderburg Formation. Another period of regression is marked by an unconformity within Lower Devonian strata, and is followed by a period of transgression and subsequent deposition of the Oriskany Sandstone, overlying Onondaga Limestone, and shales of the Hamilton Group (marking the onset of the Acadian Orogeny). Dip sections D1-D1' shallow (Figure 19) and D2-D2' shallow (Figure 20), and strike sections S1-S1' shallow (Figure 21) and S2-S2' shallow (Figure 22) illustrate the variation in thickness of the units deposited above the Knox unconformity to the top of the Berea Sandstone.

During the Late Devonian Acadian Orogeny, tropical seas again inundated the region with deposition of the Sonyea, West Falls, and Rhinestreet Formations, and Ohio Shale into a partially restricted marine basin. The overlying Bedford Shale and Berea Sandstone represent the progradation of gray shales and sandstones. The regional stratigraphy is shown in Figures 19, 20, 21, and 22. An Early Mississippian marine transgression resulted in the deposition of the Sunbury Shale. Renewed mountain building in eastern North America with the Alleghenian Orogeny during the Early Mississippian resulted in delta progradation and the deposition of the Cuyahoga and Logan Formations, followed by a minor marine transgression with deposition of the Greenbrier Limestone and equivalents. Continued mountain building to the east resulted in extensive fluvial, clastic deposition including coals with minor limestone accumulations throughout the Pennsylvanian and Permian Systems.

REVIEW OF OIL AND GAS PLAYS

Introduction

While enhanced recovery of oil and gas from CO₂ injection is not a primary objective of the Battelle project at New Haven, the impact of injection on hydrocarbon deposits is a significant consideration. Especially since some formations with potential hydrocarbon reserves may be targeted for CO₂ injection. Updated maps (extracted from DGS oil and gas fields digital maps and WVGES digital data) of oil and gas plays in the AOR are provided to assist in understanding their potential to impact CO₂ sequestration. In the AOR, the following plays are discussed: the Cambrian Conasauga Group, the Cambrian-Ordovician Knox Group, the Middle Ordovician Lexington/Trenton and Black River group carbonates, the Lower Silurian "Clinton"/Tuscarora Sandstone, the Lower Devonian Oriskany Sandstone and the Upper Silurian Newburg Sandstone and Lockport Dolomite, the Upper Devonian Black Shales, the Upper Mississippian and Lower Devonian Berea Sandstone, the Upper and Lower Mississippian sandstones, and the Lower and Middle Pennsylvanian Allegheny and Pottsville Groups (figs. 23-31). A detailed description of these plays is present in the Atlas of Major Appalachian Gas Plays (Roen and Walker, 1996).

Cambrian Conasauga Group

Drilling to Cambrian-Ordovician stratigraphic units in the AOR is very rare due to great depth and rare hydrocarbon production. About 25 miles SE of the New Haven site, the #1 McCoy well (APINO 4703501366, Jackson County) reported open-flow gas production of 9.2 million cubic feet of gas per day (MMcfd) from a Conasauga Group sandstone unit (Harris and Baranoski, 1996). The zone produced over 400 MMcf during a 5-month period and correlates to the lower part of the upper portion of the Maryville Formation of this report. Shows of gas have been reported from the Maryville within the AOR (Table 2). Thus, hydrocarbon production from the Maryville at the New Haven site is possible if good reservoir and trapping mechanisms are present.

Cambrian-Ordovician Knox Group (including the Rose Run sandstone) and St. Peter sandstone

In Ohio, Knox hydrocarbon production occurs in the Beekmantown dolomite, Rose Run sandstone, and Copper Ridge dolomite. There is no historic Knox production in West Virginia. Nearest Knox hydrocarbon-producing fields to the proposed site are about 50 miles to the NW in Hocking County, Ohio (Figure 23). Production in this field is from the Beekmantown dolomite and Rose Run sandstone. Isolated producing wells (not shown) are also present in Jackson and Vinton counties. The majority of active Knox drilling and production is from the Rose Run sandstone to the west and north along the Rose Run subcrop trend. Although there is currently no historic production near the proposed site, this may be a favorable area for future fractured Beekmantown, St. Peter sandstone and Rose Run production.

Middle Ordovician Lexington/Trenton Limestone and Black River Group carbonates

In the Ohio portion of the AOR, the nearest Lexington/Trenton and Black River production (includes the Utica Shale) is approximately 35 miles to the north in Hocking and Washington counties (Figure 24). All Trenton or deeper well penetrations for West Virginia are also shown in Figure 24; however, it is difficult to determine the producing formation and well status for many of these wells because of the 2-year time period for holding permits. More detailed well-specific information can be obtained from the WVGES. Approximately 40 miles to the southeast of the proposed site (Figure 24) in Roane County, the discovery of large volumes of gas in the Trenton/Black River has led to a flurry of drilling activity. The discovery #20097 Parker well (APINO 4708704250, Roane County) had a reported natural open flow of 50 MMcfd, with a reported rock pressure of 5,750 pounds per square inch (psi) in an open-hole completion at 10,255 to 10,271 feet (Avary, 2002). Over 100 wells in 12 West Virginia counties have been permitted to the Trenton through March, 2001. The pay is from highly fractured carbonates in the Trenton/Black River interval, thought to be reactivated basement faults associated with the Rome Trough. Information on these wells is available on the WVGES website, www.wvgs.wvnet.edu. The proximity of the New Haven site to the Rome Trough and possible deep structures make the AOR an area of potential Trenton/Black River hydrocarbon production.

Lower Silurian “Clinton-Medina”/Tuscarora Sandstone

Scattered hydrocarbon production in the “Clinton-Medina”/Tuscarora sandstone is present in the AOR (Figure 25). In Ohio, the nearest “Clinton-Medina” fields are approximately 10 miles to the north of the proposed New Haven site. Ohio has 186 “Clinton-Medina” sandstone fields with approximately 60,000 wells that produced over 5 trillion cubic feet of gas (tcf) (McCormac and others, 1996). The major producing “Clinton-Medina” sandstone fields are located north and west of the AOR where porosity and permeability are higher. Reservoir rock is not as well developed in the “Clinton-Medina” sandstone in the AOR ((Figure 27; #1 Baker (APINO 3410523520, Meigs County)). In West Virginia, the nearest Tuscarora hydrocarbon field in the AOR is approximately 20 miles southeast of New Haven in Jackson County. Most of West Virginia Tuscarora hydrocarbon production is in Kanawha County, outside of the AOR. It is important to note that the Tuscarora sandstone reservoir is characterized as having a high carbon dioxide (CO₂) and nitrogen (N₂) content. The reported CO₂ content ranges from 4 to 83 percent and the reported nitrogen content ranges from 13.9 to 35 percent (Avary, 1996). Some of the CO₂ produced was subsequently used for repressuring and secondary recovery in nearby fields (Cardwell, 1977).

