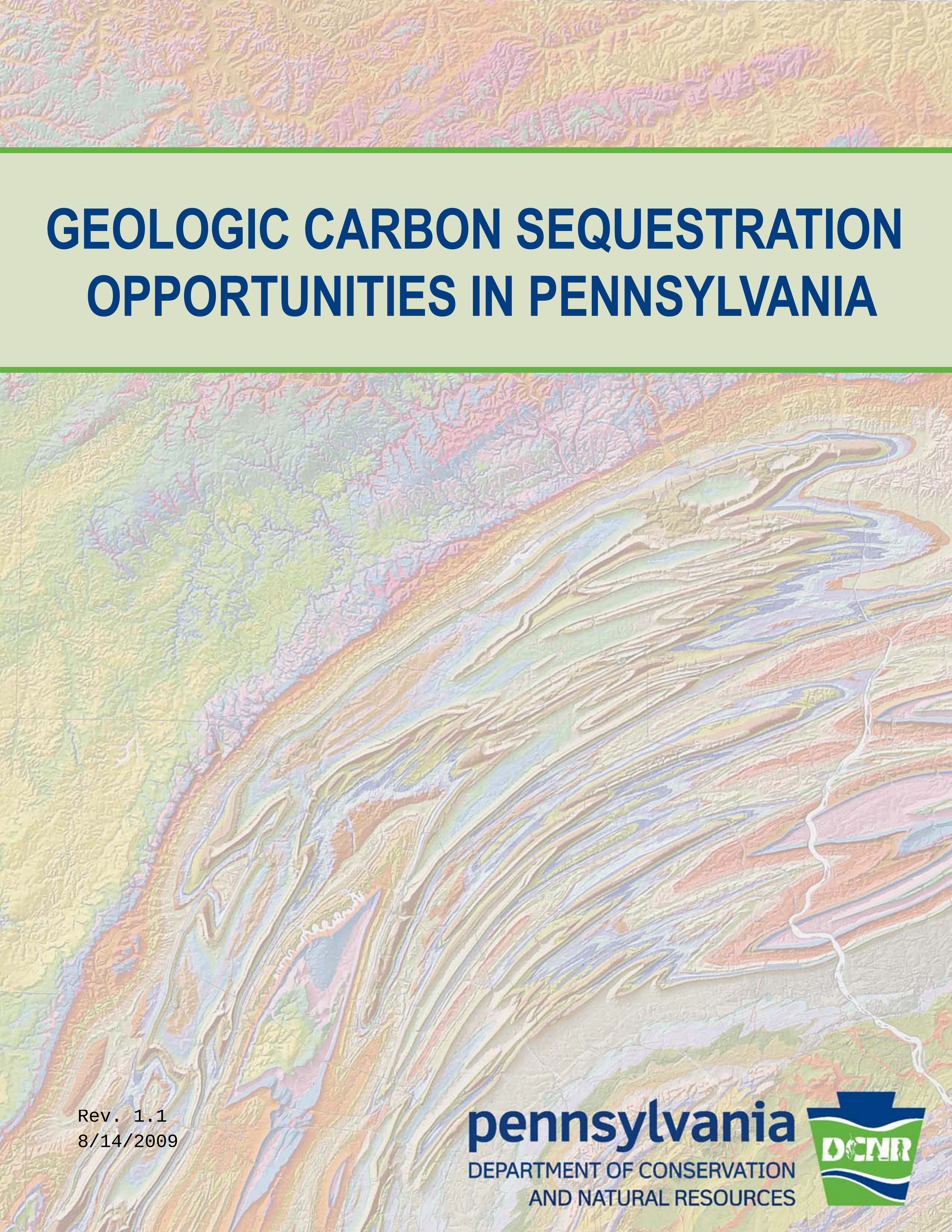

GEOLOGIC CARBON SEQUESTRATION OPPORTUNITIES IN PENNSYLVANIA

Rev. 1.1
8/14/2009

pennsylvania
DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

GEOLOGIC CARBON SEQUESTRATION OPPORTUNITIES IN PENNSYLVANIA

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Acronyms Used in This Report

CAT – Computerized Axial Tomography
CBM – coalbed methane
CCS – carbon capture and sequestration
CMAG – Carbon Management Advisory Group
CSN – Carbon Sequestration Network
DCNR – Pennsylvania Department of Conservation and Natural Resources
DEP – Pennsylvania Department of Environmental Protection
DESDynI – Deformation, Ecosystem Structure and Dynamics of Ice
Dho – fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone play
Doc – Lower Devonian Oriskany Sandstone combination structural and stratigraphic traps play
Dop – Lower Devonian Oriskany Sandstone updip permeability pinchout play
Dos – Lower Devonian Oriskany Sandstone structural play
EOR – enhanced oil recovery
FMI – formation microimager
GHG – greenhouse gases
GIS – geographic information system
InSAR – Interferometric Synthetic Aperture Radar
IPCC – Intergovernmental Panel on Climate Change
LiDAR – Light Detection and Ranging
MIT – Massachusetts Institute of Technology
MMV – Measurement, Monitoring, and Verification
MRCSP – Midwest Regional Carbon Sequestration Partnership
NASA – National Aeronautics and Space Administration
NIR – Near infrared
PaGS – Pennsylvania Bureau of Topographic and Geologic Survey
PUC – Public Utility Commission
UAVSAR – Uninhabited Aerial Vehicle Synthetic Aperture Radar
U.S. DOE – United States Department of Energy
U.S. EPA – United States Environmental Protection Agency
USGS – United States Geological Survey
WIS – Wells Information System

English and Metric Unit Abbreviations

Length	
foot	ft
meter	m
mile	mi
kilometer	km
Area	
square miles	mi^2
square kilometers	km^2
Mass	
short ton	ton
metric tonne	t
gigatonnes	Gt
Density	
pounds per cubic foot	lb/ft^3
kilograms per cubic meter	kg/m^3
Pressure	
pounds per square inch	psi
megapascals	MPa
Temperature	
degrees Fahrenheit	°F
degrees Celsius	°C
Volume	
million cubic feet	MMCF
billion cubic feet	BCF
million barrels of oil	MMBO
Flow Rate	
gallons per minute	gpm
liters per minute	lpm
gallons per day	gpd
liters per day	lpd
Permeability	
millidarcy	md
Water Quality	
parts per million	ppm

FOREWORD

The overwhelming scientific consensus is that the Earth's climate is changing rapidly due to the atmospheric buildup of human-generated, heat-trapping emissions, primarily carbon dioxide pollution from power plants and automobiles. Global climate change is the most significant environmental problem facing the world today – one that threatens our environment, our economy, public health, our national security, and our way of life.

- The threats to Pennsylvania's environment are many – more frequent and severe storms and increased flooding; a reduction in biodiversity; loss of cold water fisheries and winter outdoor recreation; changes in forest composition and diversity; and reductions in stream and river flows, lake levels, and groundwater, to name just a few.

- In a 2006 report to the British government on the economics of climate change, Sir Nicholas Stern, Head of the UK Government Economic Service and Advisor on the economics of climate change and development, wrote that the economic costs of not acting to reduce carbon emmisions "*will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more. In contrast, the costs of action – reducing greenhouse gas emissions to avoid the worst impacts of climate change – can be limited to around 1% of global GDP each year.*"[1]

- The US Climate Change Science Program Report on Human Health Effects from Climate Change[2] found that climate change poses a human health risk for U.S. populations from:

  - Increases in heat-related illnesses and deaths;
  - Exacerbation of heart and lung diseases from increased ground level ozone;
  - Potential increases in food- and water-borne diseases;

- A greater level of health risk to the very young and old, the poor, those with health problems and disabilities, and certain occupational groups; and
- Increased health risks from increased severity of storms.

- In 2007, the Military Advisory Board of the Center for Naval Analysis released a landmark report, *National Security and the Threat of Climate Change*, that concluded that climate change will act as a "threat multiplier" for instability in some of the most volatile regions of the world.[3] General Anthony C. Zinni, USMC (retired), former Commander-in-chief of the U.S. Central Command, stated, "*We will pay for this one way or another…We will pay to reduce greenhouse gas emissions today, and we'll have to take an economic hit of some kind. Or we will pay the price later in military terms. And that will involve human lives. There will be a human toll.*"[4]

According to the National Environmental Trust, Pennsylvania emits 1 percent of the entire planet's human-caused global warming gases, and ranks third among all states in global warming emissions. The Commonwealth therefore has a special responsibility to take meaningful action to reduce global warming pollution.

Pennsylvania is also the 4th largest coal producing state in the United States. More than 50 percent of the state's electricity is coal-fired, and 30 percent of the energy generated in Pennsylvania is exported to other states. If the Commonwealth is to reduce its global warming emissions, it must find ways to burn coal as cleanly as possible.

How will the state's economy adapt under the imposition of federal carbon emission constraints? What steps does the Commonwealth need to take now to ensure environmental and economic sustainability as the world confronts the challenges of climate change?

There is certainly no single answer to these questions. Clearly, a portfolio of approaches, policies, and technologies will be required to confront the challenges of a carbon constrained world. Governor Rendell and the General Assembly have made Pennsylvania a national leader in renewable energy development, energy conservation, and energy efficiency. These initiatives will significantly reduce the Commonwealth's emissions of global warming gases. Even so, there is more work to do.

One technology that offers great promise and that is particularly appropriate for consideration by the Commonwealth is carbon capture and sequestration (CCS) – a process of capturing carbon dioxide emissions from coal-fired electric power plants and other industrial facilities to prevent them from going into the atmosphere, and then storing them permanently underground in safe geological formations.

The focus of this report, prepared in accordance with Act 129 of 2008, is an assessment of the state's geology as the foundation for a CCS network in Pennsylvania.

According to the Midwest Regional Carbon Sequestration Partnership (MRCSP),[5] Pennsylvania has an estimated geologic capacity to store hundreds of years' worth of carbon emissions at present rates. If that resource can be proven, and appropriately and safely developed along with all of the other technological requirements of CCS, the Commonwealth may be able to substantially reduce its global warming emissions and protect our environment, our economy, and public health – while preserving its position as a net energy exporter and creating jobs in the process.

Indeed, in taking such action, there is considerable opportunity. Pennsylvania's leadership in the development of renewable energy and energy efficiency technologies has already brought significant investment and jobs to the Commonwealth. Similar leadership in the development and deployment of CCS has the potential to create very significant numbers of research and development, manufacturing, retrofit, and export jobs in Pennsylvania.

This report, the first of two required of the Pennsylvania Department of Conservation and Natural Resources (DCNR) by Act 129, along with DCNR's Report of the Carbon Management Advisory Group published in May 2008,[6] are a part of DCNR's continuing contribution to the formation of Pennsylvania's policy response to the challenges of reducing the Commonwealth's global warming emissions and building a sustainable economy for our state.

There are many unanswered questions and concerns about an emerging technology like CCS. Given the magnitude of the challenge of reducing carbon dioxide emissions to avoid catastrophic impacts of climate change, it is essential that we explore the possibilities with the sense of urgency that the problem demands.

I want to acknowledge and thank the women and men of DCNR's Bureau of Topographic and Geologic Survey for their continued excellence and professionalism in preparing this report, and similarly acknowledge the invaluable contributions of DCNR's Office of Education, Communication, and Partnerships and the Pennsylvania Department of Environmental Protection.

John Quigley
Acting Secretary
Pennsylvania Department of Conservation and Natural Resources

EXECUTIVE SUMMARY

The Pennsylvania Department of Conservation and Natural Resources (DCNR) Bureau of Topographic and Geologic Survey (the Survey) has concluded an initial study of suitable geologic formations for the location of a state carbon dioxide (CO_2) sequestration network in accordance with Section 2815 of Act 129 of 2008. By enacting this legislation, Pennsylvania acknowledges what is generally regarded by many in the carbon sequestration research community – that the use of subsurface geologic reservoirs offers the most promising means of permanently sequestering large volumes of CO_2.

Based on this preliminary assessment and the geographic coverage afforded by these potential reservoirs (Figure ES-1), the geology of Pennsylvania (subject to the adequacy of storage rights and detailed characterization work to be performed at each prospective sequestration site) can support the development of a state geologic sequestration network. Further, the Commonwealth has potential for value-added enhanced oil recovery (EOR) with permanent geologic sequestration of CO_2 (Figure ES-2).

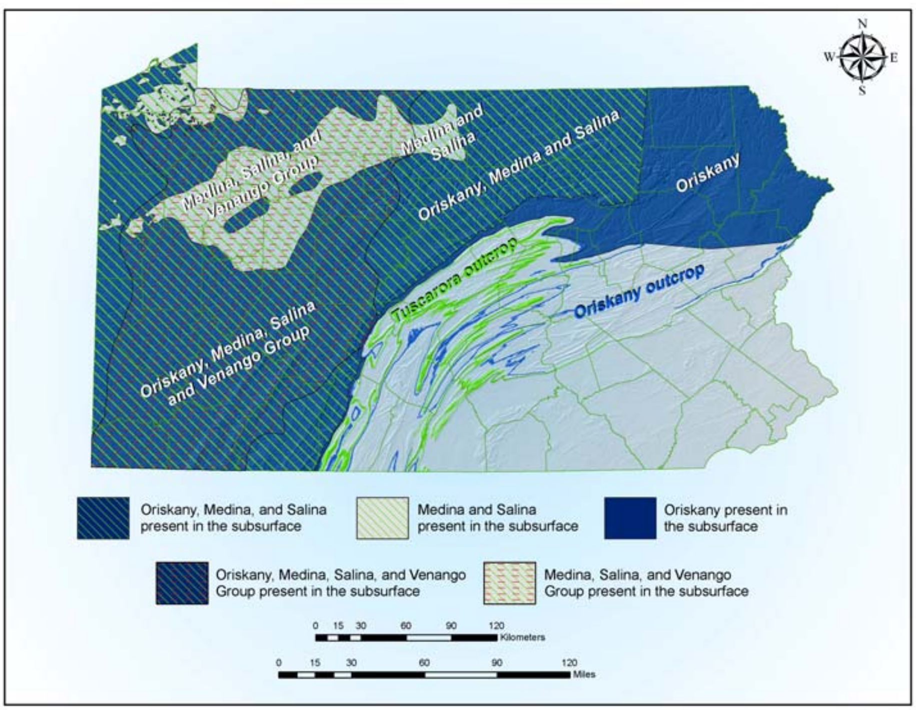

Figure ES-1. Geographic distribution of potential geologic sequestration reservoirs in Pennsylvania.

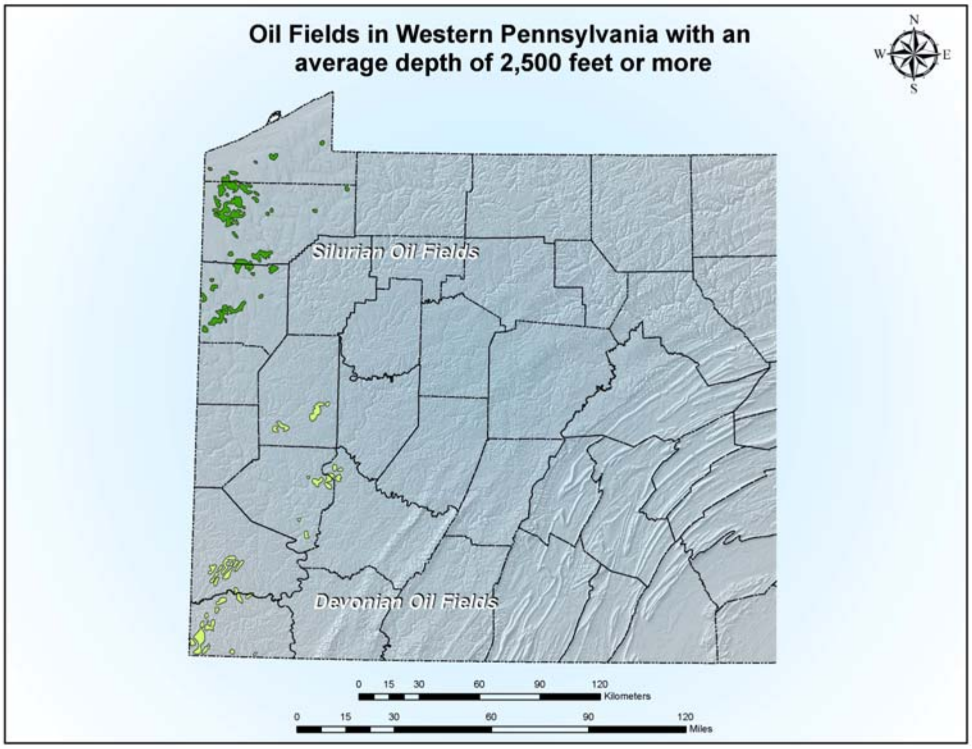

Figure ES-2. Location of oil-and-gas fields in Pennsylvania that may be used for both enhanced oil recovery (EOR) and geologic sequestration of CO_2.

In order for such a network to be successful, it must be supported by multiple and widespread "sinks" that have the capacity to collectively receive millions of metric tonnes of CO_2 annually from point sources across the Commonwealth.

Geologic sequestration involves capturing CO_2 at its source, compressing and cooling to a supercritical phase, transporting it via pipelines to a sequestration site, and injecting it into subsurface rock formations where it will remain trapped in its supercritical phase for thousands of years or longer. For the current study, we considered geologic sequestration reservoirs to include deep saline formations, "depleted" oil-and-gas reservoir rocks (which may also be used in EOR operations), unmineable coal beds, carbonaceous (organic-rich) shales, and thick salt beds. Using this list as a guide, the Survey has examined the Commonwealth's regional geology to identify four potential geologic sequestration reservoirs in western and north-central Pennsylvania, each of which meet the U.S. Department of Energy (DOE)'s criteria for consideration as a target for permanent sequestration of CO_2, that is, occurring at a minimum depth of 2,500 feet (ft) [762 meters (m)]. These include (from oldest to youngest) the Lower Silurian Medina Group/Tuscarora Sandstone, the Upper Silurian Salina Group, the Lower Devonian

Oriskany Sandstone, and certain Upper Devonian sandstone reservoirs (Figure ES-1). For each of the potential reservoirs, we include a detailed geologic assessment of reservoir characteristics, complimented with structure-contour (depth) and isopach (thickness) maps.

The geologic characteristics and potential suitability of each potential sequestration reservoir vary, and detailed site evaluations would need to be performed prior to the use of any of these for geologic sequestration of CO_2. Salient characteristics of these potential reservoirs are as follows:

- The Medina Group/Tuscarora Sandstone offers limited potential as a sequestration reservoir due to its variable lithology throughout the region and its relatively low porosity and permeability. Even so, Medina and equivalent rocks are known by the industry as reliable oil-and-gas-producing rocks with good confining layers above and below its productive sandstone units. This suggests that they may have potential for geologic sequestration in those areas of the state where sandstone layers are relatively thick and have documented notable oil and/or gas production (parts of Crawford and Erie Counties).

- The Salina Group offers the potential to geologically sequester large volumes of CO_2 through the creation of salt caverns (voids) that can be located and engineered to meet the needs at a given sequestration site/CO_2-source. Individual caverns not only have the ability to store CO_2, they are basically impermeable and allow very little injected material to escape due to the salt's inherent structural strength and low chemical reactivity. The challenges with respect to this particular sequestration reservoir involve the determination of locations here in the Commonwealth with the thickest salt reserves, the relative expense of drilling and leaching a salt cavern, and the logistical and cost components of dealing with produced brines.

- The Oriskany Sandstone promises to be a viable sequestration reservoir, particularly in those areas of the Commonwealth where the unit is known to produce oil and gas from permeability pinchouts (parts of northwestern and north-central Pennsylvania) and where it and the overlying Huntersville Chert are extensively fractured (parts of southwestern Pennsylvania). The

Oriskany has been used for both the injection of industrial wastes throughout the Appalachian Basin as well as for purposes of natural-gas storage in depleted gas fields, suggesting that this formation can be used for geologic sequestration of supercritical CO_2 under the proper circumstances. The largest, single problem for sequestering CO_2 in the Oriskany Sandstone is related to cap rock seal failure. Problems with seal integrity would be more likely to occur in those areas where structural deformation of the Oriskany and adjacent rock units is known (particularly along the Allegheny Front). Obviously, the integrity of such cap rock would need to be evaluated thoroughly prior to the use of the Oriskany Sandstone as a sequestration reservoir in these areas of the Commonwealth.

- Upper Devonian sandstone reservoirs have a notable history of oil-and-gas production in the subsurface of southwestern Pennsylvania, have favorable porosity and permeability characteristics, and consequently, may serve as feasible targets for sequestration. The volume of CO_2 that could be permanently sequestered in these rocks is limited, however, because not all the sandstone units occur at depths greater than 2,500 ft (762 m) and some may be limited in extent. The viability of these sandstone reservoirs for geologic sequestration of CO_2 is also restricted by the unknown integrity of post-production cap rock and the large number of oil-and-gas wells (active, abandoned, and orphaned) that could pose risk for CO_2 migration and leakage.

As a matter of due diligence in evaluating potential geologic sequestration opportunities statewide, the Survey has also initiated an assessment of central and eastern Pennsylvania for its prospective geologic sequestration reservoirs. In this portion of the state, significant data gaps must be filled in order to properly evaluate the complex subsurface geology that exists here, and so we are gathering data from various sources, including but not limited to existing geologic maps, geologic literature/file searches, high-resolution orthophotography, and our ongoing PAMAP program work.

As a follow-up to the geological assessment provided herein, reconnaissance-level evaluations for central and eastern Pennsylvania will be completed and should be followed by more sophisticated data collection techniques (such as remote sensing, corehole drilling, and geophysical logging) to further our understanding of the

Commonwealth's subsurface geology in prospective areas.

All data and maps generated for this study are being incorporated into a digital database simply referred to as the Carbon Sequestration Network (CSN) database. This database and the Survey's Geographic Information System (GIS) will provide a logical way to track and evaluate potential sequestration. The CSN database will consist of a set of standard criteria that will allow the Survey to organize, rank, and evaluate prospective sequestration sites, match CO_2 sources to sinks, and assist with sequestration planning efforts.

In accordance with Act 129, the next steps for the study include the detailed evaluation of risks associated with geologic sequestration of CO_2; the best approaches for measurement, monitoring, and verification of injection performance at sequestration sites; and development of an appropriate CCS public outreach, education, and acceptance program for use by the Commonwealth. The detailed risk analysis will be performed with assistance from an independent expert to be retained by DCNR. DCNR will provide a final report on this study to the Governor, the Chairmen and Minority Chairmen of the Environmental Resources and Energy Committee of both the Senate and House of Representatives by November 1, 2009.

1.0 INTRODUCTION

Increasing atmospheric concentrations of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), are affecting the Earth's climate worldwide. The scientific consensus, represented by the work of the Intergovernmental Panel on Climate Change (IPCC), is that global warming is "unequivocal," that GHGs resulting from human activity are the primary cause, and that serious and damaging societal and ecological impacts are likely to result.[7] Both the Union of Concerned Scientists and the National Academy of Sciences have issued reports concurring with these results.[8] Similarly, in a recent assessment of climate change impacts on Pennsylvania, the Union of Concerned Scientists[9] predicted longer and more intense summer heat waves, reduced winter snowpack, northward shifts in the ranges of valued plant and animal species, and declining yields of key agricultural crops.

Leading climate scientists recommend dramatic reductions in global GHG emissions by 2050, and many states have set targets ranging from 50 to 80 percent. Such reductions are necessary to stabilize the level of GHGs in our atmosphere at between 450-550 parts per million (ppm). That level, which represents approximately a 200 percent increase over pre-industrial levels, will allow us to more reasonably manage the climate impacts that are already becoming apparent.

The Commonwealth of Pennsylvania (Commonwealth) became involved in climate change issues in 2003 when geologists with the Bureau of Topographic and Geologic Survey (the Survey) in the Department of Conservation and Natural Resources (DCNR) joined with Battelle Memorial Institute and scientists, engineers, and social scientists from other eastern U.S. states to form the Midwest Regional Carbon Sequestration Partnership (MRCSP) (Figure 1.0-1).

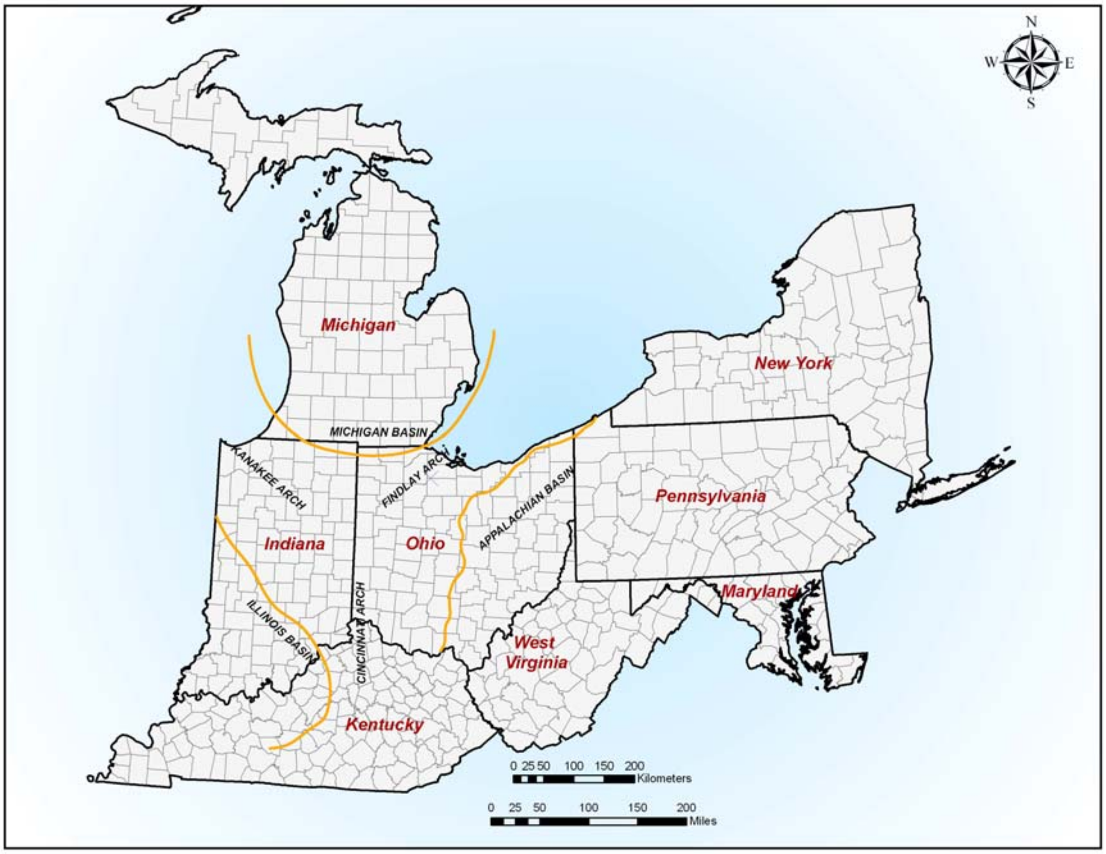

Figure 1.0-1. Eight states included in the Midwest Regional Carbon Sequestration Partnership (MRCSP).

A two-year study of western Pennsylvania's subsurface rock formations resulted in a preliminary assessment of the Commonwealth's potential to store carbon underground through geologic sequestration. Shortly afterwards, in 2006, Michael DiBerardinis, then Secretary of DCNR, created the Carbon Management Advisory Group (CMAG) in partnership with the Pennsylvania Environmental Council. This group followed a stepwise, joint fact-finding and policy-development process, and issued a final report providing recommendations dealing with forestry, landscape conservation, forest biomass energy, carbon capture and sequestration (primarily geologic sequestration), and GHG registries.[10] One of the CMAG's recommendations was to pursue an appropriate scientific, legal, and regulatory framework for geologic sequestration within the Commonwealth, and one of the proper magnitude to potentially account for the many CO_2 point-sources that are located in the state (Figure 1.0-2). The report also recommended that Pennsylvania work with interested state and federal officials to promote a consistent multi-state and/or national legal and regulatory framework to govern geologic sequestration.

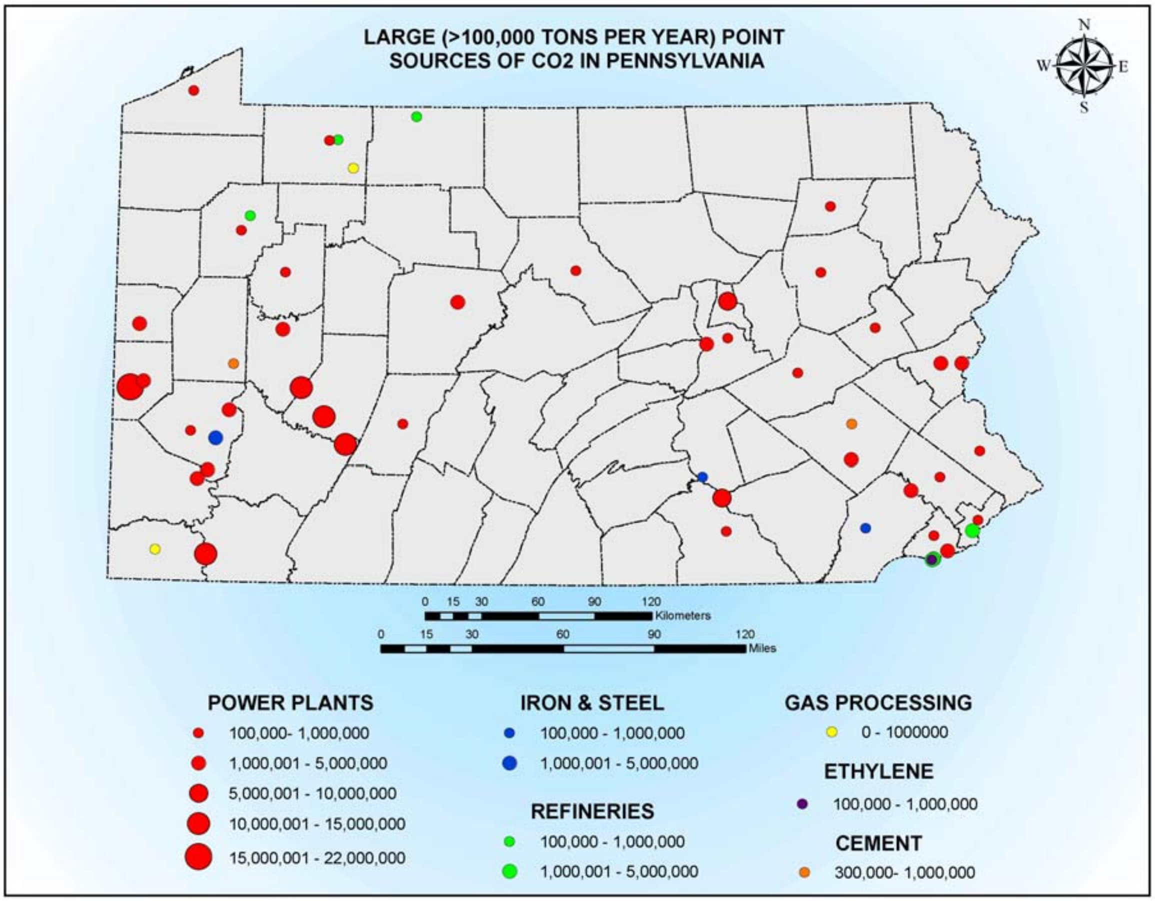

Figure 1.0-2. CO_2 point-sources in Pennsylvania.

As a result of these efforts, the Survey has continued to investigate the potential for geologic sequestration in the western part of the state where 150 years of drilling for oil and natural gas has provided a wealth of data on deep subsurface rock formations. In addition, the Survey has also begun to look for potential geologic sequestration reservoirs in central and eastern Pennsylvania where the paucity of subsurface data has made these areas more difficult to assess.

1.1 Legislative Overview

Act 129 of 2008, signed into law by Governor Edward G. Rendell on October 15, 2008, requires DCNR to conduct a series of studies relating to CO_2 sequestration in the Commonwealth.

Act 129 defines “carbon dioxide sequestration” as the storage of carbon dioxide in a supercritical phase within a geological subsurface formation such as a deep saline formation with suitable cap rock, sealing faults and anticlines that includes compression, dehydration and leak detection monitoring equipment and pipelines to transport carbon dioxide captured by an advanced coal combustion with limited carbon emissions plant to an underground storage site. Act 129 specifically excludes the use of the carbon dioxide for enhanced oil recovery from the definition of carbon dioxide sequestration.

Section 2815 of Act 129 requires DCNR to complete a study to identify suitable geological formations for the location of a state carbon dioxide sequestration network by April 1, 2009, and to submit it to the Governor, the Chairmen and Minority Chairmen of the Environmental Resources and Energy Committee of both the Senate and the House of Representatives by May 1, 2009.

Act 129 defines “state network” as a carbon dioxide sequestration network established on lands owned by the Commonwealth, or lands on which the Commonwealth has acquired the right to store carbon dioxide, that have been designated by (DCNR) for the storage of carbon dioxide.

This report has been prepared pursuant to Section 2815.

By June 1, 2009, Act 129 requires that DCNR, in consultation with the Public Utility Commission (PUC), hire one or more independent experts to conduct an assessment of the following:

- Cost estimates for the establishment, operation, and maintenance of a state CO_2 sequestration network;
- Data collection to allow a safety assessment; and
- All potential risk to individuals, property, and the environment associated with the geological sequestration of CO_2 in a state network. The assessment is required to be completed by October 1, 2009 and must include an analysis of the following:

    - Existing federal and state regulatory standards for the storage of CO_2;
    - Factors contained in the U.S. Environmental Protection

Agency (EPA)'s vulnerability evaluation framework for geologic sequestration of CO_2 (EPA-R-8-009, dated July 10, 2008);

- The different types of insurance, bonds, other instruments, and recommended levels of insurance which should be carried by the operator of the state network during the construction and operation of the state network;
- The availability of commercial insurance; and
- Models for the establishment of a Commonwealth fund to provide protection against risk to be funded by the operator.

Act 129 requires that the independent expert retained by DCNR submit the final assessment to the Governor, the Chairmen and Minority Chairmen of the Environmental Resources and Energy Committee of both the Senate and the House of Representatives by November 1, 2009.

Act 129 further requires DCNR to review the assessments described above and all geologic sequestration requirements associated with a state network, including geological site characterization, modeling, and verification of fluid movement, corrective action, well construction, operation, mechanical integrity testing, monitoring, and site closure. Following that review, Act 129 provides that DCNR may conduct a pilot project to determine the viability of establishing a state network in this Commonwealth.

1.2 Technical Overview

There are four basic ways of sequestering carbon:

- in the oceans;
- through chemistry and biochemistry;
- on land (terrestrial); and
- underground in rock reservoirs.

Oceanic sequestration involves two options – injecting liquefied CO_2 directly into the deep ocean where the increased pressures and decreased temperatures would keep it in its liquid form, and stimulating the growth and reproduction of phytoplankton that remove CO_2 from the atmosphere during photosynthesis. Both of these options have drawbacks, however; they tend to increase the acidity of seawater through the production of carbonic acid (H_2CO_3), which could have very negative consequences for organisms with calcareous (limy) skeletons.

In chemical sequestration, CO_2 mixes with an element or mineral, resulting in a stable compound, such as magnesium carbonate ($MgCO_3$), that has value in manufacturing, chemicals, and agriculture. Chemical sequestration technology, as it would apply to large point-source emitters, is not mature, and is being developed at laboratory-scale and early pilot stages. Biochemical sequestration uses microbes that can turn CO_2 into useful products such as hydrocarbons.

Terrestrial sequestration is both the simplest and most environmentally friendly form of sequestration in that it consists of growing and sustaining forests, grasslands, farms, and other vegetation-intense areas. The plants draw CO_2 from the atmosphere during photosynthesis and store the carbon in their tissues and in the soil. Wood, once harvested and cut into building products, can lock up the carbon for decades or centuries.

Underground sequestration is discussed in Section 1.2.1 below.

During the MRCSP's first two years of study (2003-2005), the Survey worked with surrounding states to prepare a Phase I geological assessment of carbon sequestration potential in the Appalachian and Michigan Basins, as well as the intervening arches in the study area (Figure 1.0-1).[11] During this Phase I study, the geological research team studied the regional geology of the area to delineate the most promising prospective geological reservoirs and sinks for CO_2 sequestration through data collection, interpretation, and mapping.

The primary attraction of geological sequestration is the potential for direct and long-term storage of captured CO_2 emissions in close proximity to the CO_2 source. Disposal wells can be drilled directly on the property of the CO_2 source in many cases, or the CO_2 can be transported by pipeline to a remote location. To achieve this objective, however, the potential capacity of any geological reservoir must be verified by both detailed regional and site-specific assessments to insure that decision-makers fully understand the characteristics of the geological sequestration system. For this reason, a major task of the Phase I study was a first-round regional assessment of the potential capacity for geological sequestration of CO_2 in the MRCSP area.

The assessment in Pennsylvania included, for the most part, only the western counties of the Commonwealth. The nature of the geological complexity, as well as a lack of sufficient well data, precluded evaluation of the central and eastern parts of the state, despite the seeming extent of mapped formations in this part of Pennsylvania. As a result, the geological sequestration potential of a large number of formations that occur only in central and eastern Pennsylvania, such as anthracite coals and Lower Cambrian rocks, is currently unknown. Evaluation of these formations will require concentrated study of outcrops and a significant number of drill holes that, so far, do not exist.

The results of Phase I of MRCSP indicate that Pennsylvania has a large potential capacity for CO_2 sequestration.[12] The total amount of potential CO_2 sequestration capacity for Pennsylvania is estimated at 97.6 billion short tons (tons) [88.5 billion metric tonnes (t), or 88.5 gigatonnes (Gt)]. The majority of this sequestration capacity, about 83.3 billion tons (75.6 Gt, approximately 85 percent of the total estimated geological CO_2 storage capacity), represents the potential of deep saline formations. This storage option alone could accommodate Pennsylvania's CO_2 emissions for roughly three hundred years. Carbonaceous (organic-rich) shales exhibit the next largest storage potential of 13.2 billion tons (12 Gt, about 14 percent of the total estimated geological CO_2 storage capacity), which may also be useful for secondary recovery of natural gas adsorbed on shale surfaces. Oil-and-gas fields have a potential sequestration capacity of about 8.4 billion tons (7.6 Gt, a little less than 1 percent of Pennsylvania's total estimated geological CO_2 storage capacity). This particular reservoir type is attractive not only for CO_2 sequestration but also for value-added enhanced oil recovery (EOR) operations, where CO_2 may be used with gas drive techniques to produce many millions of barrels of oil from existing oil fields. Pennsylvania has the largest sequestration potential in oil-and-gas fields of all the MRCSP partner states, representing about a third of the total MRCSP potential storage capacity in this type of reservoir. The smallest sequestration capacity is associated with coal beds, which offer about 1.1 billion tons (<1 Gt) of the total estimated geological storage capacity.

1.2.1 Geologic Sequestration Defined

In the most general of terms, geologic sequestration involves capturing CO_2 at its source (for example, a coal-fired power plant), compressing and cooling it to a liquid, transporting it to a sequestration site using either a specially constructed pipeline or vehicles (truck or train), and injecting it into rocks within Earth's crust where it will remain trapped for many thousands to millions of years.

There are many ways to sequester CO_2 geologically, with the most suitable depending on the specific geological characteristics at a given injection site. Based on geologic sequestration research conducted over the last decade by various researchers, these mechanisms are now fairly well described in published papers and proceedings of conferences.[13] These storage mechanisms include: (1) volumetric storage; (2) solution storage; (3) adsorption storage; (4) mineral storage; and (5) salt caverns. Volumetric storage refers to the amount of CO_2 that is retained in the pore space of a geologic unit, generally as a supercritical phase retained by structural or stratigraphic traps or by the overlying cap rock layers. Solution storage involves dissolution of a part or all of the CO_2 into the formation waters of the geologic unit. Adsorption storage involves the retention of CO_2 molecules onto the fracture faces and matrix of carbonaceous rocks such as coal or black shale. Mineral storage involves the chemical reaction of CO_2 with the minerals and brine in the geologic unit. Under appropriate geochemical conditions, some reactions may form a solid precipitate, permanently binding the carbon to the geologic unit. Finally, salt caverns are also potential repositories for CO_2 storage. In this scenario, solution mining is used to create a cavity (void) within the salt deposit consisting of 100 percent pore space, which can then be filled with supercritical CO_2. Here, the surrounding relatively impermeable salt provides its own seal.

Geologic sequestration is a known and scientifically valid concept that has been utilized around the world, primarily for the enhanced recovery of crude oil. Numerous CO_2 EOR projects have been operating in North America for about 40 years; some of the most famous include EOR projects in Texas and California and in the Weyburn-Midale oil fields in Saskatchewan, Canada. Liquid CO_2 is pumped into an oil reservoir to sweep the oil out of the pore spaces in the rock, and eventually remains in the reservoir. The Weyburn project, which was launched in 2000 and includes intentional CO_2 storage underground in depleted oil fields, uses CO_2 generated in North Dakota and shipped to the project through a 200-mile (mi) [322-kilometer (km)] long pipeline. Similarly, Statoil, a Norwegian oil company, has been sequestrating about 1 million tons (907,000 t) of CO_2 per year in a deep saline formation in the Sleipner West gas field in the North Sea since 1996. The U.S. Department of Energy (DOE)-funded carbon sequestration partnerships are currently experimenting with sequestering CO_2 in deep coal seams, with the hope that sequestration will also help produce additional coalbed methane (CBM) resources. At this time, no one is working to store CO_2 in carbonaceous shales or cavities in salt beds or salt domes, although some researchers[14] suggest it could be done inexpensively and effectively.

1.2.2 Potential Reservoirs ("Sinks") for Sequestration

The U.S. DOE has identified several categories of geologic reservoirs as potential CO_2-sequestration targets.[15] Of these, five may be considered as potential sequestration targets in Pennsylvania, including: (1) deep saline formations; (2) oil-and-gas fields; (3) unmineable coal beds; (4) carbonaceous shales; and (5) thick salt beds (Figure 1.2-1). These are described below.

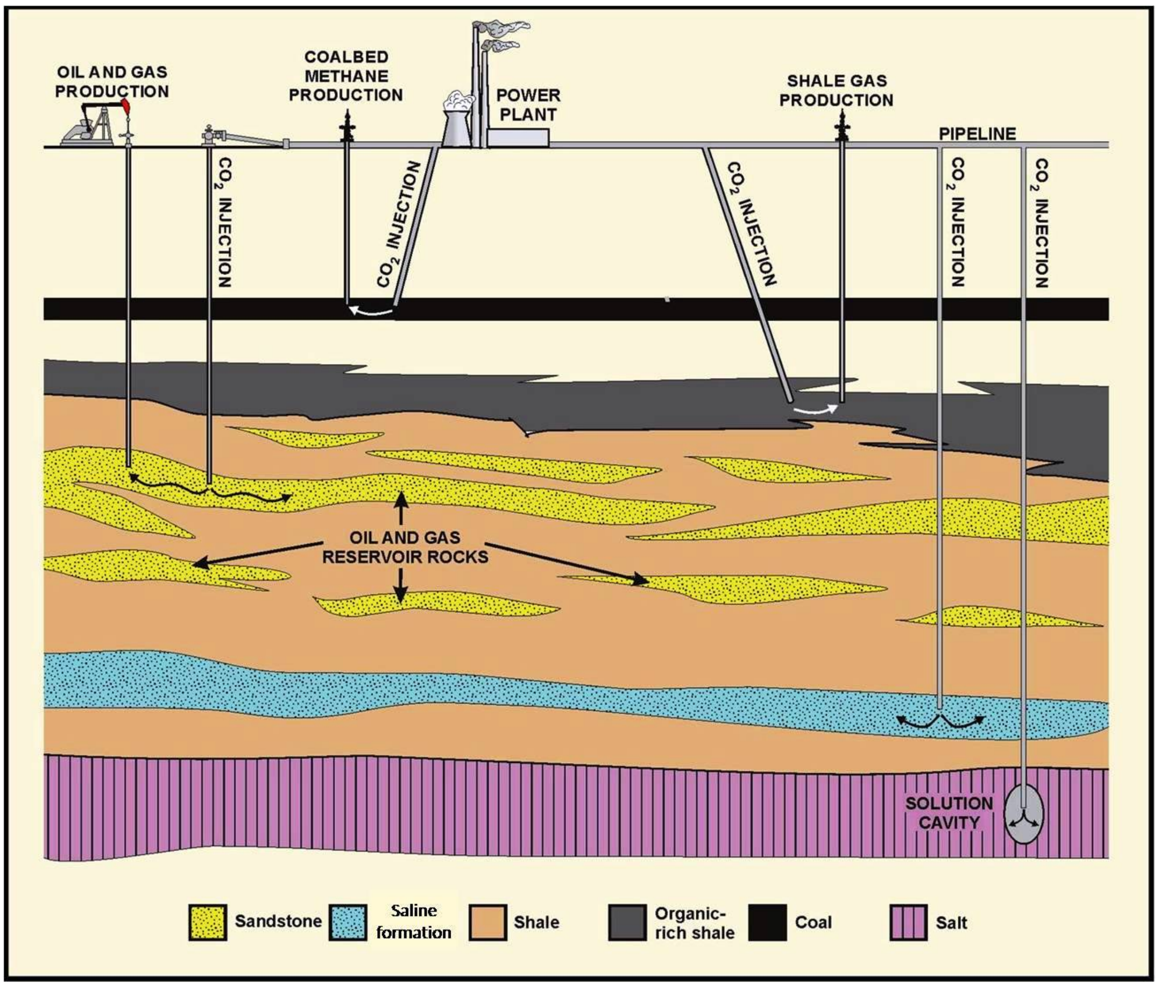

Figure 1.2-1. Potential geologic sequestration targets in Pennsylvania.