Lower Devonian Oriskany Sandstone and Upper Silurian Newburg Sandstone and Lockport Dolomite

Significant Oriskany Sandstone production is present in the AOR (Figure 26). Production is concentrated in eastern Meigs County, Ohio, and in Jackson and Mason counties, West Virginia. The first commercial Oriskany production in the Appalachian Basin occurred in early 1900. Estimated cumulative production for the Oriskany in the Appalachian Basin is 82 billion cubic feet of gas (bcf) (Opritz, 1996). Recent drilling and production since 1995 has occurred in Olive Township of Meigs County. Cross section D4-D4' (Figure 27) illustrates the Oriskany sandstone development in this area. The Oriskany sandstone in this area has an average thickness of 6 to 8 feet, and average porosities of 6 to 8 percent. The updip pinchout for the Oriskany sandstone trends north-south through central Meigs and Mason counties near the proposed site. It is not certain whether or not Oriskany will be present at New Haven.

Newburg sandstone production is also present in Meigs County, Ohio, and Jackson County, West Virginia (Figure 26). Newburg sandstone production was first discovered in 1939 in West Virginia, but the Newburg play developed in 1964 in Kanawha County. Since then, seven gas fields including 300 productive wells have been discovered. Estimated cumulative production is 290 bcf in the Appalachian basin (Patchen, 1996). Only scattered Lockport production occurs within the AOR. One small field is located in Jackson County, West Virginia. However, a Lockport reef trend extending through Meigs (OH), Mason (WV) and Jackson (WV) Counties is interpreted to be present (Smosna and others, 1989) indicating hydrocarbon potential in these reservoirs near the proposed site.

Upper Devonian Black Shales

Extensive Devonian shale production is present and is the most significant producing horizon within the AOR in terms of cumulative production and number of wells (Figure 28). The

highest concentration of production and wells drilled occurs in eastern Meigs County. Historical Devonian shale production has occurred since the late 1800's, and development of these fields was revitalized in the 1970's and 80's in response to increasing gas prices and federal tax incentives. Cumulative production for the Devonian Shales in the Appalachian Basin is estimated at approximately 3 tcf from roughly 10,000 wells (Boswell, 1996).

Upper Mississippian and Lower Devonian Berea Sandstone

The Berea sandstone is a significant producing horizon within the AOR (Figure 30). The largest productive field is the Cheshire Consolidated field in Meigs County, which had an estimated cumulative production of 1.4 bcf and 5 million barrels of oil (MMbo) (Tomastik, 1996). Berea fields occur in broad linear trends from eastern Ohio to western West Virginia. In the Appalachian Basin, 15,834 Berea wells representing 151 fields have been drilled (Tomastik, 1996). Estimated cumulative production for Berea and equivalent wells is 1.9 tcf (Tomastik, 1996).

Upper and Lower Mississippian Limestones and Sandstones

Limited historical production from the Lower and Upper Mississippian sandstones is present in the AOR (Figure 30). The Greenbrier/Newman Limestones are prolific producers of natural gas further to the east in West Virginia. Approximately 6,000 wells have hydrocarbon production from 183 fields in West Virginia and 54 wells from three fields in Ohio (Smosna, 1969). Production from the Big Injun sandstone is limited in the AOR. However, widespread and prolific hydrocarbon production occurs from the Big Injun in central West Virginia and eastern Ohio, east and north of the AOR. Cumulative production for fields in West Virginia is estimated to be 4 tcf (Vargo and others, 1996).

Lower and Middle Pennsylvanian Allegheny and Pottsville Group.

Production from the Allegheny Group was first discovered in 1860 (Hohn, 1996). Since then, isolated wells have produced gas in scattered fields in the AOR (Figure 31). Much of this production was encountered while drilling for deeper targets and was commingled. Using an average cumulative of 200 thousand cubic feet of gas (mcf), the estimated cumulative production for the Allegheny Group in the Appalachian basin is 181 bcf (Hohn, 1996). Pottsville sandstones have produced hydrocarbons since the late 1800's in the Appalachian Basin. Of 1,136 Pottsville wells on record at the DGS, 250 have a cumulative production of 20 bcf, averaging 8 MMcf per well (Hohn, 1996). Figure 31 show the current and historical production areas from both the Allegheny and Pottsville Group in the AOR.

SEISMIC REFLECTION DATA

The nearest public domain seismic reflection data to the New Haven site were acquired in Lawrence and Scioto Counties, Ohio, and Carter County, Kentucky, for the Aristech Corporation Class -1 injection site (Figure 3). The injection site is approximately 60 miles SW of the New Haven site (Figure 3). The data was acquired as a requirement for a Class 1 well permit-to-operate. The Aristech data has been reprocessed by Stiegerwalt (2002). Sundheimer (1979) acquired and processed seismic reflection data over the Cottageville oil and gas field 10 miles SE

of the New Haven site. Gao and others (2000) and Kulander (2001) are the most recent studies of the Rome Trough using seismic reflection data adjacent to the New Haven site. Gao and others (2000) used eight seismic lines and shallow well control in NW West Virginia. Kulander (2001) reprocessed 28 lines of industry seismic reflection data and 15 synthetic seismograms within the Rome Trough and adjacent NW stable shelf. This single-fold reflection data was acquired by industry during the 1950's and recently assembled into pseudo-2D modern stacked data, which was reprocessed by Kulander (2001) with modern processing techniques. Total seismic line-miles are not published.

SEISMICITY

Recent seismicity has been recorded by the Ohio Geological Survey Seismic Network near the New Haven site across the Ohio River. On May 6, 2002, a small earthquake with a magnitude of 2.8 mbLg (see web pages below for detailed discussions on the units) and estimated depth of 3 miles occurred near Antiquity, Ohio about 3 miles SE of New Haven (Hansen, 2002). A small-magnitude (3.6) (see web pages below for detailed discussions on the units) earthquake caused minor damage in the Pomeroy area of Meigs County in 1926 (<http://www.ohiodnr.com/OhioSeis/earthquakes/020506/020506.htm>). The May, 2002 event may relate to NW trending basement faulting, that appears to manifest itself by the straight line segment of the Ohio River at this location.

STRUCTURAL GEOLOGY NEAR THE NEW HAVEN SITE

Depth to Precambrian basement at the New Haven site is estimated to be 8,600 feet below mean sea level (MSL), based on very sparse deep well and seismic reflection data (Figure 32). The site is located NW of the northern boundary fault of the Rome Trough in an area that was probably exposed Precambrian basement complex during most of the structural movement of the Rome Trough. The nearest documented basement fault to the New Haven site is in Jackson County, West Virginia, in the Cottageville area (Negus-de Wys and Shumaker, 1978). The fault segment trends NE-SW, subparallel to the Ohio River.

The structure map on the top of the Maryville Formation indicates regional dip to the east and southeast at a rate of approximately 100 feet per mile (Figure 33). Subsea values range from -3,000 feet MSL in the northwest to below -14,000 feet MSL in the southeast portion of the AOR. The top of the Maryville Formation surface at the New Haven site is estimated to be -8,100 MSL based on computer mapping within the AOR (Figure 33). The structure map on the top of the Rose Run sandstone indicates regional dip to the east and southeast at a rate of approximately 100 feet per mile (Figure 34). Subsea values range from -2,600 feet MSL in the northwest to less than -10,800 feet MSL in the southeast portion of the AOR. At the proposed site, the top of the Rose Run is estimated to be at a subsea depth of approximately -6,950 feet MSL. The nearest wells to the proposed site for the Maryville Formation and Rose Run structure maps are the #1 Arrington well (APINO 4705300069, Mason County) and the #2 Buckley well (APINO 3400921827, Athens County). The #2 Buckley well only penetrated the Rose Run sandstone.