<u>1.2.2.1 Deep Saline Formations</u>

Saline formations are natural salt-water-bearing intervals of porous and permeable rocks that occur beneath the level of potable groundwater. Saline formations are widespread, occur beneath many of the region's large CO_2 sources, and are thought to have large pore space volumes available for injection.[16] In order to maximize sequestration volumes in saline formations, CO_2 injection occurs after the CO_2 is compressed into a supercritical phase. In the supercritical phase, CO_2 occupies much less volume than in its gaseous phase. Based on U.S. DOE guidance, geologic sequestration targets must occur at depths in excess of 2,500 feet (ft) [762 meters (m)] to ensure that enough pressure is maintained to keep the injected CO_2 in its supercritical phase, and to provide as much overlying cap rock (confining layers) as possible to act as a geologic seal for the sequestration reservoir(s) of interest. Work recently published by the U.S. Geological Survey (USGS)[17] suggest a minimum storage depth of 3,000 ft (914 m) to ensure the CO_2 remains in its supercritical phase. For this current study, the Survey has adopted the U.S. DOE guidance of 2,500 ft (762 m) minimum depths for sequestration; therefore, no consideration was given to the sequestration potential of saline formations shallower than this.

In a deep saline formation reservoir, CO_2 is injected under pressure down a specially constructed well where it displaces and mixes with the saline water that naturally fills the pore spaces between individual grains or crystals of the reservoir rock. During this process, CO_2 may also become trapped within minerals contained in the rock matrix. Depth, permeability, injectivity, reservoir pressure, reservoir integrity, and water chemistry are some of the variables that control the sequestration potential in deep saline formations.[18] Injected CO_2 is more buoyant than the natural fluids in a saline formation so it will slowly migrate to the top of the porous injection zone. For this reason, a confining cap rock layer is necessary to keep the CO_2 from invading the overlying formations. This confining cap rock must be relatively impermeable and sufficiently thick to prevent any appreciable vertical movement of the CO_2 within the sequestration interval, thereby trapping it in the deep subsurface.

Carbon dioxide may be stored in either subsurface traps or unconfined rock units. In subsurface traps, the more buoyant CO_2 will occupy the highest portion of any structural or stratigraphic feature (for example, anticlines or pinchouts, respectively). This same mechanism of trapping is found in many of the oil-and-gas reservoirs in the study area. In subsurface traps, available pore space volumes and the size of the reservoir are the only factors that limit the volume of CO_2 to be injected. In unconfined storage units, the

CO_2 is injected in regional saline formations located in rocks without specific structural closures or stratigraphic traps. Once injected, the CO_2 will slowly migrate towards the highest portion of the saline formation and accumulate against the impermeable cap rock, which prevents further vertical movement.[19] At that point, the injected CO_2 will begin to migrate laterally, following the normal hydrodynamic flow regime of the region (usually towards shallower areas). In this scenario, it must be emphasized that flow velocities are extremely low and occur at rates measured in feet per hundreds (even thousands) of years. In any event, the CO_2 is still trapped beneath an impermeable cap rock that prevents vertical migration.

1.2.2.2 "Depleted" Oil and Natural Gas Fields

Existing oil-and-gas fields (Figure 1.2-2) represent areas where known subsurface reservoirs have significant open pore space containing hydrocarbons and have an adequate seal or cap rock for keeping these petroleum deposits in place.

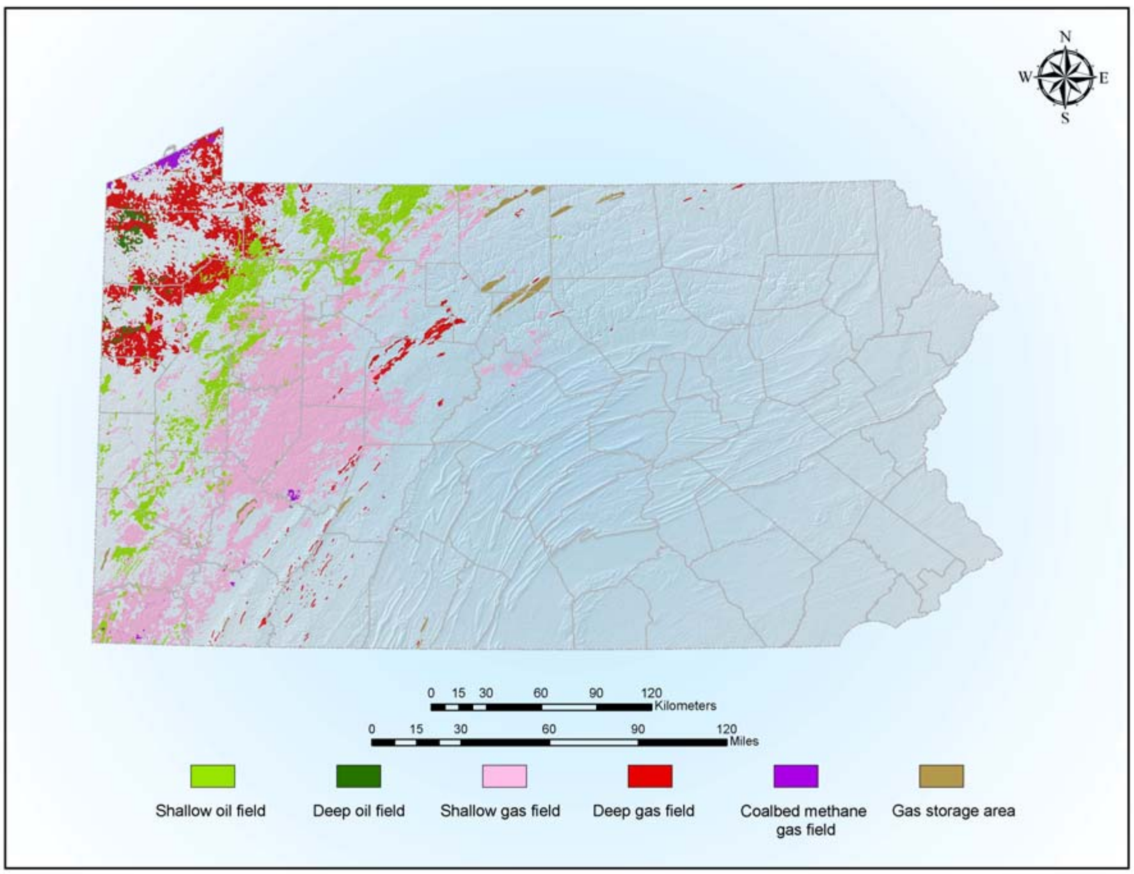

Figure 1.2-2. Pennsylvania's oil-and-gas fields.

When these known hydrocarbon reservoirs have been depleted, they become attractive targets for geologic sequestration of CO_2. In depleted or abandoned petroleum fields, CO_2 is injected into the reservoir to fill the pore volume left by the extraction of the oil or natural gas resource.[20] The injected CO_2 is trapped by the natural limits of the oil-and-gas reservoir for secure storage. Volume, permeability, injectivity, rock pressure, reservoir integrity, water chemistry, the nature of the cap rock or reservoir seal, and the history of oil-and-gas production are some of the variables that control the sequestration potential in depleted petroleum fields.[21] This sequestration option may be attractive in many portions of western or northern Pennsylvania, where oil-and-gas production have been documented in numerous petroleum reservoirs over the past 150 years.

In addition to successfully sequestering CO_2, there is a secondary economic benefit to utilizing active oil fields for geologic sequestration – EOR, a process where CO_2 is injected into a known oil-producing reservoir and any oil remaining after primary production has ended is displaced and made available for secondary recovery. The process of using CO_2 for EOR occurs in one of two ways: (1) repressurizing the reservoir, displacing and driving the remaining oil to a recovery well (immiscible flooding); or (2) directly mixing and chemically interacting with the remaining oil to reduce its viscosity and force the oil towards a producing well (miscible flooding). Approximately 70 oil fields worldwide currently inject CO_2 for EOR,[22] demonstrating the effectiveness of this value-added sequestration option. Moreover, EOR, while sequestering CO_2, could provide an economic incentive to carbon storage in Pennsylvania where CO_2 sources are proximal to oil fields.

1.2.2.3 Unmineable Coal Beds

Pennsylvania is the 4th leading coal producing state in the nation[23], and numerous unmineable coal beds offer another possible geologic means of sequestering CO_2. When coal beds are too deep or too thin to be economically extracted, they are deemed unmineable. Sequestration in unmineable coal beds is not porosity-dependent because the injected CO_2 does not occupy the open pore space but rather adsorbs (attaches) to the carbon molecule surfaces in the coal itself. In the absence of sequestration, methane adsorbs to these pore surfaces, but the adsorption ratio for CO_2 in coals is approximately twice that of methane; thus, in theory, the injected CO_2 would displace methane, allowing for the potential of enhanced CBM gas recovery.[24] The injection of CO_2 and resulting enhanced recovery of CBM can occur at shallower depths than necessary for CO_2 sequestration in hydrocarbon reservoirs or saline formations. Rising natural gas prices have led to growing interest in this energy resource in Pennsylvania in the last decade, and secondary recovery of CBM gas may provide an economic incentive for CO_2 sequestration from sources in the coal fields.

1.2.2.4 Carbonaceous Shales

The study area also contains widespread, thick deposits of carbonaceous shales. These shales are interesting in that they are often multifunctional – acting as seals for underlying reservoirs, as source rocks for oil-and-gas reservoirs, and as unconventional gas reservoirs themselves. Analogous to sequestration in coal beds, injection of CO_2 into unconventional carbonaceous-shale reservoirs could be used to enhance existing natural gas production. As an added benefit, it is believed the carbonaceous shales would adsorb the CO_2 into the shale matrix, permitting long-term storage, even at relatively shallow depths.[25]

1.2.2.5 Thick Salt Beds

Rock salt, or halite (NaCl – the mineral we know as “road salt” and, when refined, as “table salt”), is a naturally-occurring mineral found in many places around the world. Perhaps the most well-known to Americans are the thick beds of rock salt occurring along the Gulf coasts of Texas and Louisiana that have been squeezed upward by the pressure of overlying rocks to form domes in the subsurface. Although salt is considered to be a brittle mineral, it is plastic under the stresses that exist during mountain-building episodes and beneath thousands of feet of overburden material.

Salt is a water-soluble mineral, so salt-dissolution caverns typically are low in cost and capable of being created relatively rapidly. The brine produced during solution mining can be sold as a commodity, thus reducing the overall cost of the solution-mining process. Because salt has very low permeability, it is ideal for storing and containing fluids; even if leakage should occur, migration away from the cavern generally would be very slow. In addition, the pore spaces of rocks in contact with the salt typically are plugged by salt crystals, effectively reducing the risk of escaping fluids through what otherwise might be porous and permeable rocks. Since salt distorts and flows under stress, it can seal itself through creep behavior. Thus, any fractures resulting from drilling and/or the solution-mining process will heal in a relatively short timeframe. The fluid stored in solution-mined salt caverns remains there indefinitely; it can even be withdrawn through the injection wells if needed. In fact, salt-solution cavities are so ideal for storing and recovering fluids that the U.S. DOE stores crude oil for the Strategic Petroleum Reserve in caverns created in salt domes beneath the Texas and Louisiana coastline. The caverns are secure and affordable, costing as little as 10 times less than aboveground tanks and 20 times less than caverns mined in other types of rocks.[26]

Salt typically is interbedded with limestone, dolostone, anhydrite, and other sedimentary rocks such as shale, mudstone, siltstone, and sandstone. As a result, there might be limits to the utility of bedded salt for solution-mined caverns because of the distribution and thickness of low-solubility, or even insoluble, impurities. Consequently, it is imperative that such impurities be identified and characterized prior to drilling and solution-mining activities. Salt beds themselves can change thickness, pinch out or change to another rock type laterally, but they can also maintain consistency over large areas. In the latter case, solution mining at one site would provide experience with solution mining at other sites nearby.[27] Geologic data such as thickness, quality, and the distribution of associated non-salt beds can be applied to risk assessment, cavern and storage engineering, and salt stability during site evaluation for solution-mined caverns.

Storage of CO_2 in solution-mined caverns would be advantageous for all the reasons mentioned above. Pumping supercritical CO_2 into salt caverns would provide more storage capacity than if it was stored in the pore spaces of a saline formation. There would even be more storage capacity than through adsorption in coal or carbonaceous shale. In addition, the rate of filling or draining caverns is limited only by the flow capacity of the delivery system.[28]

1.2.3 CO_2 Properties

Carbon dioxide consists of a carbon atom doubly bonded to two oxygen atoms. At room temperature [68 to 77 degrees Fahrenheit (°F)] [20 to 25 degrees Celsius (°C)], CO_2 is a colorless, odorless gas. Carbon dioxide is about 50 percent heavier than air, and is very soluble in water.

The physical properties of CO_2 can affect how much of the gas can be placed into storage. The phase behavior of CO_2 is well understood and can be found in general chemical references and in literature regarding EOR.[29] Carbon dioxide can exist as four different phases (Figure 1.2-3): solid, liquid, gas, or supercritical gas. The triple point for CO_2 (the pressure-temperature condition at which CO_2 coexists in three forms – solid, liquid, and gas) is -69.826 º F (-56.57 º C) and 75.202 pounds per square inch (psi) [0.519 megapascals (MPa)] (Figure 1.2-3). At temperatures greater than 87.8º F (31.1º C) and pressures greater than 1,071 psi (7.38 MPa), CO_2 exists in a supercritical state, and behaves similar to a gas by filling all available space, while retaining the density of a liquid. For this reason, the supercritical phase of CO_2 is often referred to as a “fluid” or “liquid”.

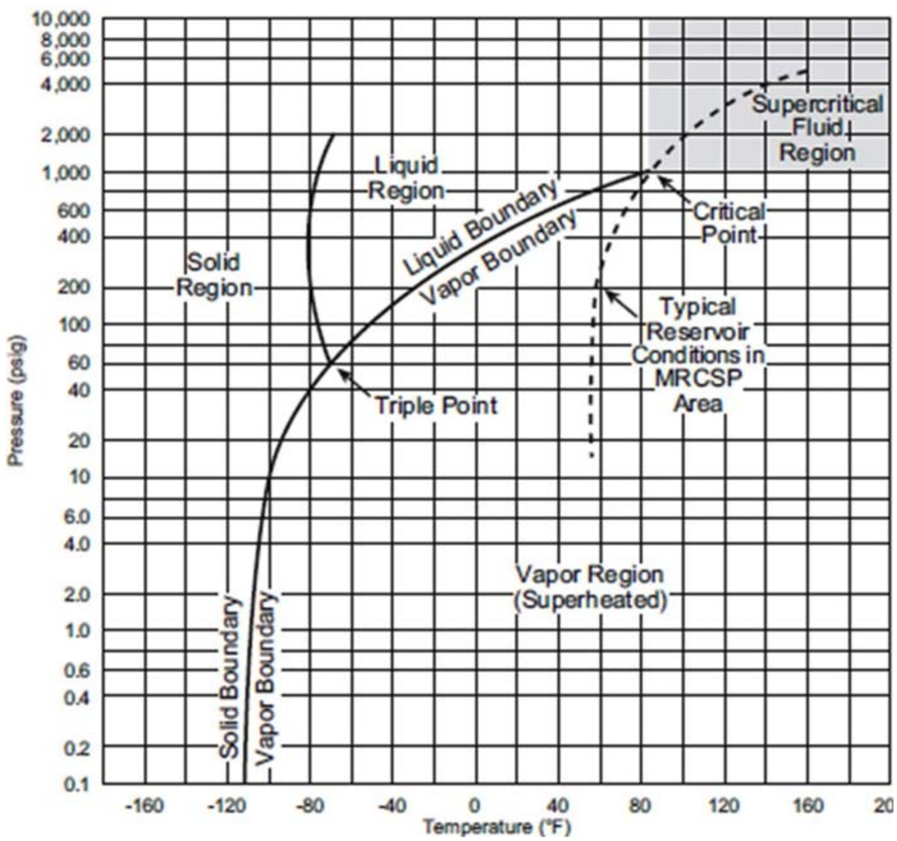

Figure 1.2-3. The four phases of carbon dioxide.[F1]

Using representative parameters for the Commonwealth – a geothermal gradient of 0.01º F/ ft (0.0182º C/ m), a surface temperature of 56º F (13.33º C), and a pressure gradient of 0.433 psi/ft (0.0098 MPa/m) – a line representing the typical pressures and temperatures occurring with depth can be superimposed on the phase diagram in Figure 1.2-3. This line shows that at shallow depths [less than ~2,500 ft (762 m)], CO_2 would be stored in a gas phase, while at greater depths [>2,500 ft (762 m)], most CO_2 will be in the supercritical phase, with only some storage as a liquid. The recognition of the supercritical phase is important because under most geologic storage scenarios evaluated herein, CO_2 storage will occur as a supercritical gas.[30]

One of the most important properties for the sequestration of CO_2 is density. At standard temperature and pressure, the density of CO_2 is only 0.1124 pounds per cubic ft (lb/ft^3) [1.8 kilograms per cubic meter (kg/m^3)]; conversely, the density at the critical point is 29.09 lb/ft^3 (466 kg/m^3) (Figure 1.2-4), an increase of about 260 times. For instance, at low pressures (similar to shallow reservoir conditions), CO_2 density is low, so the volume of a given amount of CO_2 will be large. This means that at low pressure, temperature, and density conditions, only small amounts of CO_2 can be stored in a given space. With increasing depths, the density of the CO_2 rapidly increases as it changes phases – first to a liquid, then to a supercritical gas. Moreover, at very high pressure and temperature conditions (such as those found in very deep geologic layers), the density of CO_2 may be as great as 62.43 lb/ft^3 (1000 kg/m^3), so the amount of CO_2 that can be stored in the liquid or supercritical gas phases will be several hundred times larger than what can be stored in the gaseous phase.

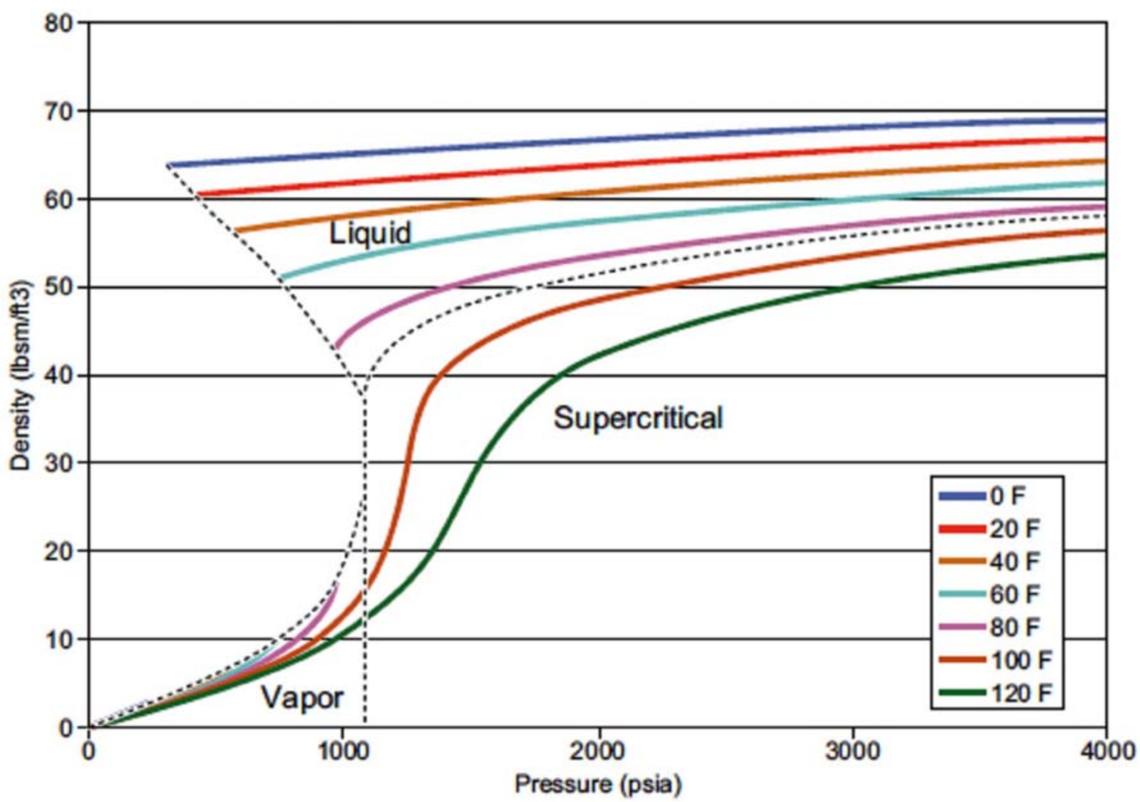

Figure 1.2-4. CO_2 diagram of different temperature curves plotted versus pressure and density.[F2]

Figure 1.2-5 illustrates how the density of CO_2 (using the temperature and pressure parameters, pressure gradient, and surface temperature values previously mentioned, and an assumption of a fresh-water pressure gradient) increases with depth for the Pennsylvania region. Therefore, this high density at depth provides a much larger storage capacity than the gas-phase storage, and is the primary reason that 2,500 ft (762 m) is considered the approximate, minimum depth for CO_2 storage in geologic layers.[31]

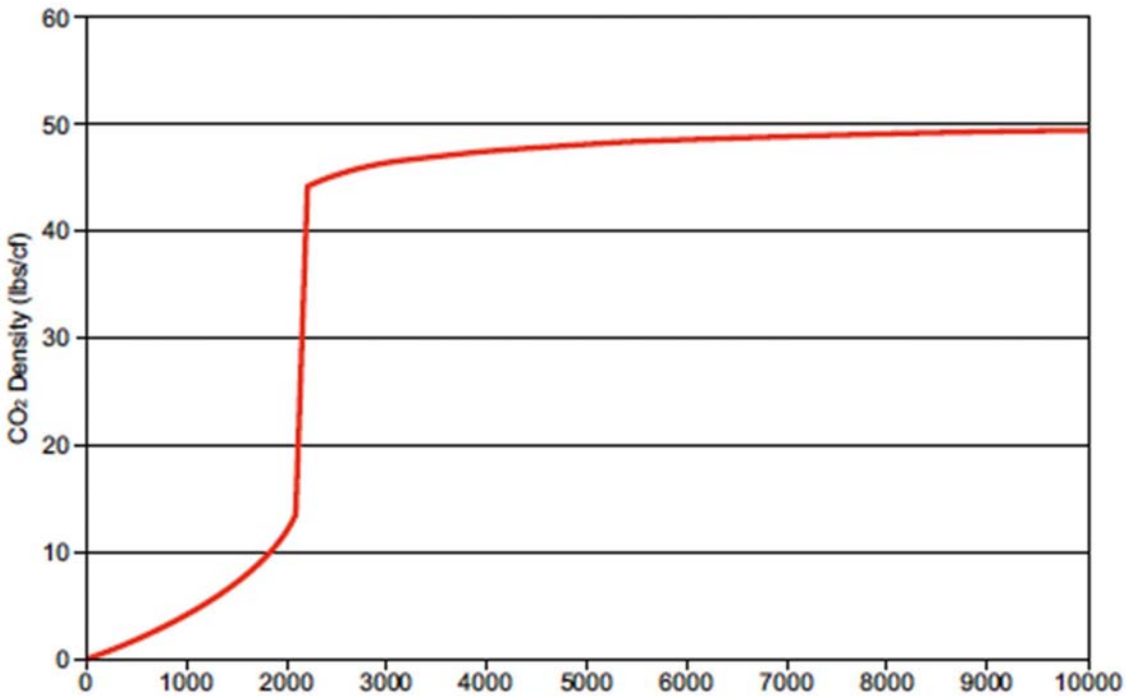

Figure 1.2-5. Plot of CO_2 density versus depth.[F3]

A primary reason why the petroleum industry is interested in injecting CO_2 is because its physical properties are amenable to EOR. In such cases, the CO_2 is injected as either a liquid or supercritical gas. In these instances, the density and viscosity of the CO_2 make it ideal for EOR because its density is similar to that of oil, but its viscosity is lower, physical attributes that facilitate the flow of CO_2 through the reservoir rock.[32] In fact, the oil-and-gas industry has used CO_2 in conjunction with other materials like gelled water or foam in the hydraulic fracturing ("frac", pronounced "frack") process to enhance recovery of petroleum hydrocarbons since the 1960s.[33] Since the 1980s, the industry began to experiment with CO_2 as a standalone fracturing agent,[34] and more recent research has employed CO_2 to frac natural gas storage wells so to restore their deliverability.[35] In these instances, most of the CO_2 is produced back out of the reservoir, so the use of CO_2 as a frac agent should not be considered a means of geologically sequestering CO_2.[36]

In order to evaluate the storage of CO_2 in brine, as would be the case in a saline formation, it is important to examine the physical properties of CO_2 in solution. Figure 1.2-6 shows the increase in solubility of CO_2 in fresh water with decreasing temperature and increasing pressure.[37]

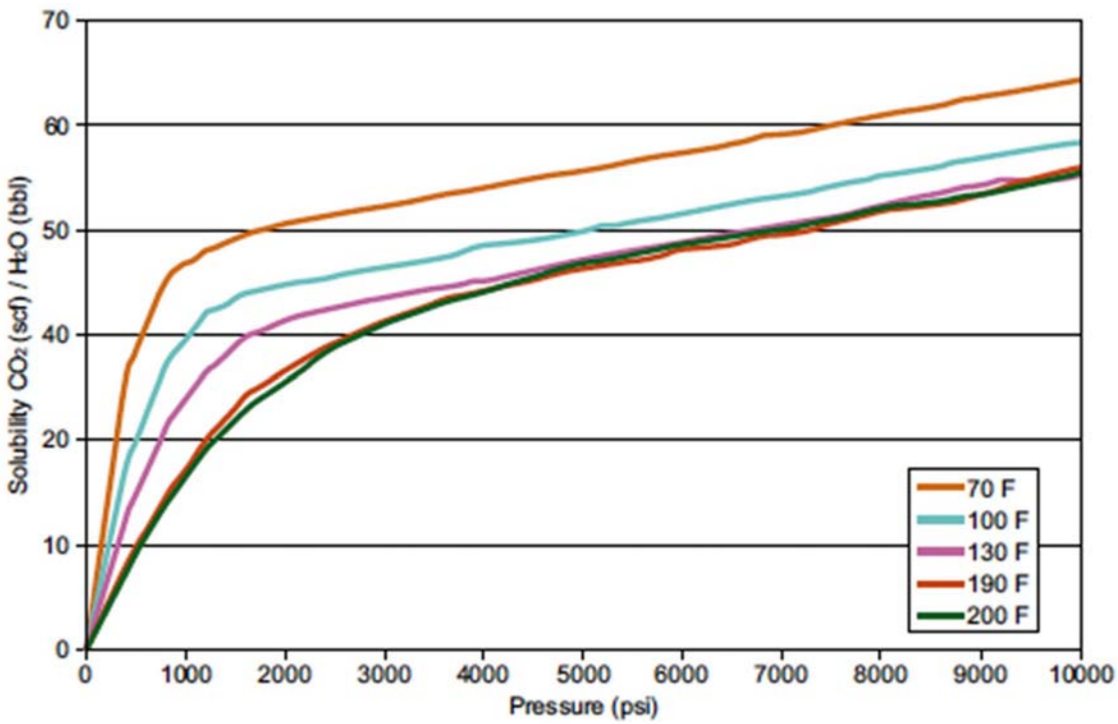

Figure 1.2-6. Plot of CO_2 solubility versus pressure at varying temperatures.[F4]

Conversely, CO_2 solubility decreases with increasing salinity (Figure 1.2-7).[38] Using salt (NaCl) as a proxy for overall brine compositions, Figure 1.2-7 illustrates a greater than 50-percent reduction in solubility as salinity increases to 200,000 ppm. Because high-salinity brine is likely to be present in most deep geologic storage reservoirs throughout Pennsylvania, solution storage will not provide a large fraction of the total storage capacity in the near future. Slowly, over time, the CO_2 may dissolve into the briny formation fluids. Ultimately, the rate of this dissolution and concurrent mineralization-based storage will be controlled by the total salinity, reaction rates, and the slow hydrodynamic flow in these layers that will inhibit mixing.

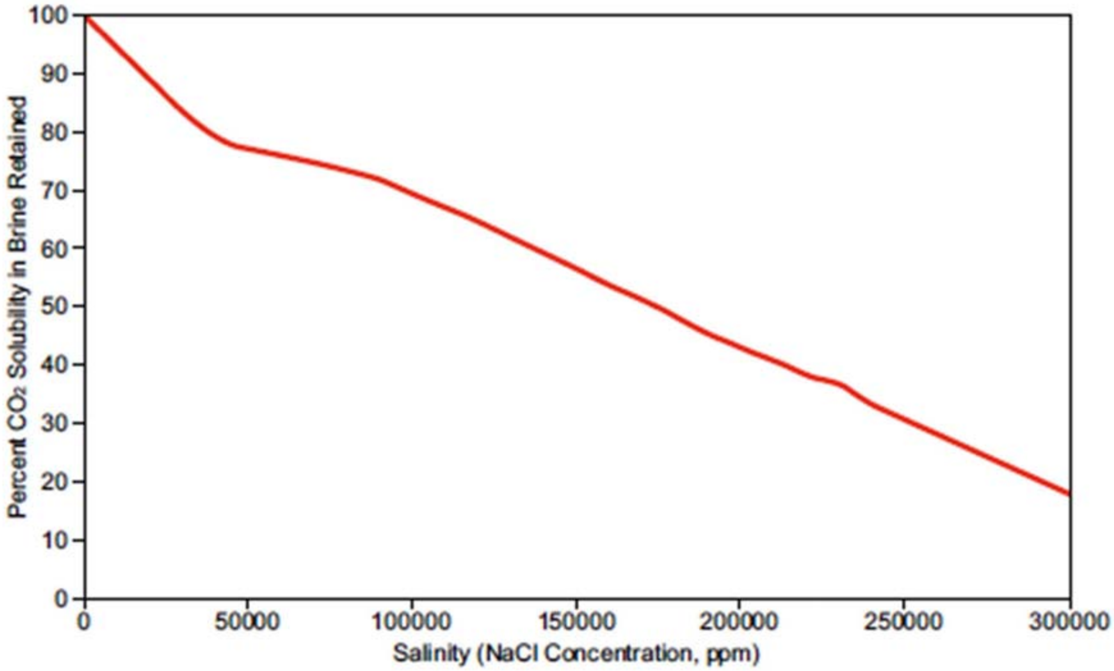

Figure 1.2-7. Plot of CO_2 solubility versus salinity.[F5]

1.2.4 Siting Requirements

The siting requirements for any geological sequestration project will ultimately depend upon the general area chosen for consideration. Choice of a sequestration site should take into account all issues related to subsurface geology, surface and subsurface ownership of oil, gas, and mineral rights, archaeological constraints, ecological constraints such as vulnerable and endangered species, and all environmental regulations. Most of these issues will be addressed in the earliest phases of planning by following the requirements set out by state and federal regulations.

A sequestration site should be chosen to provide either the maximum sequestration potential or the maximum enhanced hydrocarbon recovery (with subsequent sequestration). In many places, but especially in western Pennsylvania, sequestration may be accomplished on the site of a CO_2-producing facility through the use of multiple geologic targets. In other cases, the CO_2 will have to be transported to a suitable site via pipeline. The ideal situation for a CO_2 producer is to contract with an oil-and-gas company to supply CO_2 for enhanced recovery in the oil-and-gas fields or CBM areas. Either the oil-and-gas company or a specialty pipeline company then would be responsible for constructing, maintaining, and monitoring the pipeline. The only responsibility for the producer should be maintaining a sufficient supply of CO_2 to meet demand.

Aside from removing anthropegenic CO_2 from emission streams and storing it underground, the principal focus of a geological sequestration project is to demonstrate that CO_2 injection, storage, measurement, and monitoring are safe and effective. Several objectives must be met in order to assure this: (1) evaluation of regional and local sequestration capacity and injectivity (that is, geology and reservoir characterization), which will vary among prospective target formations and locations; (2) resolution of any field implementation issues, such as permitting, above-ground/subsurface design, and transportation, particularly through pipeline infrastructure; (3) evaluation of the various measurement, monitoring, and verification protocol options in the area of interest; (4) assurance of public and environmental safety; and (5) public outreach, education, and local acceptance. We address each of these issues in greater detail in Sections 3.0 and 4.0 (Geologic Assessment), 5.0 (Next Steps), 6.0 (Risks), 7.0 (Measurement, Monitoring, and Verification), and 8.0 (Public Education, Outreach, and Acceptance).

1.2.5 CCS Regulation and Permitting

In conjunction with the preparation of this report, the Pennsylvania Department of Environmental Protection (DEP) engaged in a multi-agency, multi-bureau effort to discuss and identify Federal and State requirements pertaining to the development of a carbon sequestration network in Pennsylvania. The goal of this effort was to frame the regulatory and other issues surrounding carbon capture and sequestration development. DEP's analysis is presented in Appendix A.

1.2.6 Assessments, Pilot Projects, and At-Scale Projects

The assessment of a prospective geologic horizon to determine its suitability to receive and sequester CO_2 is not new. The requisite technology has been widely demonstrated, though not at a commercial scale, in the variety of contexts potentially applicable in Pennsylvania. One notable project – the Great Plains Synfuels Plant in North Dakota – has taken the CO_2 through all of the steps (capture, transport, and sequestration). Since 1999, this plant has captured CO_2 for transport over 200 mi (322 km) to Canada's Weyburn oilfield, enabling the production of over 130 million barrels (MMBO) of petroleum (a doubling of its rate of oil recovery) while so far sequestering over five million tons (4.5 million t) of CO_2.[39] Numerous facilities around the globe will also complete each step: SaskPower in Canada, ZeroGen in Australia, RWE Power in Germany, and E.ON in the United Kingdom (among others).[40] At least three commercial projects have demonstrated the feasibility of sequestering CO_2 emissions.[41] The Weyburn oilfield in Canada, Sleipner in the North Sea, and In Salah in Algeria have all been sequestering carbon (for different reasons) at similar rates of at least 3,000 tons (2,722 t) of CO_2 per day for a combined total of over 20 years.[42] The challenge in Pennsylvania is to synthesize the elements of commercialization from projects like these around the world.

What *is* new to the concept of geologic sequestration is the goal of long-term storage using cost-effective means. The type of assessment discussed herein is directed toward maximizing the injected volume for permanent disposal, which requires substantially different thinking in that both the sequestration reservoir and overlying strata that would act as a seal (cap rock) are significant parts of the system. We have developed a stepwise approach to assess the Commonwealth's potential geological sequestration reservoirs, and subsequently demonstrate the suitability of prospective reservoir rocks and confining cap rocks through the implementation of pilot and at-scale projects.

1.2.6.1 Assessment Approaches – East vs. West

There is a great disparity in not only the type and complexity of subsurface geology between eastern and western Pennsylvania but also in the amount and type of legacy data that exists for our assessment of prospective geologic horizons in these two areas. For western Pennsylvania, our work is greatly facilitated by the wealth of available oil-and-gas well data (in excess of 160,000 wells of record). As the exploration community became aware of the impact of geology on the search for hydrocarbons, data were collected on the nature of the producing horizons. Over the course of the twentieth century, new techniques were developed to evaluate the key characteristics of petroleum reservoirs, and the data were preserved in the archives of the exploration companies. By the middle of the twentieth century, the Commonwealth began to require the permitting and reporting of drilling and completion information relative to the petroleum industry's efforts, and even more recently, the Mineral Resources Section of DCNR's Bureau of Forestry has required that holes drilled on Forestry property be properly located, data logged, and reported to DCNR. Collectively, these data resources enhance our ability to perform desktop evaluations of prospective reservoirs.

In addition to having access to these institutional data, Pennsylvania has been an active participant in the U.S. DOE's MRCSP since 2003. The partnership is tasked with examining and mapping data for several potential targets within an eight-state region (Figure 1.0-1). As part of this partnership, DCNR has been able to examine and characterize several potential sequestration reservoirs in western Pennsylvania.

In contrast to western Pennsylvania, almost no deep subsurface geologic data exist for the remainder of the Commonwealth. To date, only 170 wells have been drilled in central and eastern Pennsylvania, and due to this paucity of data, CO_2 sequestration prospects in this area are unknown and require much effort to properly assess. To evaluate the potential for geological sequestration in central and eastern Pennsylvania, detailed mapping of suspected reservoirs is required. This necessitates examining existing geologic maps and performing exhaustive literature/file searches for all data pertaining to geology/engineering characteristics of surface rocks and known geological structures to determine if further consideration for sequestration is warranted. Data gathering and manipulation can be done remotely for those areas where the geology and engineering characteristics of the rocks are well known (where cores have been taken for highway, bridge, dam, and building construction, for quarrying or mining operations, or where the Survey has obtained shallow cores during the course of routinely mapping an area). A search of historical records and the application of modern geological concepts will be necessary where field mapping has not been done within the past 50 years.

Fortunately, this type of data review is already underway, and has benefited from many years of participation in the USGS StateMap program. The Survey's mapping efforts (combined with high-resolution orthophotography supplied by the DCNR's PAMAP program) have provided approximately 2,130 square miles (mi^2) [(5,517 square kilometers (km^2)] of bedrock mapping and approximately 2,840 mi^2 (7,356 km^2) of new surface geologic mapping coverage for central and eastern Pennsylvania. Further, the Survey has recently engaged in a seismic data collection effort, focusing on those areas where existing (although sparse) geologic information suggest sequestration reservoirs may exist in the subsurface. Once these reconnaissance-level evaluations are completed, more sophisticated seismic and other remote sensing data collection techniques may be employed, such as aeromagnetic and gravity surveys, corehole drilling, and geophysical logging.

1.2.6.2 Pilot Projects vs. At-Scale Projects

Pilot projects refer to those efforts to demonstrate the suitability of subsurface geologic horizons to accept and sequester CO_2 during a limited timeframe using a limited volume of CO_2. As no field tests have ever been attempted in this regard in Pennsylvania, we cannot offer a state-specific example of such a pilot study. Many pilot projects, however, have been completed or at least begun in several of U.S. DOE's regional sequestration partnerships. The long-term goal of these pilot studies is to allow cost-effective development of commercial-scale sequestration sites, where large volumes (one million or more metric tonnes annually) of CO_2 can be safely injected into one or more geologic sequestration reservoirs.

Carbon dioxide emissions from the electricity sector in Pennsylvania are about 130 million tons (118 million t) per year. A carbon dioxide sequestration network, at its inception, would seek to capture and store a significant fraction of that amount. An at-scale project could start implementation at perhaps 5 million tons (4.5 million t) in the first year, depending on the number of facilities connected to it and the capture technology used, and subsequently ramp up the rate of capture and sequestration from initial network participants in the years following to, for example, 25 million tons (22.7 million t) or more per year.

It is also critical, as pointed out by the Massachusetts Institute of Technology study, *The Future of Coal*, to demonstrate geological sequestration of CO_2 on a significant scale:

> …CO_2 capture and sequestration (CCS) is the critical enabling technology that would reduce CO_2 emissions significantly while also allowing coal to meet the world's pressing energy needs…What is needed is to demonstrate an integrated system of capture, transportation, and storage of CO_2, at scale… At present government and private sector programs to implement on a timely basis the required large-scale integrated demonstrations to confirm the suitability of carbon sequestration are completely inadequate…Government support will be needed for these demonstration projects as well as for the supporting R&D program.[43]

The concept of a state carbon sequestration network in the Commonwealth speaks precisely to this critical global technological need.

1.3 Regional Geography and Geology

1.3.1 Bedrock Geology of Pennsylvania

The majority of Pennsylvania is underlain by a thick sequence of sedimentary rocks deposited over approximately 300 million years, from the Cambrian Period to the Permian Period (Figure 1.3-1). The southeastern corner of the state is the exception, and will be discussed below. These rocks were formed from sediments that accumulated as shallow seas advanced and retreated across the continent several times. The sedimentary layers tend to be thicker to the east and south, decreasing in thickness toward the northwest. During the end of this period of deposition (Pennsylvanian and Permian Periods), most of Pennsylvania was covered by vast coastal swamps which accumulated great thicknesses of peat that subsequently became coal.

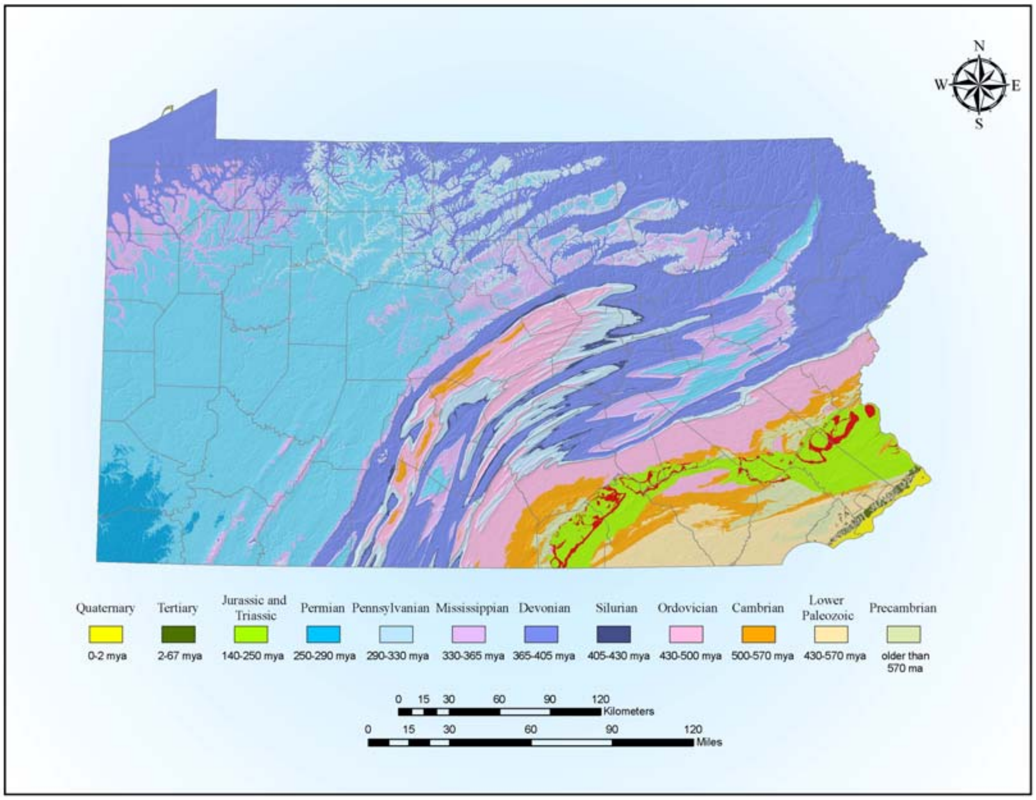

Figure 1.3-1. Geologic map of Pennsylvania.

Sedimentary layers are originally deposited as essentially horizontal sheets. If there had been no geological disturbances during or after deposition, we would see a uniform "layer-cake stratigraphy" across Pennsylvania, with the oldest rocks at the bottom and Permian rocks on the surface. These rocks were subjected to at least three episodes of compression and mountain-building, however, during the time of their deposition, and one episode of stretching after deposition as the Atlantic Ocean opened. This left the rocks folded and faulted to varying degrees, and brought different layers to the surface in different parts of the state. The rocks and geologic structures typical of the major geologic provinces of Pennsylvania are discussed below.

<u>1.3.1.1 Appalachian Plateau Geologic Province</u>

The Appalachian Plateau Province is an area of broad undulatory uplands, rounded hills, and narrow steep-sided valleys across western and northern Pennsylvania (Figure 1.3-2).