In the vicinity of Meigs County, Ohio, across the river from the New Haven site, NW-SE-trending faults and SE-plunging structural noses and troughs have been mapped on Devonian and

Mississippian surfaces based on shallow formation tops from geophysical logs (Ohio Division of Geological Survey, 1988; Baranoski and Riley, in review). Reactivated basement faulting in Meigs County during the Paleozoic was attributed to these mapped structures.

POTENTIAL INJECTION ZONES, ISOPACH, NET SANDSTONE (DENSITY CUTOFF) MAPPING

Stratigraphic analyses of Cambrian units in the AOR based on subsurface mapping, geophysical well logs, and sample and core descriptions resulted in two potential injection zones: the “lower unit” of the Maryville Formation of the Conasauga Group and the Rose Run sandstone of the Knox Group. Also, the possibility exists for previously unknown porous and permeable zones beneath the Maryville within the AOR. Although highly speculative, the potential for these older potential zones is based on seismic reflection data in the region and is discussed below. Based on computer-generated isopach maps, the estimated gross thickness of the Maryville “lower unit” is 280 feet and the Rose Run is 125 feet at the New Haven site (figs. 16 and 18). The computer-generated map thickness of 280 feet for the Maryville “lower unit” is most likely optimistic, precluding a previously unknown tectonic subsidence of the Middle Cambrian at New Haven. Based on the #1 Arrington well (APINO 4705300069, Mason County) a thickness of between 100 and 200 feet is expected for the Maryville “lower unit” at New Haven. Acquisition of reflection seismic data and drilling a test well will be required to arrive at an accurate value.

Cambrian Maryville Formation

Based on cores within the AOR, both the Maryville Formation and the Rose Run sandstone consists of a sequence of quartz arenites and subarkoses interbedded with thin beds of nonporous dolomite (Appendices A and B, DGS cores 2898, 768, and 3049). Both of these units underwent a long and complicated burial and diagenetic history, which influenced the present day porosity and permeability. Cementation plays an important role in permeability and porosity variations, which affect reservoir character. Figures 35 and 36 are bulk density (RHOB) type-logs with arbitrary cutoff points used for the analyses for this study.

Cambrian Maryville Formation “lower unit”

The Maryville Formation “lower unit” consists of a range of lithologies from dolomite to arkosic quartz arenite. Terratek, (1990) provides a detailed discussion of the petrography for the Maryville core from the Aristech site in Scioto County, Ohio. Ooids, stromatolites and fossil fragments are common and typically completely replaced with dolomite. Dolomite cement and voids filled with dolomite and anhydrite are common within carbonate-dominated intervals (Terratek, 1990). The quartz arenite is typically fine to medium grained arkose and subarkose with clay minerals common. Cement types vary from authigenic silica and feldspar overgrowths to dolomite, calcite, chlorite, ankerite, and anhydrite pore and fracture fillings (Terratek, 1990). Porosity types include: intergranular, intragranular, fracture, and clay microporosity with secondary intergranular and intragranular porosity also present (Terratek, 1990). Appendix E lists possible diagenetic sequence for the Maryville carbonate and quartz arenites at the Aristech site (Terratek, 1990).

The average porosity calculated from analyses of 29 feet of Maryville “lower unit” core from the #1 Aristech well (APINO 3414520212, Scioto County) was 12 percent with an average permeability of 27 millidarcies (md) and a calculated core bulk density (RHOB) ≤ 2.55 g/cc (Table 3). Core analyses of the Maryville “lower unit” from the #1 Aristech well (APINO 3414520252, Scioto County) yielded an average porosity of 8 percent and average permeability of 25 md for the entire “lower unit”. The bulk density ≤ 2.68 qualitatively is much closer to RHOB calculated from the electric log for this interval. The core analyses from the #2 Aristech well (APINO 3414520252, Scioto County), yielding an average porosity of 8 percent, are considered more reasonable than those values that average 12 percent core porosity. We suspect a difference in the calculation method used for the #1 Aristech well, thus resulting in a very optimistic average porosity. The methods used for ALL porosity calculations from cores and geophysical well logs should be standardized if possible with actual stratigraphic test well data from New Haven.

Net footage of RHOB using three arbitrary cutoff density points was calculated to isolate qualitative areas of lower bulk density, which hypothetically represent areas of higher porosity. The arbitrary cutoff values used were RHOB ≤ 2.68 g/cc (≥ 0 % porosity), RHOB ≤ 2.55 g/cc (≥ 6 % porosity), and RHOB ≤ 2.40 g/cc (≥ 15 % porosity) (figs. 35 and 36). Maps for the arbitrary RHOB cutoffs were computer contoured at 5-foot intervals (figs. 37-43). For the Maryville “lower unit”, a line representing the Rome Trough was added because three of the wells yielding contoured density data are located within the Rome Trough. Also, a dashed line depicting the eastern pinchout of the Cambrian Mount Simon is shown on the Maryville maps as this unit does not occur in the New Haven area. The maps were not interpreted beyond computer-generated contouring and show possible injection zone thickness at arbitrary density cutoffs. Table 3A shows total thickness and average RHOB of the Maryville Formation and “lower unit” and RHOB ≤ 2.68 g/cc (≥ 0 % porosity), RHOB ≤ 2.55 g/cc (≥ 6 % porosity), and RHOB ≤ 2.40 g/cc (≥ 15 % porosity) for wells analyzed within the AOR. The #1 Kingery well (APINO 4701120537, Cabell County) was not used during the analyses because the data was suspect. Appendix C and E lists RHOB, porosity, and permeability calculations from core within the AOR. These data were used to qualitatively calibrate the RHOB data from their respective wells.

Net footage of Maryville “lower unit” with RHOB ≤ 2.68 g/cc (≥ 0 % porosity) ranges from 54 to 226 feet of quartz sandstone (Figure 37). Net footage of RHOB ≤ 2.55 g/cc (≥ 6 % porosity) for the Maryville “lower unit” ranges from 1 to 182 feet (Figure 38). Net footage of RHOB ≤ 2.40 g/cc (≥ 15 % porosity) for the Maryville “lower unit” ranges from 0 to 71 feet (Figure 39). The “raw uninterpreted” contoured RHOB maps suggest that net quartz sandstone footage of Maryville “lower unit” at New Haven is: 210 feet of RHOB ≤ 2.68 g/cc (≥ 0 % porosity); 40 feet of RHOB ≤ 2.55 g/cc (≥ 6 % porosity); and 10 feet of RHOB ≤ 2.40 g/cc (≥ 15 % porosity). Overall, areas west of the AOR have the thickest development of Maryville “lower unit” sandstone porosity.