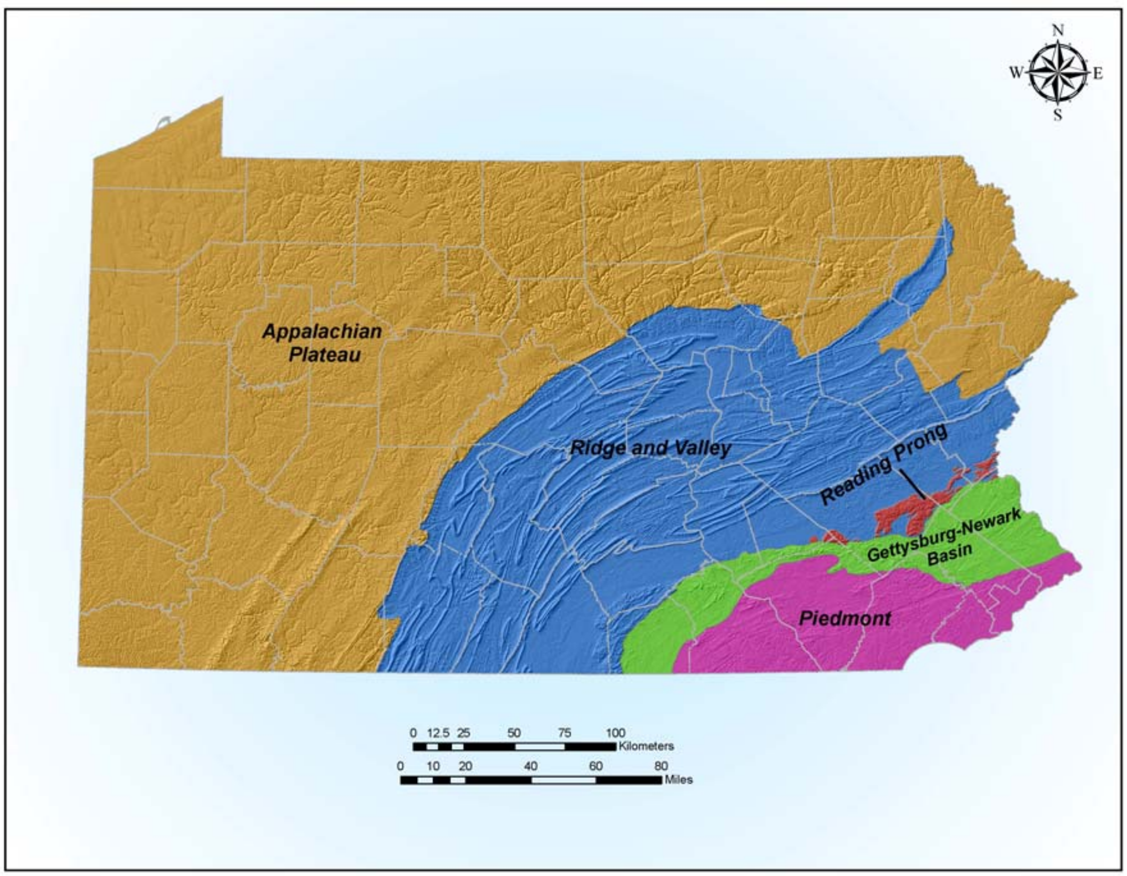

Figure 1.3-2. Geologic provinces of Pennsylvania.

The sedimentary bedrock underlying this region is about 5,000 ft (1,524 m) thick near

Lake Erie, and increases steadily to 25,000-30,000 ft (7,620-9,144 m) thick at the boundary with the Ridge and Valley Geologic Province to the south and east. The upper part of this sedimentary stack comprises repeating sequences of sandstone, shale, limestone, and coal. This section is about 3, 000 ft (914 m) thick in the main coal fields in western Pennsylvania and roughly 300 ft (91 m) thick in the smaller coal fields in the north-central part of the state. The sedimentary stack is absent in the eastern part of the Plateau, where Devonian-age rocks are exposed at the surface. Below the coal-bearing rocks are a variety of sandstone, shale, and limestone layers of various thicknesses. The rock layers beneath the Appalachian Plateau are relatively flat-lying with only broad, gentle folds. There are some faults several thousand feet below the surface; however, these only locally disturb the rocks at depth.

1.3.1.2 Ridge and Valley Geologic Province

This region forms a curving band through the central part of Pennsylvania from the Maryland border to the Delaware River. It is underlain by a variety of sandstone, shale, and limestone layers reaching a total thickness of 35,000 ft (10,668 m) or more. The sedimentary bedrock is complexly folded and faulted. The long, sinuous ridges that characterize the topography of this region are held up by resistant sandstone layers that trace the complex outlines of the folds. The ridges are separated by broad valleys underlain by limestone. The same Cambrian to Devonian-age layers that are buried thousands of feet deep under the Plateau are exposed at the surface in the Ridge and Valley. The coal-bearing rocks have been removed by erosion from most of this area. They are preserved only in two broad downfolds – the Broad Top Basin in Bedford, Fulton, and Huntingdon Counties, and the anthracite basin in Dauphin through Lackawanna Counties. As this region was squeezed from the southeast during mountain-building events, rock layers deep in the stratigraphic section broke along faults, which carried stacks of rock toward the northwest and placed them above adjacent stacks of the same rock layers. Consequently, the older rock layers that were originally deep in the section are repeated vertically several times, creating great thicknesses of sedimentary rock even though the upper parts of the section have been removed.

1.3.1.3 Reading Prong

This small geologic province in eastern Pennsylvania consists of a series of fault slices of metamorphic rock that is primarily granite-like in composition, probably several thousand feet thick. Although they are older than the sedimentary rocks of the Ridge and

Valley Province, these rocks have been raised up and moved along thrust faults so that they now lie on top of the sedimentary rocks.

<u>1.3.1.4 Gettysburg-Newark Basin</u>

This province is a relatively narrow band that extends from Adams County in the southwest to Bucks County in the northeast. It is an asymmetric basin with its deepest part [about 15,000 ft (4,572 m)] towards the north side. The basin formed as the continent of Africa pulled away from North America, stretching the Earth's crust and causing a series of blocks to drop along large faults. River systems developed in the lowlands formed by the downdropped blocks. Sediments from these rivers and lakes filled the basin, and became the sandstones, shales, and conglomerates that we find in the area today. Dikes (cutting across the sedimentary layers) and sills (parallel to the sedimentary layers) of diabase are irregularly interspersed with the sedimentary rocks. Diabase is an igneous rock similar to the basalt that is erupted out of volcanoes like those in Hawaii today. The dikes may only be a few feet across, but the sills are up to 2,000 ft (610 m) thick. All the rocks in this basin are of Jurassic and Triassic age (much younger than the other sedimentary rocks in Pennsylvania). There were probably volcanoes in Pennsylvania in the Jurassic, but they have been eroded away and the rocks that cooled underground are all we see now.

<u>1.3.1.5 Piedmont Geologic Province</u>

The Piedmont occupies the southeastern corner of Pennsylvania. This subdued landscape of rolling hills and shallow valleys is underlain by a variety of metamorphic rocks – schist, gneiss, quartzite, marble, and serpentinite. These rocks are complexly folded and faulted. The distribution of rock types has been mapped at the surface. Little subsurface exploration has been done in this province, however, and geologic structures are poorly understood at depths beyond about 1,000 ft (305 m).

1.3.2 The Appalachian Basin

The northern Appalachian Basin is an elongate, asymmetric sedimentary basin extending through parts of Kentucky, Ohio, West Virginia, western Maryland, Pennsylvania, and New York. In Pennsylvania, the Plateau and Ridge and Valley geologic provinces are part of the Appalachian Basin. The western margin of the basin is in east-central Kentucky and central Ohio. The axis, or deepest part, of the basin is closer to the eastern side than to the western side. The fossil fuel industry generally uses the name in a more restricted sense to indicate those areas where coal-bearing rocks are at or close to the surface.

Although it is no longer a topographic basin, the area was a lowland throughout the Paleozoic Era, when it received sediments shed from mountainous areas that lay to the east and south, and to a lesser extent from continental areas to the northwest. The deepest part of the basin is in central Pennsylvania, where the Precambrian-aged continental basement is overlain by more than 45,000 ft (13,716 m) of sedimentary rock. Sedimentary rocks in the Appalachian Basin range from Neoproterozoic to Permian in age.

1.3.3 Selection of Mapped Units and Limitations

The selection of units mapped for this study was based on several factors and data sources, most notably DCNR's ongoing work with the MRCSP, the availability of subsurface geologic data from Survey files and publications, and oil-and-gas well geologic and production data in DCNR's Wells Information System (WIS) database. Accordingly, the Survey consulted oil-and-gas-well data files, previously completed geologic maps, published and unpublished Survey studies, and other miscellaneous data (such as core and sample records, previous seismic interpretations, and geochemical analyses) to conduct this work.

Using these data, four potential sequestration reservoirs (Figure 1.3-3) were chosen for regional mapping and further analysis. It should be noted, however, that these reservoirs are by no means all-inclusive for the state. In fact, additional prospective reservoirs have been identified through our work with the MRCSP and are currently being evaluated as part of that ongoing research effort. Further, many assumptions had to be made when mapping these potential reservoirs at a such a regional scale (for example, how to interpolate subsurface geologic data between well points, especially when data were sparse, and to what level of detail to represent faulting in certain areas, particularly near the Allegheny Front). For these reasons, the findings reported herein constitute a *first* analysis of those potential sequestration reservoirs having sufficient data to complete a desktop study for sequestration potential. Over time, additional subsurface geologic data and refinements in our understanding of geologic sequestration technologies will allow the Survey to improve and enhance our understanding of the viability of prospective sequestration reservoirs in the Commonwealth.

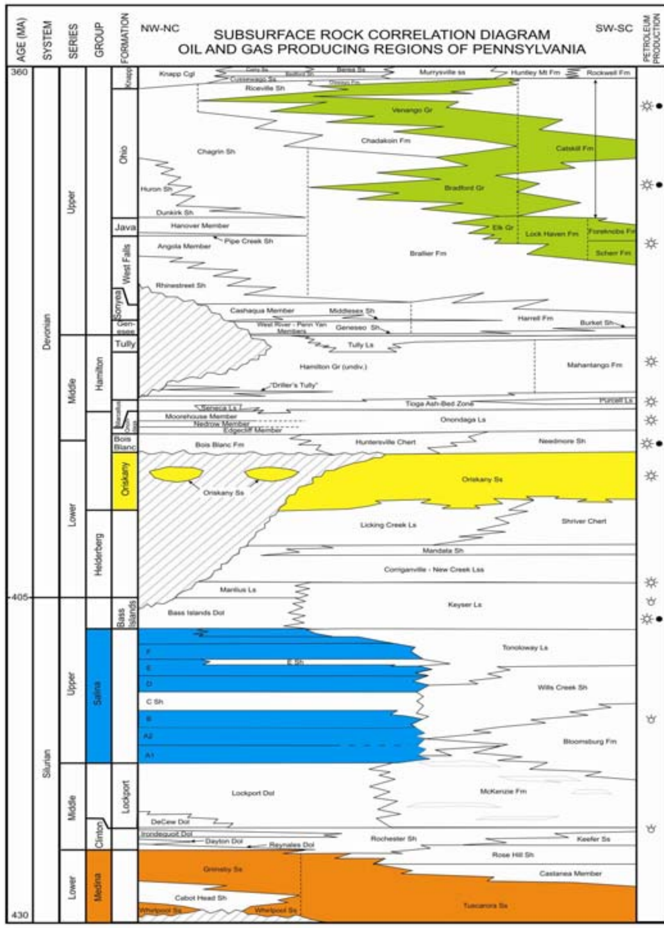

Figure 1.3-3. Subsurface rock correlation diagram for western Pennsylvania, indicating potential subsurface sequestration reservoirs (Upper Devonian sandstone reservoirs in green, Oriskany Sandstone in yellow, Salina Group in blue, and Medina Group in orange.

2.0 METHODS

The central products of this geologic report include a series of digital geologic maps and associated geodatabases, with the overall goal being to create a Geographic Information System (GIS) database to support planning for the Commonwealth's statewide carbon sequestration network. The following sections detail our mapping and database approaches in further detail.

2.1 Digital Geologic Mapping

The primary goal of our mapping effort was to interpret and assimilate all available and relevant geologic information into a digital format. The use of such a digital format allows for map publication and display as well as detailed analysis of geologic information related to potential sequestration units. Existing statewide digital maps of surficial geology (Figure 1.3-1) and major oil-and-gas fields (Figure 1.2-2) provide a backdrop for digital subsurface geologic maps expressly prepared for the current project. These new maps include the structural elevation (depth) and isopach (thickness) of the the Lower Silurian Medina Group/Tuscarora Sandstone, the Upper Silurian Salina Group, and the Lower Devonian Oriskany Sandstone; and a thickness and distribution map for several Upper Devonian sandstone reservoirs.

Structure and isopach maps were generated using elevations and of geologic formation tops identified in oil-and-gas-well records of DCNR's WIS database, supported by geologic mapping and outcrop data from other Survey sources as needed. Point data from these sources were converted to contour maps using a combination of PETRA and ArcGIS software packages, along with manual interpretations and editing, as necessary.

Manual manipulation of contour lines was required to create geologic maps that conformed to both the data and geologic knowledge. Specifically, editing of digital isolines was conducted to remove edge effects, repair errors caused by data scarcity, and rectify matching errors with pre-existing maps. Line editing was generally accomplished digitally using ArcEdit (an ArcGIS product). The bulk of the editing was done to fill in data gaps and to rectify contour lines to match surface and subcrop lines.

All GIS data generated as part of this mapping effort has been archived in several ArcGIS geodatabases. For each geologic sequestration reservoir, structure and isopach contour and grid data, geologic-unit crop lines, and fault locations have been stored. The point data we used in the mapping process have been stored as a database containing all formation tops with a listing of basic well-header data (well operator, location, producing formation, well status, etc.).

2.2 Carbon Sequestration Network Database

In order to create a state CO_2 sequestration network in accordance with Act 129, it is necessary to evaluate each potential sequestration site based on a set of standard criteria.

As interest from potential industry partners grows, managing and evaluating site-specific data could become a daunting task, but by using a systematic approach for data organization, we can efficiently evaluate and rank potential sites. The most logical system for tracking and evaluating potential sites in the Commonwealth is to create an electronic database that is linked to a statewide GIS. This Carbon Sequestration Network (CSN) database will allow us to merge necessary logistical information such as surface and subsurface ownership about a prospective site with technical information about underlying potential sequestration reservoirs in the same area. Accordingly, the Survey proposes that the CSN database consist of two parts: (1) a digital database; and (2) the Survey's statewide GIS of sequestration-relevant data. Datasets and GIS layers can be used together to perform initial analyses of sites based on geographic location and basic geologic information. The ultimate product will be a series of maps and data that support the decision whether or not to proceed with a proposed site.

All database tables will be populated using customized forms created using the database software package. We have identified six initial forms that will be used to collect and organize the information in this database: (1) potential site identification information; (2) surface and subsurface control; (3) infrastructure; (4) environmental considerations; (5) existing data; and (6) geologic information. The information to be included for each potential site is summarized below. Example database tables are included in Appendix B.

2.2.1 Potential Site Information

When a potential partner (owner, subsurface rights owner, etc.) initially expresses interest in collaborating with DCNR on our sequestration effort, we will assign them a unique site identification number and enter them into the CSN database. Following initial contact the following fields will be populated: (1) contact information; (2) facility name, type, and status; and (3) acreage availability. The unique site identification number assigned to each potential site will link that site identification table to all other tables in the database.

2.2.2 Surface and Subsurface Control

In Pennsylvania, surface owners do not necessarily own the mineral, oil, or gas rights underlying their property. Such severed ownership can pose significant issues during site selection. If a potential site owner does not control their subsurface rights, then it follows that they do not own the pore space necessary for sequestering CO_2. In the subsurface control section of the database, we will track what (if any) portion of the subsurface rights are held by the surface owner and how much subsurface acreage is available for sequestration.

2.2.3 Infrastructure

The geographic location and available infrastructure must also be considered for each potential site. The information used to populate the fields in this form relates to proximity of a site to a pipeline network, a potential CO_2 source (if not onsite), and amount of CO_2 generated by the source. This is also where the site will be classified according to population and land use using a ranking system. The most populated or urban areas will receive the lowest numeric ranking (1), and rural areas will receive the highest ranking (5).

2.2.4 Environmental Considerations

Although specific environmental concerns will certainly need to be addressed during the risk assessment phase of any CO_2 sequestration project, some initial environmental considerations can be noted even prior to site selection. The proximity to any environmentally sensitive areas will be determined, and potable groundwater sources will be identified and mapped, with assistance from the GIS component of the CSN database. Potential geologic hazards including, but not limited to, sinkholes, existing oil-and-gas wells, mines, and gas-storage fields will be mapped, as appropriate. In addition, the GIS component of the CSN database will be constructed to support the development of appropriate buffer zones between sequestration sites and areas deemed as environmentally sensitive.

2.2.5 Existing Data

The collection of subsurface data can be cost-prohibitive, so identification of existing data that can be used to characterize potential sequestration reservoirs will be a very important component of the CSN database. Existing core samples and thin sections can be used to assess rock properties such as porosity and permeability; these will be inventoried in the GIS component of the database. DCNR's WIS database provides a wealth of information for existing wells in Pennsylvania, including depth and thickness of geologic formations, production data, and geophysical logs. The number of available wells from WIS will be tracked in the GIS database component. The database will also identify the source of existing datasets (Survey, educational institutions, industry partners, or the like) and determine if the potential partner can contribute geological information that will be useful in performing site-specific evaluations. Previously published geologic reports relating to the geology of the site will be inventoried and referenced, and converted to digital format if needed.

Existing digital datasets will also be very important for creating geologic maps of potential sequestration units. Creating digital data sets is time-consuming, and acquiring existing datasets can be expensive. Existing Survey digital data sets include PAMAP imagery, Light Detection and Ranging (LiDAR) data, and other GIS data. The GIS component of the CSN database will be used to track the existence and availability of digital or analog data that relates to prospective sites. In addition, we will include a numeric ranking system to assess the reliability of the data based on the source and collection date. Acquiring reliable existing digital data sets will expedite the characterization of any site for potential injection of CO_2.

2.2.6 Geologic Information

The most important and most extensive part of the database component of the CSN database will be the form for tracking geologic information. Much of the information will be closely related to the existing data section of the database. The geologic information section identifies the target of interest and determines the likelihood of this unit to successfully sequester adequate volumes of CO_2. After identifying the potential reservoir(s) underlying a site, we will enter basic descriptive information about the unit including lithology, depth, and thickness. The vertical and lateral extent of the unit, the structural setting, and the overlying and underlying geologic seals are also important factors that will be considered and included by querying the GIS component. Much of this initial geologic information will be general, but when available specific data such as porosity and permeability values are available, they will also be included.

The description of database fields, forms, and tables described above have been compiled based on the Survey’s experience with oil and gas geology, as well as our CMAG and MRCSP research experience. In the future, the CSN database will evolve based on what we learn from any site-specific studies performed at project sites in the Commonwealth. The digital data involved in current and future studies are dynamic, and will be updated as new and more relevant information becomes available.

3.0 GEOLOGIC ASSESSMENT OF POTENTIAL RESERVOIRS

In order to assess the statewide geological potential for sequestration it is necessary to gather as much data as possible on the potential sinks within the area. In the broadest sense, the Survey has already done this for western and north-central Pennsylvania as part of the MRCSP Phase I project,[44] and studies currently underway for Phase II are adding to our knowledge base on several of these potential sinks. There is still much room for refinement of the data, however, particularly since there are significant uncertainties in the storage potential of the sequestration reservoirs as estimated by this project. These uncertainties are due to physical differences (heterogeneities) inherent within every rock unit, and to the lack of data on most of the deeper geologic formations. In no way can either a limited number of CO_2 injection tests conducted in a regional area, or all of the oil-and-gas wells that have been drilled, completely eliminate these uncertainties. Instead, each potential site will have to be evaluated individually based on extensive geologic data collection and analysis. Such data, where combined with the data from various regional and local fluid injection programs (including waste disposal wells, standard-practice hydraulic fracturing of hydrocarbon reservoirs in oil-and-gas wells, and injection of gas in natural gas storage areas), can significantly enhance the confidence level in both the capacity and the security of any particular geological sink.

The first step in any geological assessment of a potential sequestration site is to acquire and evaluate all of the available data concerning the subsurface geology in the vicinity of the site. These data can include geological assessments of reservoir rocks, oil-and-gas records, geophysical logs, drill cuttings and cores, mud logs, drill-stem pressure tests, and fluid injection data, among others.

Following the initial assessment, the next step is to acquire, process, and analyze seismic reflection data, which will be critical in determining the structural framework (folds, faults, etc.) of the geologic strata that exist in the subsurface below a prospective project. This is especially important in areas of the Commonwealth that are situated outside the area studied by MRCSP (primarily central and eastern Pennsylvania). Seismic reflection data might also be useful for additional characterization of any potential injection reservoirs and confining intervals. It should be noted that, in order to be seen in a seismic survey image, any formations or features of interest must be adequately thick and/or extensive enough to be imaged from properly acquired and processed seismic reflection data. Numerous seismic surveys have already been run in many areas of Pennsylvania as part of regional oil-and-gas exploration programs. As such, it probably would be less expensive to purchase existing data than to run new seismic surveys, at least preliminarily. In order to best determine any geologic structures in the area, however, there should be at least two seismic surveys run approximately perpendicular to each other. The length of the survey lines will depend on the proposed depth of a sequestration well; each line should be at least five miles long, increasing in length as the proposed depth of the well is increased. The use of three-dimensional (3-D) seismic data will be essential in areas of complex subsurface folding and faulting.

Upon analysis of the seismic data, and assuming the seismic data do not indicate any potential problems with the target formations, the next step is to drill a well. All DEP regulations for drilling and completing an oil or gas well must be followed, including, for example, the setting/cementing of casing to protect mineable coal seams and potable groundwater zones. Carbon dioxide will remain in the supercritical phase only at depths greater than 2,500 ft (762 m), so any proposed well should be at least that deep. The exception to this is if the target formation is one or more deep unmineable coal seams. Rather than occupying pore space, as within a brine-saturated sandstone, CO_2 adsorbs onto the organic matrix of coal. Therefore, the miscibility concerns are not an issue and sequestration (with enhanced recovery of CBM) theoretically will occur at significantly shallower depths.

During drilling, any prospective injection intervals should be sampled for both interstitial fluids and fluid pressures. Once the well has been drilled, an extensive suite of modern geophysical logging tools should be should be run in the hole to determine the physical and chemical characteristics of the rocks. These would include gamma-ray, neutron, density, dual induction resistivity, photoelectric, sonic, dipmeter, and others (Appendix C). If possible, a good borehole imaging log, such as a formation microimager (FMI), would be useful in identifying fractures, bedding, and other features. The logs will also be critical in deciding which intervals to core, particularly in areas where the depths and configurations of the potential targets are not well known. Sidewall coring is less expensive and less disruptive to the drilling process than full-barrel coring, and has the added benefit of allowing the prospective intervals to be precisely identified on geophysical logs prior to coring.   Sidewall cores should be taken of all prospective injection intervals and sealing units for analysis. Tests should include, among other things, the determination of porosity and permeability (vertical and horizontal), injectivity, capillary pressure, and mineralogy of each unit. Only after these steps have been taken will there be sufficient data to determine if one or more geological formations at the site have the capability of accepting and storing CO_2 in large quantities.

Included below are regional assessments of what the Survey believes are the major geologic reservoirs with sequestration potential in Pennsylvania. It is entirely probable that these are not the only potential "sinks". At this time, however, there is not enough accurate information for assessments of geological formations deeper than the Medina Group/Tuscarora Sandstone in western and north-central Pennsylvania. In addition, the lack of non-proprietary seismic survey data and abundant drilling information in central and eastern Pennsylvania precludes the identification of any potential sinks or sites in those areas until extensive further research has been done.

3.1 Lower Silurian Medina Group/Tuscarora Sandstone

3.1.1 Lithostratigraphy

The Medina Group of northwestern Pennsylvania consists of three major stratigraphic units, in ascending order: (1) the Whirlpool Sandstone; (2) the Cabot Head Shale; and (3) the Grimsby Formation.[45] The Whirlpool Sandstone forms the basal unit of this lithostratigraphic interval, and throughout much of the basin, is composed of a white to light-gray to red, fine- to very fine-grained, moderately well-sorted quartzose sandstone with subangular to subrounded grains.[46] The Cabot Head Shale is a dark-green to black marine shale with thin quartzose siltstone and sandstone laminations that increase in number and, in places, thicken upward in the unit.[47] The sandstones of the Grimsby Formation are very fine to medium-grained monocrystalline quartzose rocks, with subangular to subrounded grains, variable sorting, and contain thin discontinuous silty shale interbeds. Cementing materials include secondary silica, evaporites, hematite, and carbonate minerals.[48]

In south-central and central Pennsylvania, the stratigraphic equivalent of the Medina Group is the Tuscarora Sandstone.[49] This unit is typified by alternating beds of massive orthoquartzite and thin shale. The Tuscarora is comprised of fine-grained to conglomeratic quartzose sandstone that is cemented with quartz and contains minor clay minerals. Increasing amounts of shale are present in the Tuscarora moving north and west from south-central Pennsylvania.[50]

3.1.2 Significant Earlier Studies on this Interval

Early studies of the Medina and equivalent units were performed in the 1960s through early 1980s.[51] A summary of these and related works is provided in McCormac and others.[52] With the advent of sequence stratigraphy as an important reservoir rock interpretation tool in the 1990s, several studies reevaluated Early Silurian-age rocks in the northern Appalachian Basin, including those of Castle, Hettinger, and Ryder.[53]

3.1.3 Nature of Lower and Upper Contacts

The nature of the contacts of the Medina Group with overlying and underlying units varies depending upon which stratigraphic approach is applied. The traditional lithostratigraphic view of Early Silurian-age rocks in the Appalachian Basin is consistent with a regionally unconformable upper contact between the Medina Group/Tuscarora Sandstone and a combination of conformable and unconformable lower contacts between this sequence and Upper Ordovician clastics.[54] In distal portions of the basin (northwestern Pennsylvania), the Medina Group is interpreted as overlying an unconformity that occurs on top of the Queenston Shale.[55] The origin of this unconformity is associated with a rise in sea level during Late Ordovician time. In the proximal portions of the basin (south-central and central Pennsylvania), however, the Medina Group grades into the Tuscarora Sandstone and traditional lithostratigraphy interpretations suggest a gradational contact exists between it and the Juniata Formation, the Queenston Shale's equivalent.[56]

As discussed above, current oil-and-gas exploration efforts often use sequence stratigraphy to interpret reservoir rock relationships. Using the stratigraphic framework developed by this process as a guide, the Medina Group/Tuscarora Sandstone is interpreted as unconformably overlying the Queenston Shale and Juniata Formation basin-wide.[57] Hettinger[58] identified the Cherokee unconformity as the sequence boundary between the Queenston Shale and overlying Medina Group; this boundary relationship between the Tuscarora and Juniata Formations is inferred in south-central Pennsylvania.

3.1.4 Discussion of Depth and Thickness Ranges

The Medina Group crops out in northern New York, and in central Pennsylvania, outcrops of the equivalent Tuscarora Sandstone are present. In the remainder of the

Appalachian Basin, the Medina and equivalent units only occur in the subsurface. The depth to this reservoir ranges from less than 1,000 to 6,700 ft (305 to 2,042 m), with wells located offshore in central Lake Erie reporting depths of over 2,200 ft (671 m).[59]

Figure 3.1-1 illustrates the regional structure of the Medina Group/Tuscarora Sandstone throughout Pennsylvania. Structure contours are given in subsea elevations using an interval of 500 ft (152 m). The structure on top of the Medina Group/Tuscarora strikes northeast-southwest and dips southeastward at approximately 40 to 70 ft per mile (8 to 13 m/km), with more shallowly dipping rock closer to the western and northern basin margins. The unit is deepest [9,000 ft (2,743 m) below sea level] in southwestern Pennsylvania. East of this point, toward the Allegheny Front, the Medina-equivalent (Tuscarora) dips steeply to the northwest at rates of 70 to about 180 ft per mile (13 to 34 m/km).

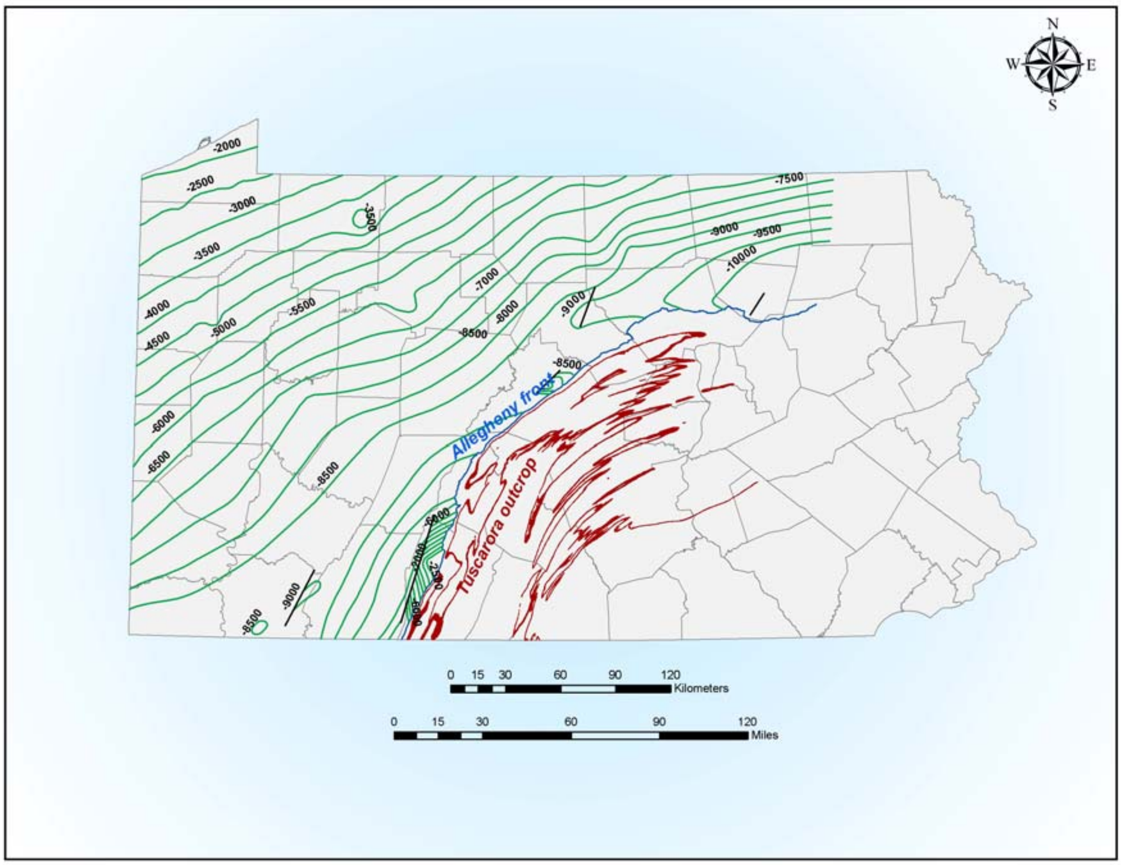

Figure 3.1-1. Structure contour map drawn on top of the Medina Group/Tuscarora Sandstone interval.

Figure 3.1-2 illustrates the thickness of the Medina Group/Tuscarora Sandstone in

Pennsylvania using 50-ft (15-m) contour intervals. The thickness of the reservoir ranges from 0 in the northwestern Pennsylvania to over 600 ft (183 m) in Fayette County, Pennsylvania. These thicknesses are generally consistent with those of other researchers.[60] The actual pay zones within the Medina/Tuscarora (where reservoir porosity and permeability are favorable) comprise only a portion of this overall thickness, however, and range from 3 to 50 ft (0.9 to 15 m) in thickness, with an average of 23 ft (7 m).[61]

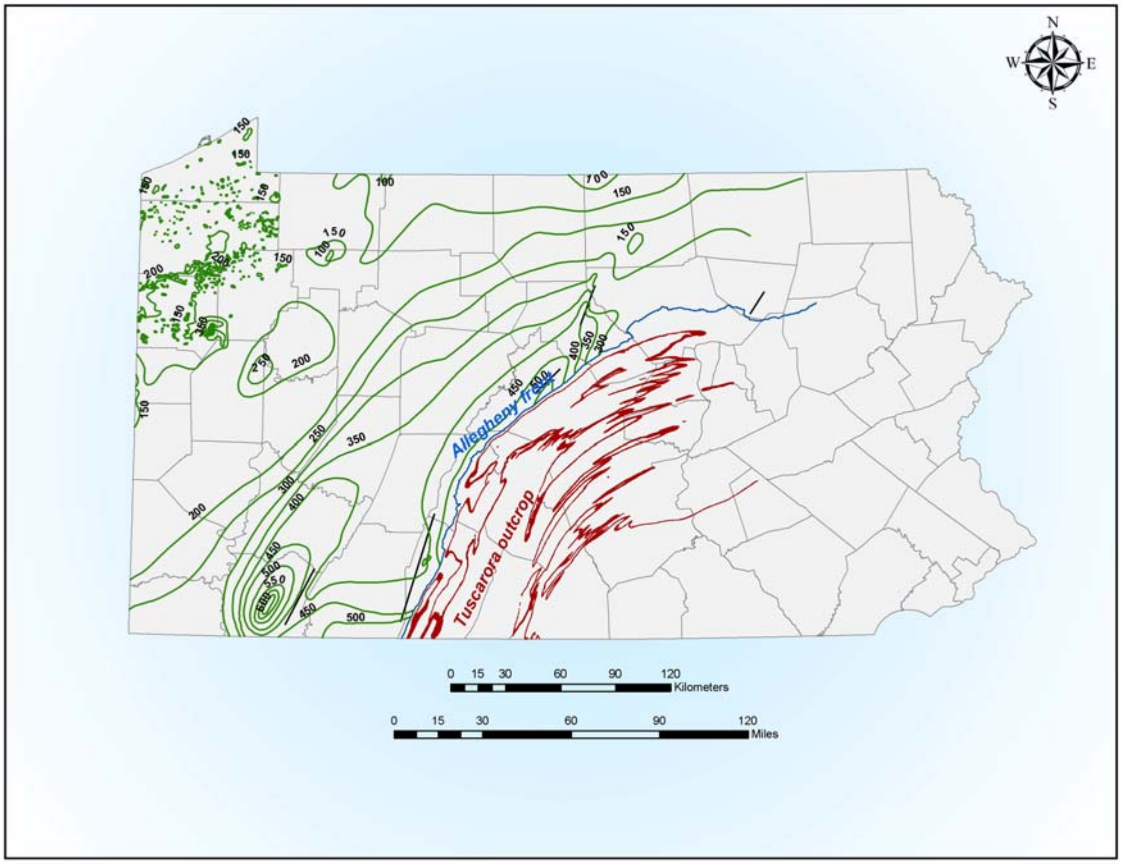

Figure 3.1-2. Map showing the gross thickness of the Medina Group/Tuscarora Sandstone interval.

3.1.5 Formative Processes

The depositional history of the Medina Group and equivalent Tuscarora Sandstone began near the end of the Taconic Orogeny in Early Silurian time. During this period, clastic material was being eroded from both foreland fold-belt highlands adjacent to the eastern edge of the Appalachian Basin and the plutonic igneous rocks of the island arc orogen.[62] The directions of sediment transport from these highlands were both parallel (northeast-southwest trending) and perpendicular (northwestward) to the shoreline,[63] which ran from what is now northern Beaver County to central Warren County.[64] The Medina depositional system represents a shelf/longshore-bar/tidal-flat/delta complex. The Whirlpool Sandstone is the basal transgressive unit of this system, and is overlain by shelf muds, transitional silty sands, and lower shoreface sands of the Cabot Head Shale. These sediments were in turn overlain by shoreface and nearshore sands of the lower Grimsby Formation, and later, argillaceous sands at the top of this unit.[65] Laughrey[66] divided the Medina Group's depositional system into five facies: (1) tidal flat, tidal creek, and lagoonal sediments; (2) braided fluvial-channel sediments; (3) littoral deposits, (4) offshore bars; and (5) sublittoral sheet sands. Facies 1, 2, and 3 sediments comprise the Grimsby Formation, which was deposited in a complex deltaic to shallow-marine environment. The deeper offshore-mud and sand-bar deposits of Facies 4 were reworked by both storm and tidal currents to become transitional sandstones of the Cabot Head Shale. The Whirlpool Sandstone is included in Facies 5, which formed in nearshore marine and fluvial, braided-river environments that existed at the beginning of a marine transgression.[67]

Sequence stratigraphic research performed by Castle[68] on Medina and equivalent cores and outcrops throughout the basin identified six different depositional facies for this rock sequence, including fluvial, estuarine, upper shoreface, lower shoreface, tidal channel, and tidal flat. Furthermore, Castle identified three types of sequences in these rocks, including a sequence with fining-upward deposits, and two sequences with coarsening-upward deposits representative of progradational and aggradational shorelines.[69]

3.1.6 Geologic Structure and Trapping Mechanisms

Throughout the Appalachian Basin, stratigraphic traps have been shown to control the occurrence of gas in the Medina Group – although in localized areas (Mercer County), gas production may be enhanced by geologic structure.[70] The overall heterogeneity of this reservoir is evidenced by the variety of mechanisms forming the stratigraphic traps; these include sandstone-facies pinchouts, porosity changes, gas-water contacts, and diagenesis.[71]

3.2 Upper Silurian Salina Group

The Salina Group is a thick sequence of Silurian rocks in the Appalachian and Michigan Basins that contains repetitive, often thickened beds of rock salt interbedded with dolostone, shale, and anhydrite. Figure 3.2-1 shows the approximate areal extent of the Salina Group in eastern North America.

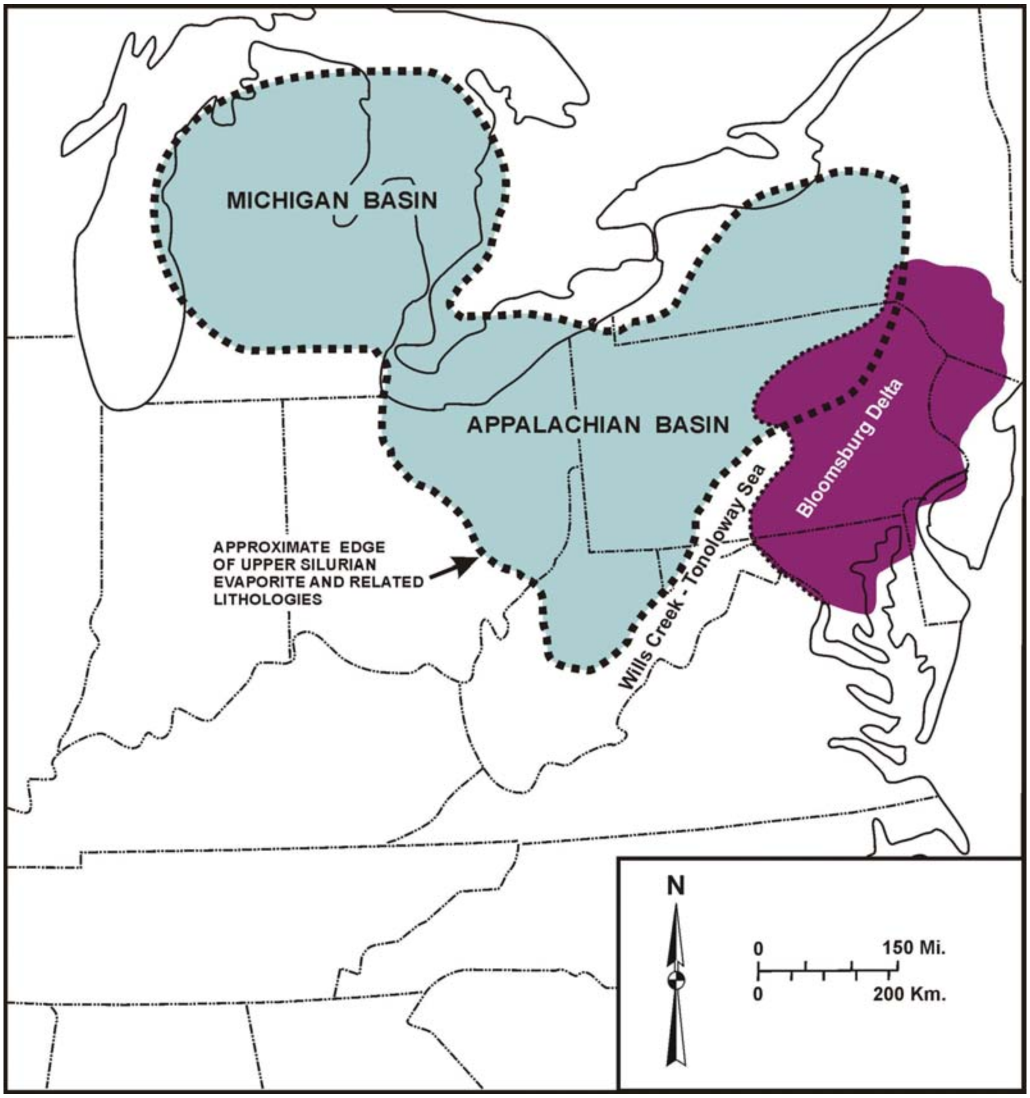

Figure 3.2-1. Location of the Salina salt basins in eastern North America.[F6]

Michigan, Ohio, New York, and West Virginia have been utilizing the extensive salt reserves of the Salina Group as a raw material source for the food and chemical industries for many years. This has not been the case in Pennsylvania, however, where the Salina Group salts generally have been too deep for commercial exploitation. Only recently have these salt beds been considered as anything but a problem in drilling for deep oil-and-gas reserves because bedded salt deforms readily under stress and can easily crush steel drill string and casing given the right conditions.

In the early 1990s, a group of oil-and-gas industry companies formed NE Hub Partners to study and utilize the thick salt beds in the subsurface of Tioga County, Pennsylvania for natural gas storage. The plan was to drill a well to the top of the bedded salt and to solution-mine the salt with fresh water piped in from a nearby source. Although the first well was drilled, the partnership failed before solution-mining could begin and plans for salt-cavern gas storage have been placed on hold for almost two decades.

This study suggests that thick Salina Group salt beds could be used for CO_2 storage in Pennsylvania by creating solution-mined caverns in the same manner as had been planned for gas storage, and has been feasibly demonstrated in many places around the world.[72] The filing submitted to DEP and U.S. EPA for the NE Hub Partners project has much data that would be useful for a preliminary evaluation of the salt as a target for CO_2 sequestration in solution-mined cavities.[73]

3.2.1 Lithostratigraphy

Classical studies of the Silurian rocks in the northeastern United States have principally involved the sediments at the margins of the depositional basins, such as in New York. Consequently, the stratigraphic nomenclature in these areas reflects the bias of the basin margin area, and that nomenclature often becomes stratigraphically meaningless when extended to rocks in the center of the basin, such as the Salina Group in Pennsylvania.

Previous workers divided the Salina Group in Pennsylvania into seven informal units designated by the letters A to G.[74] Unit A represents the basal unit and Unit G is the uppermost unit. Figure 3.2-2 shows the vertical and lateral relationships of the Salina Group and its correlative formations within the Silurian stratigraphic section in Pennsylvania and surrounding states. Figure 3.2-3 illustrates the distribution of salt within the Salina Group across northern Pennsylvania.

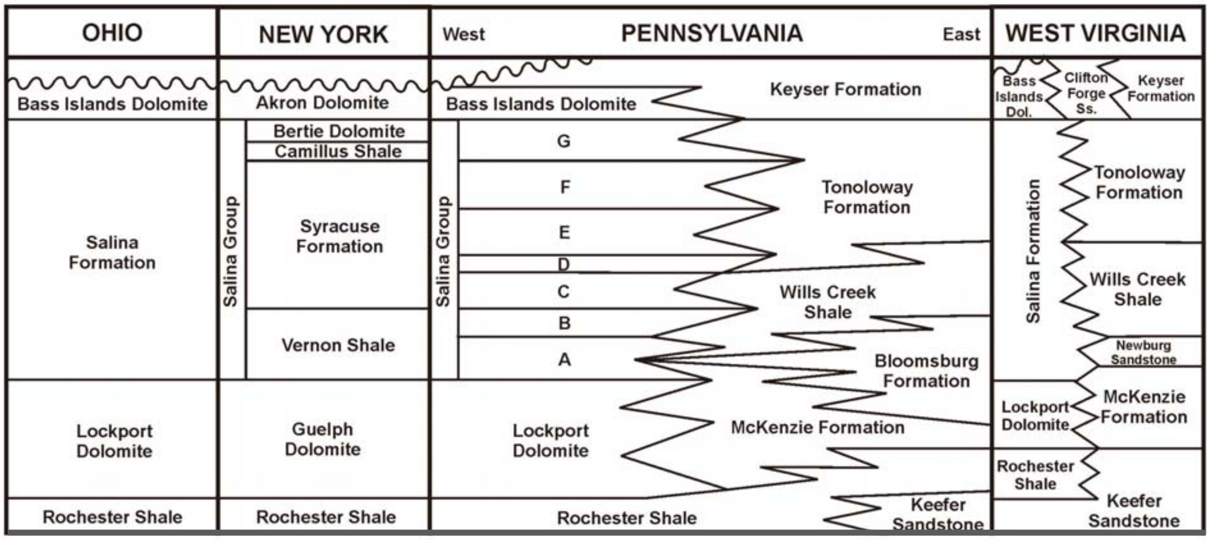

Figure 3.2-2. Stratigraphic relationships of the Salina Group in western and north-central Pennsylvania with equivalent Silurian-age rocks in the Appalachian Basin.