As seen on the Maryville “lower unit” RHOB maps, the thickest areas with RHOB ≤ 2.68 g/cc (≥ 0 % porosity) are developed within the Rome Trough and the NW portion of the AOR. The increased net thickness of RHOB ≤ 2.68 g/cc (≥ 0 % porosity) in the Rome Trough is attributed to rapid accumulation of sediments during structural movement. Net thickness

decrease in the Rome Trough with $\text{RHOB} \leq 2.55 \text{ g/cc}$ ($\geq 6 \%$ porosity) and 2.40 g/cc ($\geq 15 \%$ porosity) most likely is due to increased compaction and cementation during diagenesis and deep burial. The thick net RHOB areas in the western AOR are attributed to higher energy shelf environment, in closer proximity to the source of the quartz sandstone, which may have less compaction and cementation during burial and diagenesis. In general, areas west and southwest of the AOR have the best-developed net quartz sandstone. Other areas within the AOR have very low to no net feet of the lower RHOB cutoff developed. Comparing the core analyses with the net RHOB $\leq 2.55 \text{ g/cc}$ ($\geq 6 \%$ porosity) mapping values suggests that net sandstone footage of Maryville “lower unit” in the New Haven site area is an estimated 35 to 40 feet thick.

Based on core data and geophysical well log analyses, the regional stratigraphy trending SW-NE from Scioto County, Ohio, to Wood County, West Virginia, supports a model of an extensive carbonate marine shelf environment decreasing in quartz sandstone eastward for the Maryville Formation (including the “lower unit”). Core and log analyses also indicate the quartz sandstone of the “lower unit” occurs in thin discontinuous beds, which are probably not connected as a reservoir (assuming vertical fractures are absent). However, contoured data $\text{RHOB} \leq 2.68 \text{ g/cc}$ ($\geq 0 \%$ porosity) suggest that the New Haven site may have between 100 and 130 net feet of quartz sandstone, based on an along-strike depositional model for the stable craton shelf between Noble (OH) and Wood Counties (WV); and Lawrence (OH) County. The greatest unknown at the New Haven site for the Maryville “lower unit” is the thickness and extent of effective reservoir porosity and permeability.

Cambrian-Ordovician Rose Run sandstone

Based on cores within the AOR, the Rose Run sandstone consists of a sequence of quartz arenites and subarkoses interbedded with thin beds of nonporous dolomite (Appendices A and B, DGS cores 2898, 768, and 3049). The Rose Run sandstone underwent a long and complicated burial and diagenetic history, which influenced the present-day porosity and permeability. The most abundant cement in the Rose Run sandstones is dolomite, which formed during two or more periods of dolomitization and plays an important role in permeability and porosity variations. Other cements include quartz overgrowths, feldspar overgrowths, and clay minerals (Riley and others, 1993). Dominant pore textures in the Rose Run include: 1) intergranular pores, 2) oversized pores, 3) moldic pores, 4) intraconstituent pores, and 5) fractures. It is important to note that the Rose Run sandstone is not a blanket sandstone, but is heterogeneous with porosity and permeability variability within the individual sandstone beds interbedded with dolomite (Riley and others, 1993).

Core data also indicate that the Rose Run sandstone reservoir quality, similar to the Maryville, decreases to the east and southeast. The most detailed Rose Run core data within the AOR is from the #1 Trepanier well (APINO 3407920102, Jackson County), which is located approximately 40 miles west and updip of the proposed New Haven site (Figure 1). Core porosities in this well range from 1.5 to 14.9 percent and average 9 percent. Maximum permeabilities range from 0.1 to 198 md and average 47 md. Rose Run grain density ranges from 2.62 to 2.77 gm/cc with an average of 2.66 gm/cc. Rose Run core samples were analyzed in the #1 Trepanier well and the #4 Aristech well (APINO 3414560141, Scioto County) (Appendix C). Permeabilities for these samples were 6 and 86 md (average of 46 md). Porosities range from 9.1

and 12.7 percent with an average of 10.9 percent. Grain density was 2.64 and 2.65 with an average of 2.65. The #1 Power Oil Company well (APINO 4710700351, Wood County), located approximately 40 miles northeast and downdip from the proposed site, contained the lowest core porosity values. Core porosities in this well for the Rose Run sandstone range from 0.45 to 0.50 percent and averaged 0.47 percent. Grain density ranged from 2.63 to 2.79 gm/cc and averages 2.67 gm/cc.

Rose Run net sandstone maps (figs. 40, 41, 42) also were constructed using density cutoffs of ≤ 2.40 g/cc (≥ 15 % porosity), ≤ 2.55 g/cc (≥ 6 % porosity), and ≤ 2.68 g/cc (≥ 15 % porosity). These values are summarized in Table 3b along with the gross thickness and average density within the Rose Run sandstone interval. This table only includes those wells with bulk-density curves using a standard 2.0- to 3.0-gm/cc calibration. Average bulk-density measurements in the AOR range from 2.55 to 2.73 gm/cc (average 2.65 gm/cc) and increased generally to the east and southeast indicating more carbonate and less quartz sandstone content in the Rose Run interval in that direction (Figure 43). The #1 Jividen (APINO 4705300297, Mason County) is the nearest downdip well to the proposed New Haven site, and had the second highest average bulk density (2.71 gm/cc) in the AOR, which indicates a high percentage of carbonates in the Rose Run interval. Two Rose Run wells intervals in the western portion of the AOR had average bulk density values of 2.55 and 2.56 gm/cc, indicating a much higher percentage of sandstone.

Calculated net footage Rose Run sandstone values for the bulk-density cutoff of ≤ 2.68 g/cc (≥ 15 % porosity) range from 28 to 66 feet (average 43 feet) (Table 3, Figure 40). The net footage quartz sandstone map shows the greatest net sandstone footage to be in northern Lawrence County, Ohio. The proposed New Haven site has an estimated net Rose Run sandstone footage of approximately 42 feet (at the 2.68 gm/cc cutoff). The nearest well with a density log is the #1 Jividen (APINO 4705300297, Mason County), which is approximately 25 miles to the south. Higher values of net Rose Run sandstone footage may be present in the Rome Trough to the east of the proposed site, where thicker accumulations of sand may have been deposited.

The amount of net Rose Run sandstone footage in the AOR decreases with a density cutoff of ≤ 2.55 gm/cc (≥ 6 % porosity). Calculated values range from about 2 to 42 feet (average 21 feet) (Table 3, Figure 41). The highest net Rose Run sandstone footage value in the AOR at this cutoff is about 42 feet in Hocking County, Ohio. The New Haven site has a mapped net sandstone value at ≤ 2.55 g/cc (≥ 6 % porosity) of approximately 18 feet.

Using a bulk density cutoff of ≤ 2.40 g/cc (≥ 15 %), the net Rose Run sandstone values look much worse for injection potential. Calculated values range from 0 to 22 feet (average 5 feet) (Table 3, Figure 42). The highest value is in Jackson County, Ohio. The New Haven site has approximately 16 feet of net quartz sandstone footage at this cutoff. As with the previous net Rose Run sandstone footage maps, the better sandstone development is to the north and west closer to the source. There may be thicker net Rose Run sandstone deposits accumulated in the Rome Trough to the east of the proposed site.