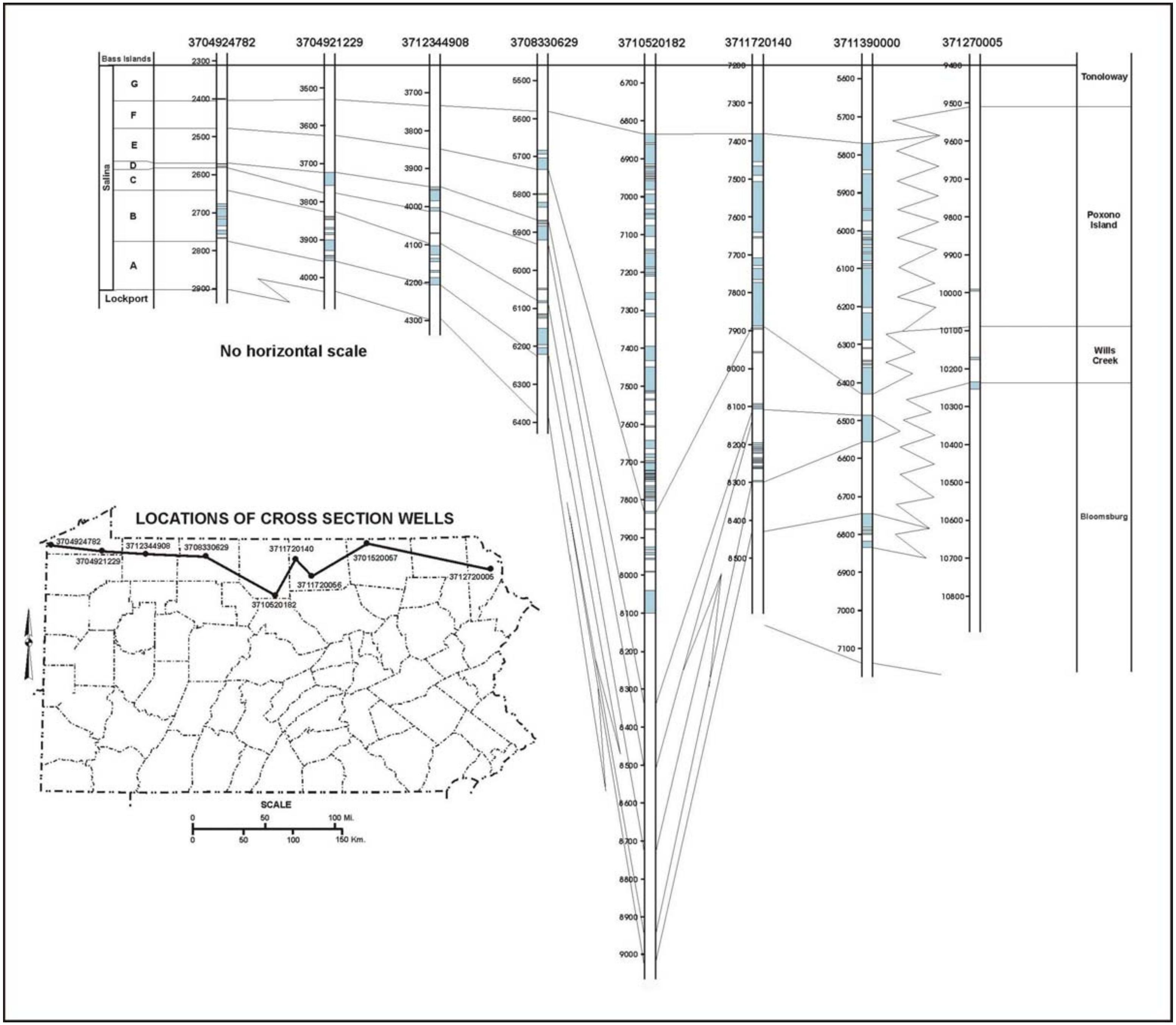

Figure 3.2-3. West-east cross section across northern Pennsylvania based on oil-and-gas well data showing rock sequences of the Salina Group and positions of the bedded salt.

The Salina Group consists of a sequence of shale, dolostone, anhydrite, and salt interbedded in almost rhythmic sequences.[75] Individual dolostone and shale beds typically are more continuous across the basin than are salt and anhydrite beds, even those that cover hundreds of square miles. Because there are seven individual units recognized in the Salina Group, each is described separately below.

Unit A consists of dolostone, anhydrite, and some light gray sandy shale in the upper part. It ranges in thickness from 50 ft (15.2 m) in the western part of Pennsylvania to over 500 ft (152 m) in Bradford County.

Unit B contains the first salt beds deposited in the Salina Group, but it does not contain salt in all areas across the extent of the group in Pennsylvania. The salt typically occurs in two beds separated by 10 to 50 ft (3.1 to 15.2 m) of shale, anhydrite, and dolostone. The salt beds are thin and form a sinuous ribbon-like pattern across northwestern Pennsylvania before connecting with the thicker basin deposits in the north-central area.[76] Unit B ranges in thickness from a little more than 100 ft (30 m) in Erie County to well over 700 ft (213 m) in Tioga County. It becomes thinner to the southwest, but increases in thickness to the east in Bedford and Somerset Counties where it grades into the Wills Creek Formation.

Unit C consists primarily (from 35 to 75 percent) of gray to green shale with some shaly dolostone and anhydrite, but in some areas the entire unit is composed of the shaly dolostone. Unit C contains a few thin salt beds in some wells, but by and large it is absent of salt. In northeastern Pennsylvania, Unit C contains more dolostone and less shale than it does to the west.

Unit D contains salt, often greater than 200 ft (61 m) thick in north-central Pennsylvania, but it can also consist only of dolostone and anhydrite. It is typically thinner in the southwest.

Unit E varies in composition, but the top is always marked by a sequence of shale that range from a few tens to almost 100 ft (30 m) thick. The remainder of the unit consists of interbedded dolostone, anhydrite, and sporadic salt. The salt beds typically are thin, rarely attaining thicknesses greater than 30 ft (9 m), but thick sequences are not unknown.

Unit F is the thickest Salina unit, ranging from 64 ft (20 m) in Erie County to more than 1,300 ft (396 m) in Fayette County. It consists of thick salt beds separated by beds of dolostone, shaly dolostone, and dolomitic shale. Six distinct salt-bearing sections occur within Unit F in the Michigan Basin, but typically only the lower two or three of these occur in Pennsylvania. The upper three salt beds of Michigan are represented by anhydrite, or are missing, in Pennsylvania.

Unit G consists of a lower, relatively thick shale sequence (the Camillus Shale of New York State) and an upper sequence of dolostone and anhydrite. The anhydrite beds occur at the top of the unit and mark the uppermost boundary of the Salina Group.

Salina dolostones typically are dense, finely crystalline, and dark brown in color as a result of mixing with dark brown mud during deposition. The rock contains solution cavities (vugs) filled with anhydrite and calcite. Anhydrites exist as finely disseminated sediment and vug fillings, as well as distinct beds. The salt also occurs in this fashion, although it most commonly forms nearly pure beds of coarsely crystalline halite.

3.2.2 Significant Earlier Studies on this Interval

The stratigraphic terminology used for the Salina Group in Pennsylvania follows that used in Michigan.[77] A later study established that the Michigan terminology could be used effectively in northeastern Ohio adjacent to the Pennsylvania border, and the terminology was subsequently brought into Pennsylvania.[78]

The term “Salina” as used in Pennsylvania is restricted to the subsurface, and implies that the unit includes bedded salt and/or considerable anhydrite.[79] Where no bedded salt occurs in the stratigraphic position of the Salina, the names Tonoloway (primarily limestone), Wills Creek (shale with some interbedded sandstone and limestone), and Bloomsburg (primarily red shale) formations (Figure 3.2-2) are applied to the rock sequence. These formations have type sections in Maryland and central Pennsylvania, but they are easily recognizable in the subsurface of western and north-central Pennsylvania in both well cuttings and geophysical logs. The Tonoloway and Wills Creek in central Pennsylvania commonly have isolated casts and molds of individual halite and gypsum crystals, indicating their relationship with the Salina rocks.

3.2.3 Nature of Lower and Upper Contacts

In general, where the Salina Group is best developed, the contact between the Salina and the overlying Bass Islands Dolomite is conformable. The top of Unit G of the Salina Group occurs at the first bedded anhydrite, or dolostone with sufficient anhydrite crystals in large matrix pores (vugs), encountered in the well bore. The upper contact of the Salina is also generally considered to be laterally correlative with the upper boundary of the Tonoloway Formation.

The contact between the Salina and the underlying Lockport Dolomite is gradational and harder to pick than the upper boundary. The Lockport and Unit A of the Salina both primarily comprise homogeneous dolostones, but Unit A typically has bedded anhydrites where the Lockport does not. Therefore, the boundary is placed at the base of the lowest bedded anhydrite,[80] which is often easily recognizable with the proper geophysical logs (density or photoelectric curves).

To the south and east, the Salina grades laterally into the Tonoloway, Wills Creek, and Bloomsburg formations (Figure 3.2-2). The transition from the Salina to these three formations is so gradual it is sometimes difficult to firmly establish proper stratigraphic names to the rock sequence encountered in the well bore. The transition takes place gradually over many miles. Dolostones and anhydrites of Unit A grade laterally into the red shales and siltstones of the Bloomsburg Formation, whereas the shales of Unit C thicken upward into the dolostones and bedded salt of Unit D and downward into the dolostones and bedded salt of Unit B. Where this occurs, the combined Unit B-C-D shale is called Wills Creek Formation. Units E, F, and G typically grade laterally from dolostone, shale, anhydrite, and bedded salt to limestone and/or dolostone. Where this occurs, the rocks constitute the Tonoloway Formation.

3.2.4 Discussion of Depth and Thickness Ranges

The top of the Salina Group in the Appalachian Basin ranges from 0 along the outcrop in New York and western Ohio to more than 9,000 ft (2,743 m) deep in the center of the depositional basin. In Pennsylvania, the top of the Salina ranges from about 1,400 ft (427 m) beneath along the shore of Lake Erie to more than 10,000 ft (3,048 m) below sea level in the vicinity of Muncy, Lycoming County.[81] The group as a whole ranges in thickness from about 300 ft (91 m) in Erie County to over 2,200 ft (671 m) in north-central Pennsylvania (Tioga and Bradford Counties) (Figure 3.2-4). In southwestern

Pennsylvania, it attains a gross thickness of more than 1,900 ft (579 m) in Fayette County.[82] The group thins dramatically to the east by way of lithologic change, from carbonates and evaporites to shales, near the Fayette/Somerset border and along regional strike to the northeast.

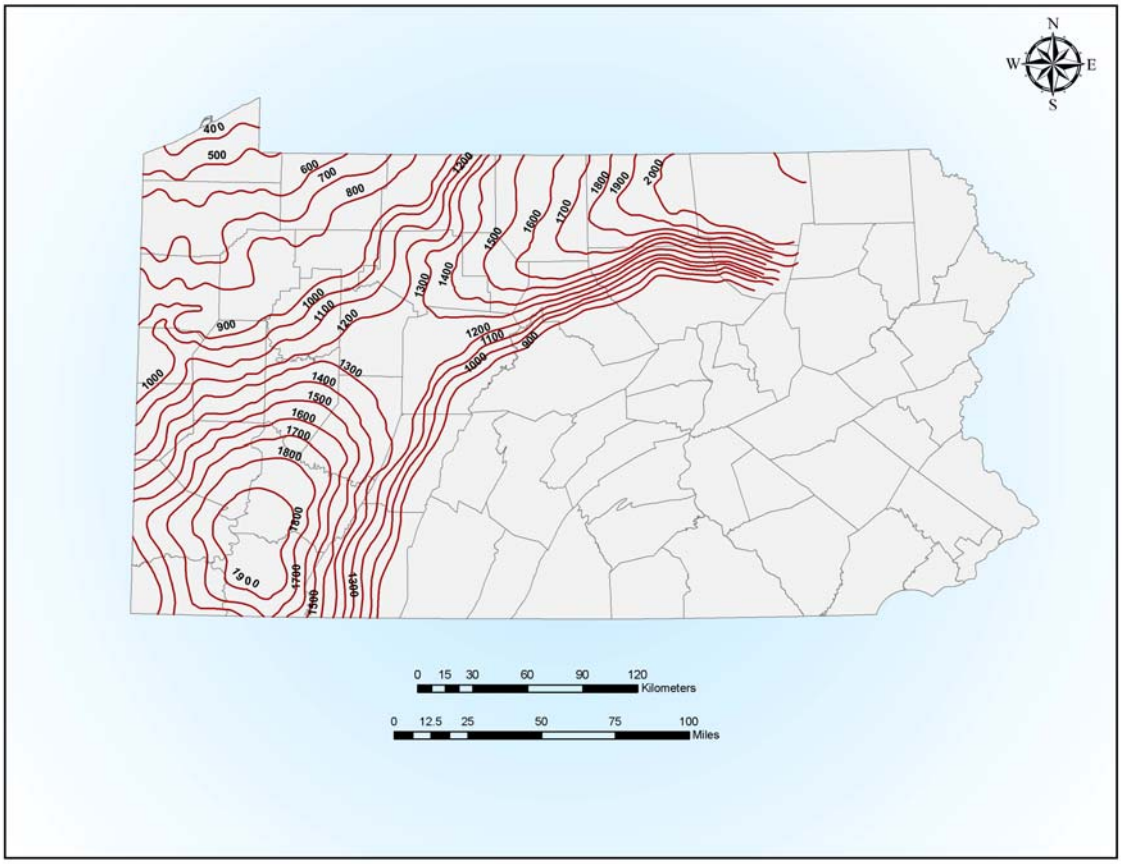

Figure 3.2-4. Gross isopach map of the Salina Group in Pennsylvania.[F7]

A preliminary evaluation of net salt thickness in the Salina Group illustrates net thicknesses from 0 to over 900 ft (274 m) through western and north-central Pennsylvania (Figure 3.2-5).[83]

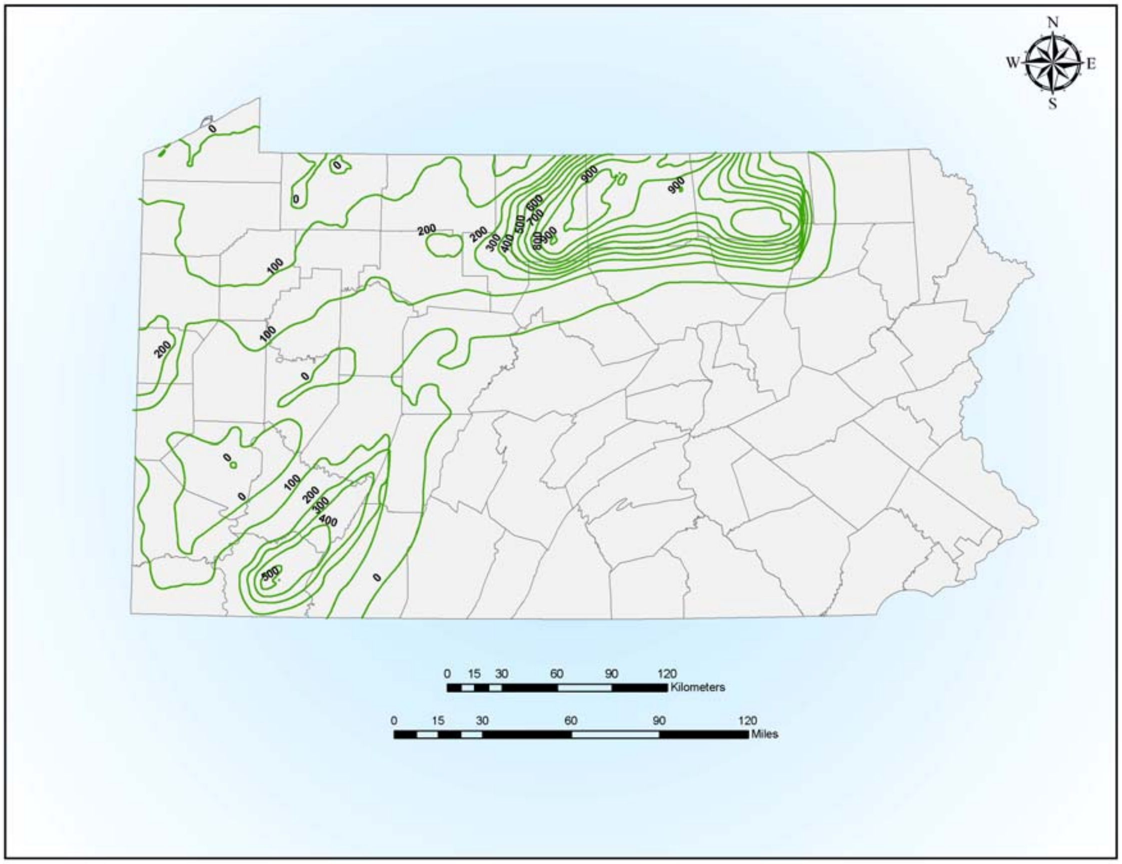

Figure 3.2-5. Net isopach map of the Salina Group in Pennsylvania.[F8]

3.2.5 Formative Processes

Most of the typical Salina rocks – the salt, anhydrite, and dolostone – are evaporites, that is, rocks formed from minerals precipitated out of evaporating sea water. Earlier researchers have suggested that reef development in the underlying Lockport Dolomite created shallow basins isolated from the main Appalachian inland sea.[84] Restricted circulation within these basins led to increasing salinity, and an increasingly dry climate led to evaporation and precipitation. Although this is probably valid for the Michigan Basin, later authors dispute this concept for the Appalachian Salina because there is no evidence of Lockport reef development in the areas postulated by the earlier authors.[85] It has been suggested that the Salina evaporites were deposited in a deep-water, barred basin, based on known rates of salt precipitation compared with the rates of deposition for the stratigraphic framework of the Salina as a whole.[86] Water depths during evaporation and precipitation have been concluded to have been on the order of 100 to 600 ft (30 to 183 m).[87] Another worker[88] suggested that a deep basin, separated from the open sea by a shallow sill or platform, and located in a warm, dry climate, would lead to evaporation and precipitation by the following process: (1) dense brines formed by evaporation of sea water sink to the bottom of the basin; (2) an influx of fresh sea water replaces the volume of water lost through evaporation; (3) a stagnant phase ensues; and (4) deposition of evaporites displaces the concentrated brine on the basin floor. This cycle continues until the basin is completely filled with evaporites, the climate changes, the influx of sea water to the basin changes, or the basin is filled in by sediment input or destroyed by tectonic activity.

There is much evidence for the deep basin concept, particularly given that the Salina basin appears to be coincident with the Rome Trough (see below). The huge wedge of mud, silt, and sand that poured into the Appalachian Basin from the Bloomsburg delta in eastern Pennsylvania restricted circulation to the east, while the basin was restricted on the north by the craton (Canadian Shield) and marginal platforms developed to the south and west (Figure 3.2-6).

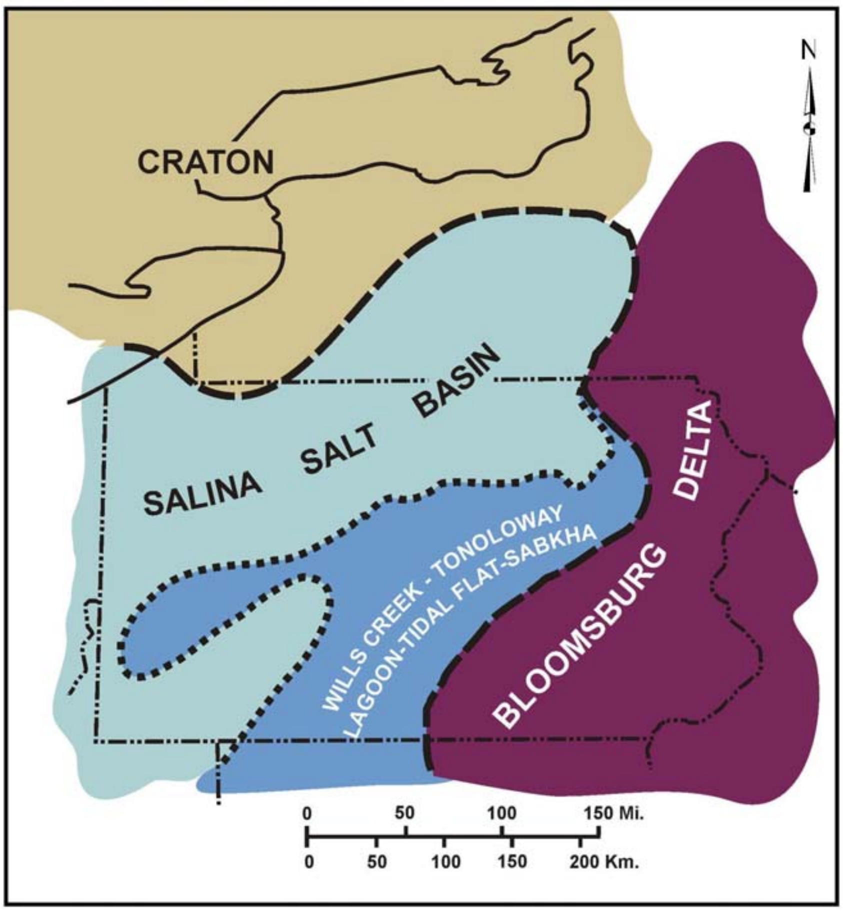

Figure 3.2-6. Generalized paleogeography of Pennsylvania and adjacent areas during deposition of the Salina salt.[F9]

3.2.6 Geologic Structure and Trapping Mechanisms

The Salina salt basin in Pennsylvania is coincident with the Rome Trough, a deep faulted depression in the crust of the Earth that has affected deposition throughout geologic time (Figure 3.2-7).[89] Both the overall thickness map of the Salina and the distribution of thick bedded salts fall within the axis of the trough from southwestern to north-central Pennsylvania and into New York. When combined with the concept shown in Figure 3.2-6, it seems certain that the Rome Trough was the primary factor in the development of the depositional basin, and that the Bloomsburg delta to the southeast and the craton to the northwest were merely marginal features that assisted in restricting circulation through the basin.