Speculative deep-injection zones

Very little is known about the Precambrian basement complex and lowermost Cambrian strata in the AOR. Although very speculative, the possibility of porous and permeable pre-Maryville sediments within the AOR including the Rome Trough, which would enhance the Maryville “lower unit” injection-zone should be discussed. The presence of deep, layered seismic reflectors within the AOR and proximity to the Rome Trough increase the possibility that such sediments may be present. Published and unpublished seismic reflection data in Ohio indicates local areas of thicker basal Paleozoic/Precambrian sediments, which may represent the following depositional settings dominated by clastic sediments: Rome Formation of the Rome Trough, basal Paleozoic incised river systems, Middle Cambrian rift basins, Precambrian Neoproterozoic rift basins, Mesoproterozoic rift basins, and Grenville foreland basins. The acquisition of seismic reflection data at the New Haven site would assist in recognizing the presence of these speculative zones.

Shallow Potential Injection Intervals

The Ordovician St. Peter sandstone, Silurian “Clinton”/Tuscarora sandstone, Newburg sandstone, and the Devonian Oriskany sandstone were also examined to evaluate their potential as injection zones. The nearest well to the New Haven site with St. Peter sandstone is the #1 Arrington well (APINO 4705300069, Mason County). At this well location, the St. Peter interval is at a depth of 6,646 to 6,682 feet, and consists of a white, very fine to medium-grained, glauconitic sandstone (Overbey, 1961). In the AOR, the St. Peter occurs locally on the Knox unconformity, and may not be present at the New Haven site. The nearest producing field is the Stephens field in Elliot County, Kentucky, where the average log porosity is 7 percent.

The “Clinton”/Tuscarora sandstone occurs as a sequence of interbedded sandstones, siltstones, and shales. Lithologically, the individual reservoir beds consist of a white to gray to red, medium- to very fine-grained, monocrystalline, quartzose sandstone (McCormac and others, 1996). Based on correlation to the #1 Baker well (APINO 3410523520, Meigs County), the “Clinton”/Tuscarora sandstone occurs at a depth of approximately 5,600 feet (Figure 27). This well is approximately 13 miles to the northeast of the New Haven site. Gross thickness for the interval is approximately 150 feet and net sandstone thickness is 38 feet. Log porosities range from 4 to 6 percent and average 5 percent in this well. There is no nearby core data available, but as mentioned earlier, the porosity and permeability of the “Clinton”/Tuscarora sandstone decreases to the east and southeast.

The Newburg sandstone consists of a thin, white to gray, very fine- to fine-grained, well-sorted sandstone (Patchen, 1996). Nearest wells which encountered the Newburg sandstone are in eastern Meigs County, approximately 7 miles to the east of the New Haven site. Here the Newburg sandstone occurs at a depth ranging from 4,800 to 5,100 feet. Net thickness is approximately 3 feet and the average log porosity is 11 percent (Patchen, 1996). It is not certain if the Newburg sandstone will be present at the New Haven site.

The Oriskany Sandstone is an unconformity sandstone overlying the Helderberg Formation and underlying the Onondaga Limestone. Lithologically, this unit consists of well-sorted, white to light gray, and gray-brown, quartzose sandstone (Opritzka, 1996). The updip pinchout of the Oriskany sandstone trends north-south through eastern Meigs County and central Mason County (Opritzka, 1996). Presence of this unit at the New Haven site is questionable

because of its proximity to the updip pinchout. A cross section across northern Meigs County, approximately 15 miles to the northeast (Figure 27), illustrates the local stratigraphy of this unit. Here, the Oriskany occurs at depths ranging from 4,100 to 4,250 feet. Average net thickness is 15 feet and the average log porosity is 6 percent.

CONFINING UNITS FOR POTENTIAL INJECTION INTERVALS

Cambrian Maryville “lower unit”

At the New Haven site, the Maryville “lower unit” is unconformably confined below by the Precambrian basement complex and above by the remaining Conasauga Group (Maryville Formation, Nolichucky Shale, Maynardville Limestone) and Copper Ridge Dolomite. While little is known about the Precambrian basement in this area, a general assumption is that it consists of Grenville igneous and metamorphic rocks, which will provide effective confinement in the absence of open fractures, faults and porous, permeable, fault gouge.

Approximately 1,100 feet of dolomite and shale act as the confining unit between the Maryville “lower unit” and Rose Run sandstone. Porosity in the Maryville Formation confining interval is generally less than 1 per cent; permeability is less than 1 md based on the #1 Aristech (APINO 3414520252, Scioto County) core analyses. Core analyses for the Copper Ridge shows similar low porosity and permeability values. (Appendix C, E)

Cambrian-Ordovician Rose Run sandstone

At the proposed site, estimated thickness values for units confining and overlying the Rose Run sandstone are based on correlation to the nearest logged wells to the site and along strike for the Rose Run structure (Figure 34; #1 Arrington and #1 Jividen (APINOs 4705300069 and 47053000297, Mason County)). Actual thickness values encountered at the New Haven site may vary from those predicted depending on presence of faulting in the area and its effect on deposition. The immediate confining zone for the Rose Run sandstone consists of the Ordovician Wells Creek Formation, the Black River Group, and the Lexington Limestone (Figure 9). Estimated combined total thickness for this interval at the proposed site ranges from 840 to 1,070 feet.

In the vicinity of the proposed site, estimated thickness of the Wells Creek Formation is 130 feet. Thickness of the Wells Creek Formation can vary greatly depending on the Knox paleotopography, and may be locally absent because of nondeposition over paleotopographic highs. Estimated thickness of the Black River Group and Lexington Limestone ranges from 640 to 860 feet and 70 to 80 feet respectively.

The Wells Creek Formation unconformably overlies the Knox Dolomite. It is composed of very fine-grained dolomite interbedded with thin gray to green to black shale lenses. A sandstone unit informally called the St. Peter sandstone occurs locally on the Knox unconformity surface. Thickness of the Wells Creek ranges from 22 to 654 feet in the AOR. The Black River Group conformably overlies the Wells Creek Formation and consists of light brown to gray, slightly argillaceous, finely crystalline limestone.

Between the top of the confining zone (Lexington Limestone) and the base of the lowermost USDW (Pennsylvanian), the overlying rocks at New Haven have an estimated total thickness ranging from 3,955 to 4,180 feet. As discussed in the regional stratigraphy section, this section of rock strata includes the Upper Ordovician shale, the Silurian-Devonian carbonates, and the Upper and Middle Devonian shale (Figure 9). At the proposed site, the estimated thickness for these overlying units ranges from 1,335 to 1,400 feet (Upper Ordovician shale section), 1,140 to 1,150 feet (Silurian-Devonian carbonate section), and 1,480 to 1,630 feet (Upper and Middle Devonian shale section). Total thickness for this interval ranges from 520 to 2,109 feet in the AOR.

SUMMARY

An evaluation of 128 wells deeper than the Ordovician Trenton Limestone within or adjacent to a 7,300 mi² area centered on New Haven, West Virginia indicates two potential CO₂ injections zones: Cambrian Maryville “lower unit” and Rose Run sandstone. The possibility also exists for previously unknown porous and permeable zones beneath the Maryville within the AOR. Although highly speculative, the potential for these older zones is based on seismic reflection data from Ohio and West Virginia.

Based on cores within the AOR, both the Maryville Formation and the Rose Run sandstone consists of a sequence of quartz arenites and subarkoses interbedded with thin beds of nonporous dolomite with very similar depositional environments, ranging from shallow marine to subtidal on an extensive shallow cratonic shelf. Within the AOR, the quartz sandstone facies for both units (the Maryville Formation “lower unit” and the Rose Run sandstone) occurs in thin discontinuous beds. Each of these units is a separate reservoir, separated by hundreds of feet of carbonates and shales. Within each unit, the individual beds are probably not connected as a reservoir (assuming fractures are absent). The source of quartz arenites appears to be generally from the north and west as dolomite predominates eastward and southeastward. Both of these units underwent a long and complicated burial and diagenetic history, which influenced the present day porosity and permeability.

The greatest unknown at the New Haven site for the potential injection zones is the thickness and extent of effective reservoir porosity and permeability. However, at the New Haven site, the two zones have a combined estimated thickness between 50 and 100 feet with average porosity greater than 8 per cent. Depths to the Maryville “lower unit” and Rose Run sandstone is estimated at –8,000 feet MSL and –6,950 feet MSL respectively at the site. Depth to Precambrian basement is estimated at –8,600 feet MSL. Other speculative injection zones may exist in the Cambrian and Precambrian units beneath the Maryville “lower unit” based on seismic reflection data in Ohio and West Virginia.

Confining units are regionally very impermeable with low porosity and should provide adequate confinement for the injection zones in the absence of open fractures, open faults, and fault gouge. The Maryville “lower unit” is confined by about 1,100 feet of dolomite and shale at New Haven. The Rose Run sandstone is confined by about 1,000 feet of limestone and shale at the site.

It is recommended that strike and dip seismic reflection data be acquired crossing the Ohio River at New Haven. The seismic evaluation would tie to existing seismic reflection data and the geologic evaluation from this report to determine the best geological location(s) for drilling a stratigraphic test well. A stratigraphic test well will be required to realistically characterize the stratigraphy, thickness, porosity, and permeability of the prospective injection intervals and the geology, composition, and character of the Precambrian complex. The methods used for ALL porosity calculations from cores and geophysical well logs should be standardized if possible with actual stratigraphic test well data from New Haven. This well data, accompanied by seismic reflection data, will facilitate modeling of the subsurface geology at the New Haven site, and thus assist in the determination of realistic injectivity and storativity values necessary to evaluate the suitability of the site to sustain the volumes of CO₂ injection for the proposed project.

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Figure 1. Map of the New Haven AOR showing location of cores, cross sections, and oil and gas wells used in the study. Formation at total depth for oil and gas wells is indicated by color. Also shown are the mapped area and the location of the New Haven site.

JANSSENS (1973) NOMENCLATURE		NOMENCLATURE USED FOR THIS REPORT		System	
Central Ohio	Eastern Ohio	Southeastern OH, northwestern WV shelf area	Northwestern WV Rome Trough		
Wells Creek Fm	Wells Creek Fm	Wells Creek Fm	Wells Creek Fm	Mid. Lower	Ordovician
St. Peter Ss	St. Peter Ss	St. Peter Ss	St. Peter Ss
Beekmantown dol	Beekmantown dol	Beekmantown Dol	Beekmantown Dol		
Rose Run ss	Rose Run ss	Rose Run Ss	Rose Run Ss	Upper	Cambrian
Copper Ridge dol	Copper Ridge dol	upper unit B-zone lower unit Copper Ridge Dol	upper unit B-zone lower unit Copper Ridge Dol		
Kerbel Fm		Maynardville Ls	Maynardville Ls		
Conasauga Fm	Conasauga Fm	Nolichucky Sh	Nolichucky Sh		
Rome Fm	Rome Fm	Maryville Ls	Maryville Ls
Maryville Ls lower unit	Maryville Ls lower unit		
Mt. Simon Ss	Mt. Simon Ss	Mt. Simon Ss
Grenville Province rocks			Rogersville Sh		
			Rutledge Ls		
			Pumpkin Valley Sh		
			Rome Fm		
			Shady Dol		
			basal sandstone	Lower	Pre-cambrian
		Grenville Province rocks			

FIGURE 2. Stratigraphic correlation chart for the AOR showing the Cambrian and lower part of the Ordovician (modified from Janssens, 1973 and Harris and Baranoski, 1996).

FIGURE 3. Map showing structure on unconformity Precambrian surface in Ohio and surrounding region and location of the New Haven site (modified from Baranoski, 2002). Contour interval = 500 feet. See figure 5 for names of major features discussed in the text.

FIGURE 4. Map showing Precambrian Provinces and location of the New Haven site (modified from Baranoski, 2002).

FIGURE 5. Map showing major Cambrian structures and location of the New Haven site (modified from Baranoski, 2002).

FIGURE 6. Map showing regional extent of the Rome Trough, major Cambrian structures and location of the New Haven site (modified from Harris and Baranoski, 1996).

FIGURE 7. Stratigraphic cross section from Sandusky County, Ohio to Pendleton County, West Virginia showing Cambrian and Ordovician sequences (modified from Ryder and other, 1998). See Figure 6 for location of the cross section.

FIGURE 8. Map showing major post-Cambrian structures and location of the New Haven site (modified from Baranoski, 2002).

FIGURE 9. Stratigraphic column for the New Haven site and potential injection zones (modified from Larsen, 1998).

KNOX UNCONFORMITY

ROSE RUN SANDSTONE

MAYNARDVILLE L.S.

NOLICHUCKY SH.

MARYVILLE L.S.

MARYVILLE L.S. 'LOWER UNIT'

ROME FM.

SHADY DOLOMITE

BASAL SANDSTONE

PRECAMBRIAN UNCONFORMITY

FIGURE 14.--Map showing isopach of the Maryville Limestone within AOR and location of the New Haven site. Contour interval = 100 feet.

FIGURE 15. Maryville Limestone core interval 5205.5 to 5214.5 well APINO 3414560141. See Appendix A core interval description.

5 0 5 10 15 mi

SCALE IS 1:800,000

Eastern pinch-out of the Mount Simon Sandstone

Rome Trough (RT) fault system

Well location with isopach number in feet

New Haven site

FIGURE 16.--Map showing isopach of the Maryville Limestone "lower unit" within AOR and location of the New Haven site. Contour interval = 20 feet.

FIGURE 17. Lower unit of the Maryville Limestone core interval 5558.8 to 5572.3 well APINO 3414520212. See Appendix A core interval description.

FIGURE 18.--Map showing isopach of the Rose Run within AOR and location of the New Haven site. Contour interval = 10 feet.

FIGURE 23.--Map showing the Cambrian-Ordovician Knox Dolomite and St. Peter sandstone oil and gas fields and location of the New Haven site.

FIGURE 24.--Map showing the Middle Ordovician Lexington/Trenton Limestone, Black River Group carbonates, and Utica shale oil and gas fields in Ohio, and location of the New Haven site. Also shown are wells permitted to the Trenton in West Virginia.

FIGURE 25.--Map showing the Lower Silurian "Clinton-Medina"/Tuscarora sandstone oil and gas fields and location of the New Haven site.

FIGURE 26.--Map showing the Lower Devonian Oriskany Sandstone and Upper Silurian Newburg Sandstone and Lockport Dolomite oil and gas fields and location of the New Haven site.

FIGURE 28.--Map showing the Upper Devonian Black Shales oil and gas fields and location of the New Haven site.

FIGURE 29.--Map showing the Upper Mississippian and Lower Devonian Berea Sandstone oil and gas fields and location of the New Haven site.

FIGURE 30.--Map showing the Upper and Lower Mississippian limestones and sandstones oil and gas fields and location of the New Haven site.

FIGURE 31.--Map showing the Lower and Middle Pennsylvanian Allegheny and Pottsville Group oil and gas fields and location of the New Haven site.

FIGURE 32.--Structure map on the top of the Precambrian unconformity surface in the AOR and location of the New Haven site. Contour interval = 500 feet.

SCALE IS 1:800,000

- Rose Run subcrops northwest of this line
- Well location with subsea number in feet
- New Haven with estimated subsea number in feet
- SITE

FIGURE 34.--Structure map on the top of the Rose Run Sandstone in the AOR and location of the New Haven site. Contour interval = 100 feet.

Well	NUCORP ENERGY TREPANIER, F & C 1
Well ID	3407920102
Field	SE OHIO
County	JACKSON
State/Province	OH
Country	USA

FIGURE 36. Type density log showing arbitrary net RHOB from well APINO 3407920102 Nucorp Trepanier well. Estimated porosity equivalent assuming 100% quartz arenite sandstone.

FIGURE 37.--Maryville "lower unit" net RHOB at ≤ 2.68 g/cc (equivalent to $\geq 0\%$ porosity assuming 100% quartz arenite) cutoff and location of the New Haven site. Contour interval = 5 feet.

FIGURE 38.-- Maryville "lower unit" net RHOB at ≤ 2.55 g/cc (equivalent to $\geq 6\%$ porosity assuming 100% quartz arenite) cutoff and location of the New Haven site. Contour interval = 5 feet.

FIGURE 39.-- Maryville "lower unit" net RHOB at ≤ 2.40 g/cc (equivalent to $\geq 15\%$ porosity assuming 100% quartz arenite) cutoff and location of the New Haven site. Contour interval = 2 feet.

FIGURE 40.--Rose Run net RHOB at ≤ 2.68 g/cc (equivalent to $\geq 0\%$ porosity assuming 100% quartz arenite) cutoff and location of the New Haven site. Contour interval = 5 feet.

SCALE IS 1:800,000

- Rose Run subcrops northwest of this line
- Well location with net thickness number in feet
- New Haven
- SITE

FIGURE 41.--Rose Run net RHOB at ≤ 2.55 g/cc (equivalent to $\geq 6\%$ porosity assuming 100% quartz arenite) cutoff and location of the New Haven site. Contour interval = 5 feet.

SCALE IS 1:800,000

- Rose Run subcrops northwest of this line
- Well location with net thickness number in feet
- 22
- SITE
- New Haven

FIGURE 42.--Rose Run net RHOB at ≤ 2.40 g/cc (equivalent to $\geq 15\%$ porosity assuming 100% quartz arenite) cutoff and location of the New Haven site. Contour interval = 5 feet.

SCALE IS 1:800,000

- Rose Run subcrops northwest of this line
- Well location with number in g/cc
- New Haven
- SITE

FIGURE 43.--Map showing average bulk density from geophysical logs for Rose Run Haven site.

FieldName	Type	Size	Description
APINO	Text	14	14 digit American Petroleum Institute well number
SHRT_APINO	Text	10	10 digit American Petroleum Institute well number
PERMIT	Text	8	well permit
ST_PRV	Text	12	
MAPX83	Long Integer	4	Ohio state plane X coordinate North American Datum 1983 feet
MAPY83	Single	4	Ohio state plane Y coordinate North American Datum 1983 feet
LAT	Double	8	Latitude
LONG	Double	8	Longitude
CNTY	Text	20	County
TWP	Text	20	Township
LOCATION	Text	255	Footage location
QUAD	Text	30	USGS 7.5 minute quadrangle
COMPNAME	Text	54	company name
LEASE	Text	54	lease/farm name
WELL_NO	Text	8	well number
END_DATE	Date/Time	8	drilling end date
STATUS	Text	8	well status
ABANDONED	Date/Time	8	well abandoned
LOGCON	Text	25	logging contractor
LOGS	Text	255	geophysical logs
DIG_LOGS	Text	2	digital geophysical logs
SAMPLE_NO	Text	8	well cuttings sample number
SAMP_RNG	Text	54	well cuttings sample range in feet
CORE_NO	Text	8	well core number
CORE_RNG	Text	155	well core range in feet
SAMPDESC	Text	2	sample description Y/N
SAMPINTR	Text	255	sample description interval
ELEV	Long Integer	5	well reference elevation
SNBR	Long Integer	5	top Sunbury Sh.
BERE	Long Integer	5	top Berea Ss.
OHIO	Long Integer	5	top Ohio Sh.
ONDG	Long Integer	5	top Onondaga Ls.
ORSK	Long Integer	5	top Oriskany Ss.
BASE_ORSK	Long Integer	5	base Oriskany Ss.
SLIN	Long Integer	5	top Salina Gp.

NWBGSS	Long Integer	5	top Newberg Ss.
BASE_NWBGSS	Long Integer	5	base Newberg Ss.
LCKP	Long Integer	5	top Lockport Dol.
BASE_PCKS	Long Integer	5	base Packer shell
BRSF	Long Integer	5	top Brassfield
TUSC	Long Integer	5	top Tuscarora
OVUV	Long Integer	5	top Ordovician undifferentiated
TRNN	Long Integer	5	top Trenton Ls.
BKRV	Long Integer	5	top Black River Gp.
GLRV	Long Integer	5	top Gull River Ls.
WLCK	Long Integer	5	top Wells Creek Fm.
WLCK2	Long Integer	5	top Wells Creek Fm. lower unit
SNPR	Long Integer	5	top St. Peter Ss.
KNOX	Long Integer	5	top Knox unconformity
BKMN	Long Integer	5	top Beekmantown Dol.
RSRN	Long Integer	5	top Rose Run Sandstone
NET_RSRN	Long Integer	5	net thickness Rose Run Sandstone
CPRG	Long Integer	5	top Copper Ridge Dol.
KNOXB	Long Integer	5	top Knox B-zone
BASE_KNOXB	Long Integer	5	base Knox B-zone
BASE_KNOX	Long Integer	5	base Knox Dol.
CNSG_GP	Long Integer	5	top Conasauga Gp.
MDVL	Long Integer	5	top Maynardville Ls.
NCKK	Long Integer	5	top Nolichucky Sh.
MRVL	Long Integer	5	top Maryville Ls.
ROME	Long Integer	5	top Rome Fm.
MNSM	Long Integer	5	top Mt. Simon Ss.
NET_MRVL	Long Integer	5	net thickness Maryville Ls.
PCMB	Long Integer	5	top Precambrian unconformity
TD	Long Integer	5	well total depth
FMTD	Text	8	well formation at total depth
BATTELLE_PROJ	Yes/No	1	
CTYNUM	Long Integer	4	county identification number
PERF_INT	Text	64	well perforated interval
CSGREC	Text	255	well casing record
ROCKPRES	Double	8	well rock pressure

TABLE 2 REPORTED SUB-KNOX OIL & GAS SHOWS AND PRODUCTION IN OHIO, KENTUCKY, AND WEST VIRGINIA FOR AOR													
API No.	State	County	Company	Lease	Total Depth (feet)	Formation at TD	MCF	Formation	GAS Depth / Interval	BO	Formation	OIL Depth / Interval	Comment
3407920078	OH	JACKSON	RALPH C. HALBERT	SLAVENS	5,681	PCMB		Conasauga Gp.	4960; 5120-5150				gas show; gas cut saltwater
3412121278	OH	NOBLE	AMOCO	R ULLMAN	11,442	PCMB		Conasauga Gp.	10611				gas cut water
3412920003	OH	PICKAWAY	MCMAHON-BULLINGTON DRLG.	J DUNLAP	3,525	ROME					Conasauga Gp.		small oil show
3412920006	OH	PICKAWAY	MIDWEST OIL & GAS CO.	C MILLER	4,179	PCMB					Conasauga Gp.	3949-3958	oil show
3412920129	OH	PICKAWAY	REDMAN OIL CO.	THOMPSON, VERA	3,690	MNSM	25	Conasauga Gp.	3600-3606; 3690-3698				gas show
3414560141	OH	SCIOTO	ARISTECH CHEMICAL CORP	ARISTECH CHEMICAL CORP	5,650	MRVL		Conasauga Gp.	5188-5198				slight petroleum odor; fluor. in core; gas blow during drilling
	6 wells												
1601918327	KY	BOYD	INLAND GAS CO, INC	WHITE, L O ET AL	7,676	ROME	90	Conasauga Gp.	7445; 7516-7574	15	Conasauga Gp.	7516-7574	well completion
160435730	KY	CARTER	INLAND GAS CO, INC	MCDavid, EVERETT & MYRTLE	9,980	BASL		Tomstown; basal sand	7672; 8898				gas show
1604398E9	KY	CARTER	UNITED FUEL GAS CO	STAMPER, LLOYD L ET AL	5,085	PCMB		ROME, basal ss					gas show
	3 wells												
4701120537	WV	CABELL	CYCLOPS CORP	E KINGERY	8,552	PCMB		Pre-Knox					gas show
4703521366	WV	JACKSON	EXXON USA	McCOY	17,675	PCMB	9,100	Conasauga Gp.	14358				gas completion
4704321469	WV	LINCOLN	EXXON USA	D E MCCORMICK	19,124	PCMB		Conasauga Gp.	11608				gas show
4705920805	WV	MINGO	COLUMBIA GAS TRNS	COLUMBIA GAS	19,537	PCMB		Conasauga Gp.					gas show
4710700351	WV	WOOD	HOPE NATURAL GAS	POWER OIL	13,331	PCMB		Conasauga Gp.					gas show
	5 wells												
PRODUCTION ABBREVIATIONS													
MCF	thousands of cubic feet of gas per day												
BO	barrels of oil per day												
					3415124751	White text on purple background signifies a completion.							
GEOLOGIC UNIT ABBREVIATIONS													
MRVL	Maryville Limestone				Compiled from information available from the Ohio Division of Geological Survey, the Kentucky Geological Survey, and Harris and Baranoski (1996).								
MNSM	Mount Simon Sandstone												
ROME	Rome Formation												
BASL	basal sandstone												
PCMB	Precambrian undifferentiated												

	TABLE 3A MARYVILLE FM. THICKNESS AND RHOB CALCULATIONS						
WELL ID	MRVL TOTAL	RHOB ave.	LOWER MRVL	RHOB ave.	RHOB <= 2.68 NET FEET >= 0% porosity	RHOB <= 2.55 NET FEET >= 6% porosity	RHOB <= 2.40 NET FEET >= 15% porosity
	thickness	MRLV	thickness	LOWER MRVL	LOWER MRVL thickness	LOWER MRVL thickness	LOWER MRVL thickness
1608921256	363	2.71	100	2.57	66	54	14
1613521132	373	2.66	117	2.54	77	59	41
3400120005	398	2.56	135	2.54	102	64	25
3407920076	448	2.71	150	2.58	109	59	13
3407920102	463	2.75	114	2.58	94	44	8
3408720174	517	2.73	226	2.67	136	14	2
3412121278	743	2.80	263	2.71	105	13	0
3412726595	590	2.73	265	2.65	145	47	0
3412920020	524	2.58	236	2.48	208	182	71
3412920024	463	2.64	175	2.50	137	111	71
3414520212	373	2.63	102	2.63	54	35	2
3414520257	420	2.62	141	2.58	98	58	12
4703501366	1535	2.65	303	2.65	193	1	0
4705300297	763	2.74	327	2.66	197	34	0
4710700756	1048	2.71	421	2.67	226	37	8
AVERAGE	601	2.68	205	2.60	130	54	18
	TABLE 3B ROSE RUN THICKNESS AND RHOB CALCULATIONS						
APINO	RSRN TOTAL	RHOB ave.			RHOB <= 2.68 NET FEET >= 0% porosity	RHOB <= 2.55 NET FEET >= 6% porosity	RHOB <= 2.40 NET FEET >= 15% porosity
	thickness	RSRN			RSRN thickness	RSRN thickness	RSRN thickness
3407323283	140	2.70			47	30	0
3407323421	74	2.55			55	42	12
3407920076	88	2.62			49	27	8
3407920078	80	2.56			36	27	22
3407920102	77	2.63			39	29	5
3408720174	98	2.57			66	38	21
3408720219	82	2.65			39	18	1
3412121278	142	2.73			42	2	0
3413120036	98	2.64			54	23	0
3414520212	112	2.70			34	16	1
3414560141	88	2.67			41	17	0
4705300297	104	2.71			28	9	0
AVERAGE	99	2.64			44	23	6
MRVL= MARYVILLE FM							
RSRN = ROSE RUN SS							
RHOB = LOG BULK DENSITY IN GRAMS PER CUBIC CENTIMETER (ESTIMATED POROSITY EQUIVALENCE ASSUMING 100% QUARTZ ARENITE SANDSTONE)							