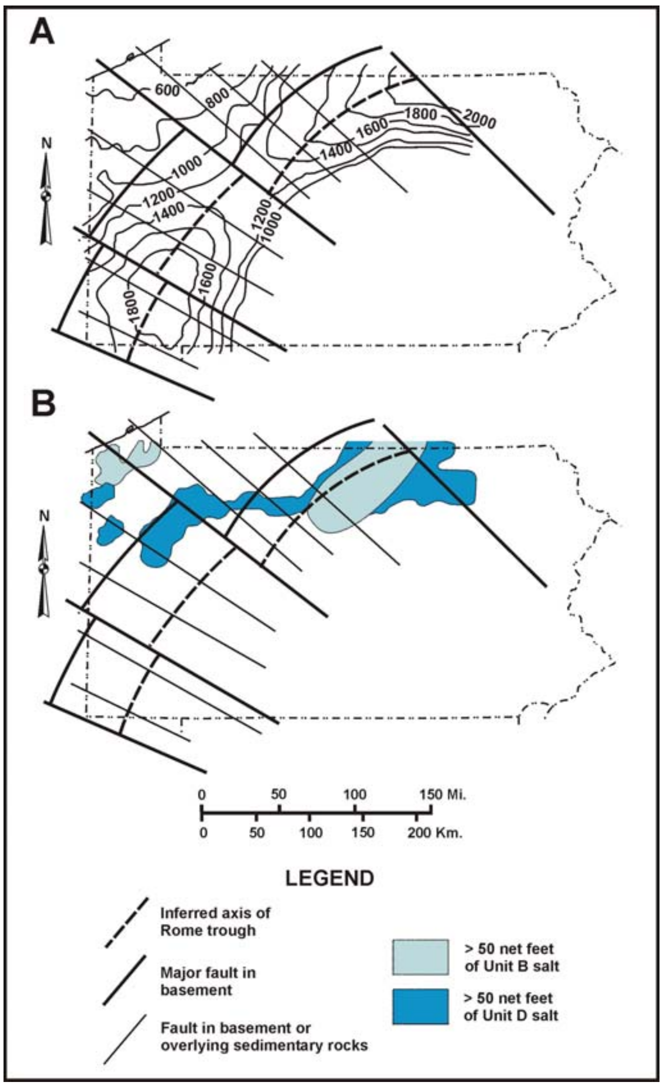

Figure 3.2-7. Coincidence of Salina deposition with the Rome Trough and other deep faults.[F10] A. Isopach map of the Salina Group. B. Map of net feet of salt in units B and D.

Although deposition of salt and other evaporites took place in basins with restricted circulation, the enormous thicknesses of salt, especially in north-central Pennsylvania, cannot be explained solely by deposition. From seismic evidence, it is obvious that thickening resulted from stress due primarily to tectonism. Overburden pressures might also have contributed, as they do in the salt-dome areas of the Gulf Coast, but without the presence of salt domes in Pennsylvania this is not certain.

It has been found that individual salt beds in northeastern Ohio, when mapped, showed local thickening and thinning related to geologic structures.[90] The same is probably true for northwestern Pennsylvania as well.[91] Local salt-related structures in this area involve both anomalous salt thicknesses and repetition of strata by faulting. Outside of northwestern Pennsylvania, overthickening of the Salina salt beds by flowage accounts for many of the folds and faults found at the surface.

At the surface, the fold structures of the Appalachian Plateau are relatively simple. These structures in the subsurface, however, are marked by a zone of complex faulting that generally begins in the Salina and ends in the Marcellus shales. Figure 3.2-8A illustrates a typical anticline at the level of the Salina salt in north-central Pennsylvania, interpreted from proprietary seismic data. The salt attains great thickness where thrust faults arise within the basal Salina. The strata above the salt show strong folding, whereas the strata below the salt are essentially flat-lying and undisturbed because the folds extend downward only as far as a tectonic glide plane (décollement surface) near the base of the Salina.[92] Based on these and other reports, it is probable that the entire Appalachian Plateau fold belt is underlain by at least one décollement within the Salina salts (deeper décollements may be present in older formations as well, and might have affected Salina structure by ramping up through the overlying strata). It is also possible that faulting in strata below the Salina décollement had an effect on the structure and thickness of the salt. In some cases, the faults are known to have penetrated the Salina and affected the overlying rocks as far above as the surface rocks (Figure 3.2-8B).

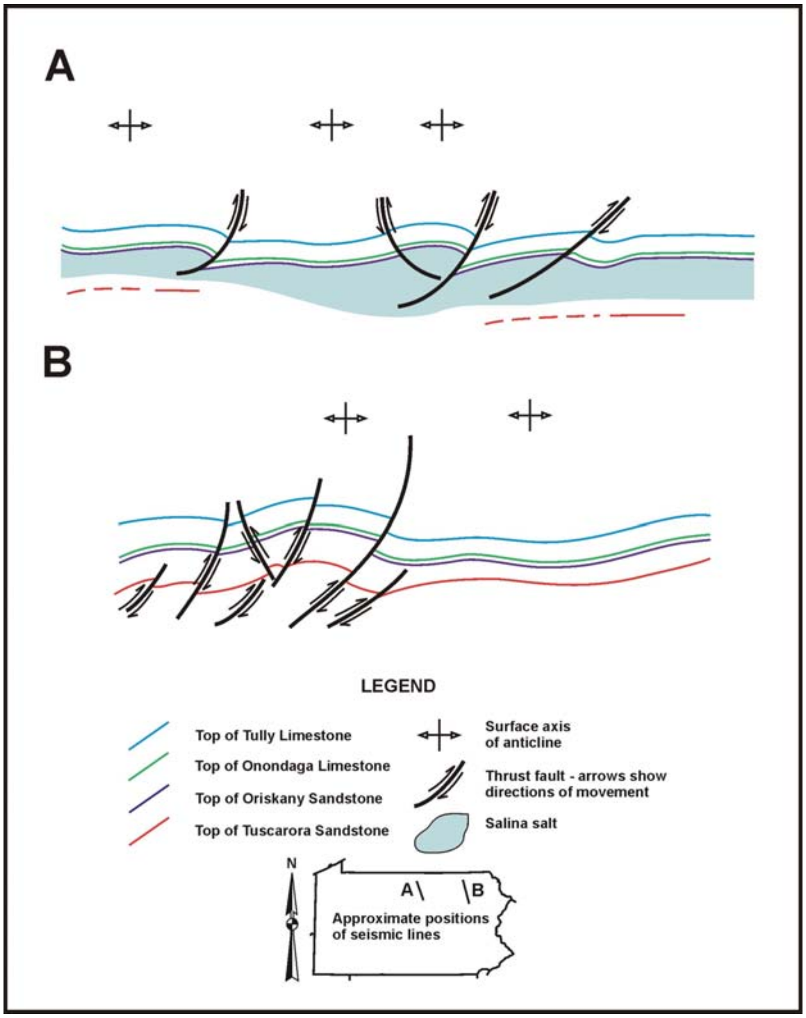

Figure 3.2-8. Geologic structures and overthickening of Salina salt in typical anticlines in northeastern Pennsylvania, interpreted from seismic data.[F11] A. Geologic structures occur only above Salina décollement. B. Geologic structures occur above and below the salt.

Despite all the evidence that Plateau folds and many faults originate within the Salina, it is unlikely these would have an effect on CO_2 sequestration because salt is naturally self-sealing as a result of its creep behavior. Fractures and faults resulting from tectonism, as well as fissures and fractures created by drilling and dissolution processes, will heal and a sound permeability seal will be reestablished in a relatively short time frame. As such, the trap within a solution-mined salt cavity is the impermeability of the salt itself, and the importance of structure is only in locating sites where the salt has become overly thickened beneath surface anticlines.

3.3 Lower Devonian Oriskany Sandstone

3.3.1 Lithostratigraphy

The Lower Devonian Oriskany Sandstone of drillers' terminology actually encompasses several discrete and formal stratigraphic units within the Appalachian Basin,[93] including: (1) the type Oriskany Sandstone of New York, which also occurs in northwestern Pennsylvania and eastern Ohio; (2) the Ridgeley Sandstone of Pennsylvania, Maryland, Virginia, and West Virginia (where it is called Oriskany), which may or may not be identical to the type Oriskany; (3) the Springvale Sandstone, a basal sandstone member or sandy aspect of the Bois Blanc Formation in Ontario, northeastern Ohio, and northwestern Pennsylvania;[94] and (4) the Palmerton Formation, a sandstone in eastern Pennsylvania that is equivalent to a portion of the basal Onondaga Limestone.[95] The stratigraphic relationships of the Oriskany to various adjacent geologic units overlying and underlying it are summarized in Figure 3.3-1.

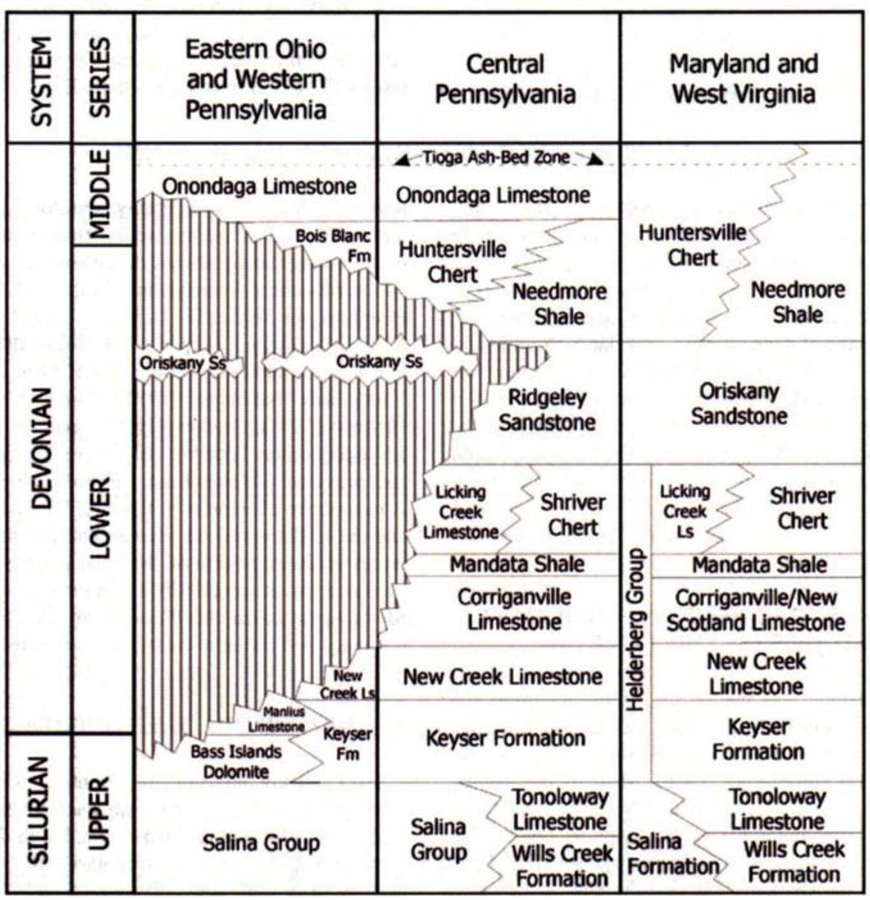

Figure 3.3-1. Stratigraphic correlation chart of the Oriskany Sandstone in the Appalachian Basin.[F12]

The Oriskany Sandstone is typically a pure, white, medium- to coarse-grained, monocrystalline, quartz sandstone containing well-sorted, well-rounded, and tightly cemented grains.[96] It may be conglomeratic in places. Quartz and calcite comprise the most common cementing materials in the formation. In many areas of the basin, the formation contains such an abundance of calcite, both as framework grains and cement, that the rock is classified as a calcareous sandstone or sandy limestone.

In addition to the primary composition of quartz and calcite grains, minor proportions of pyrite, dolomite, rutile, zircon, and other minerals have also been observed.[97] Minerals that formed in place after the Oriskany was deposited include several clay minerals, sphalerite, and pyrite.[98] Minor cements include pyrite, dolomite, ankerite, "glauconite," and chalcedony.[99]

3.3.2 Significant Earlier Studies on this Interval

The Oriskany Sandstone was named for its type locality at Oriskany Falls, Oneida County, New York.[100] Before 1930, most studies done on the formation were for purposes of clarifying the stratigraphic and paleontological relationships of Lower Devonian and Upper Silurian rocks.[101] Since then, however, the Oriskany has become one of the more important formations for gas exploration in the Appalachian Basin. As a result, the Oriskany has been the subject of numerous studies related to structure, stratigraphy, petrology, petrophysics, and other topics. The earliest studies were performed by petroleum geologists documenting the significant discoveries in south-central New York and north-central Pennsylvania in the early 1930s and 1940s.[102] Subsequent studies added to the general knowledge of the formation and provided additional data on the various reservoir properties.[103] A resurgence of interest in this prolific reservoir in the late 1970s and the 1980s resulted in what arguably is the most comprehensive and exhaustive study produced to date on the Oriskany.[104] The most recent reports, in the Atlas of Major Appalachian Gas Plays,[105] provide a summary and single source of information garnered from earlier studies.

3.3.3 Nature of Lower and Upper Contacts

The Oriskany Sandstone represents a major change during Early Devonian deposition in the Appalachian Basin. The predominant carbonate sedimentation that originated in the Late Silurian ceased or slowed, to be replaced temporarily by prevailing clastic deposition. The Early Devonian ended with a worldwide regression that resulted in erosion throughout much of North America. This discontinuity occurs at the Appalachian Basin margins as an unconformity between the carbonate rocks of the Upper Silurian/Lower Devonian and of the Middle Devonian (Figure 3.3-1). Some authors described the Oriskany as a basal sandstone deposited on a basin-wide unconformity.[106] Erosion following Oriskany deposition near the basin margins might have been more extensive than pre-Oriskany erosion—there are large areas of the basin where the Oriskany is thin or absent, for example the “Oriskany no-sand area” in northwestern Pennsylvania. It is also possible, however, that such areas occur because of the lack of deposition on positive paleotopographic highs.

The concept that the Oriskany is everywhere bounded by unconformities is very popular, resulting in many studies showing the upper and lower surfaces of the formation to be disconformable with adjacent strata across the basin.[107] From evidence in north-central Pennsylvania and Greenbrier County, West Virginia, however, the Oriskany actually lies conformably on the underlying carbonate rocks and cherts of the Helderberg Group at least throughout the main portion of the basin south and east of the cratonic margins.[108] Also, in this area, the Oriskany conformably underlies black shales and cherts of the Needmore and Huntersville formations.

3.3.4 Discussion of Depth and Thickness Ranges

The Oriskany crops out in central New York near its type locality, as well as within the complex fold-belt of central Pennsylvania, western Maryland, northeastern West Virginia, and western Virginia. In western Pennsylvania, it occurs in the subsurface, ranging in depth from about 1,200 ft (366 m) along the Lake Erie shoreline to more than 10,000 ft (3,048 m) deep in Somerset County (Figure 3.3-2). Depths within the Appalachian Plateau vary greatly as a result of both a general regional southeastward dip and occurrence of numerous anticlines paralleling the regional strike of the Valley and Ridge Province to the east.

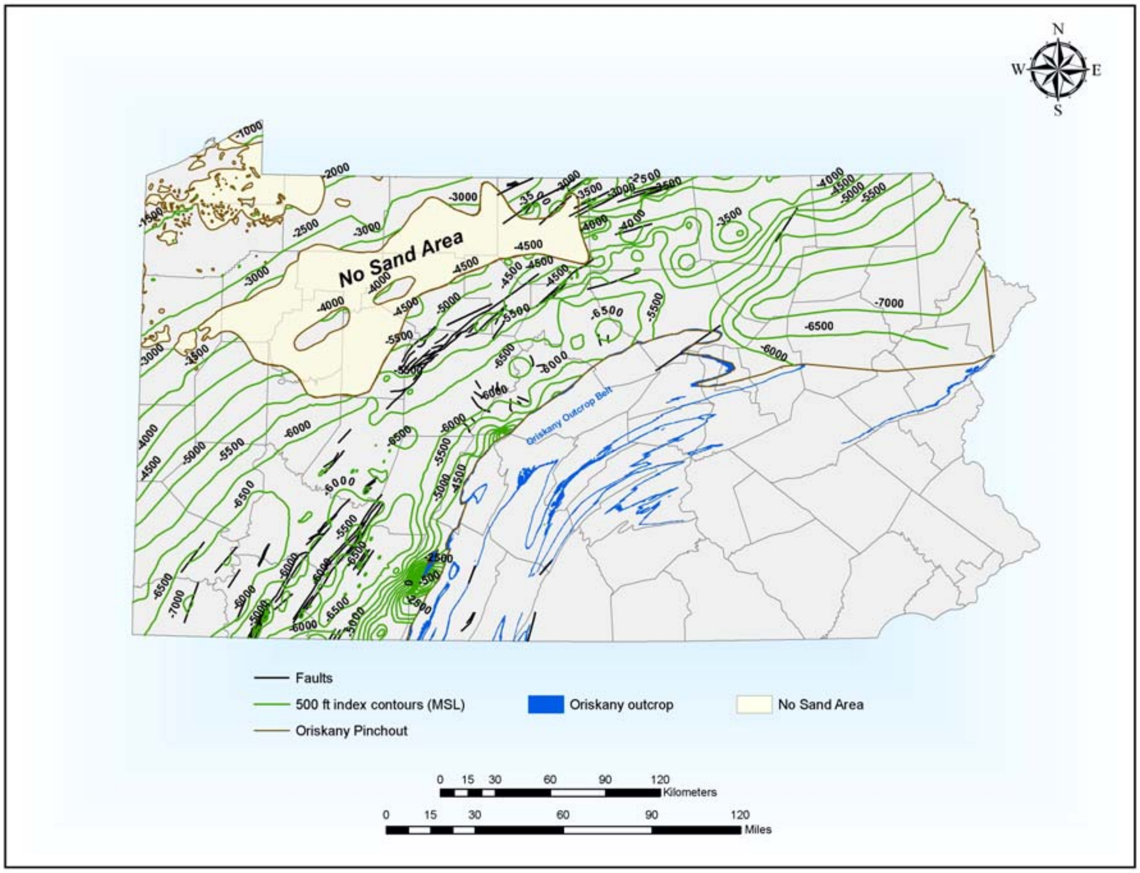

Figure 3.3-2. Structure contour map drawn on top of the Oriskany Sandstone.

Oriskany thicknesses vary within the Appalachian Plateau from 0 to over 300 ft (91 m) (Figure 3.3-3). Adjacent to pinchout areas, such as the "Oriskany no-sand area" in northwestern Pennsylvania, the reservoir sandstone typically averages between 10 and 30 ft (3 and 9 m) thick.[109] At the pinchout, the sandstone forms a thin wedge between relatively impermeable Lower and Middle Devonian carbonates and shales. Thicker zones of Oriskany typically occur in the more structurally complex areas where thrusting and vertical repetition of beds causes apparent thicknesses well in excess of 60 ft (18 m).[110]

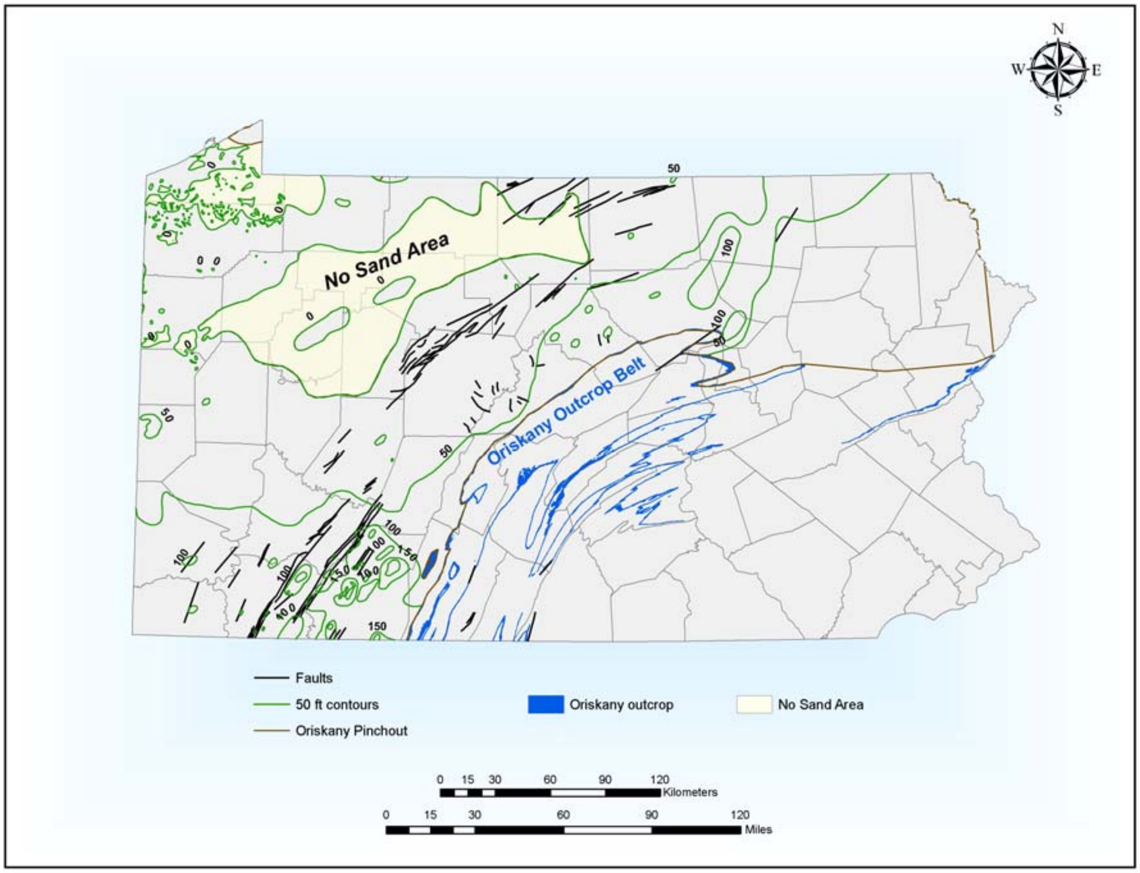

Figure 3.3-3. Map showing the gross thickness of the Oriskany Sandstone.

3.3.5 Formative Processes

The Oriskany Sandstone originated in a shallow marine setting fairly early in Devonian time when one or more emergent landmasses to the north and southeast were uplifted and eroded.[111] Although the character of the sand grains in the Oriskany indicate mature, multicycled sediments, the specific origin of the Oriskany sand deposits remains unsettled. It has been suggested that the sand originated to the southeast and spread northwestward across the basin (for northeastern Pennsylvania to southeastern West Virginia).[112] In New York, it was derived directly from crystalline rocks in the Adirondacks.[113] It was eventually shown that the characteristics of the Oriskany change dramatically in different areas.[114] Multiple source areas for the sediments have been suggested.[115] Generally concurring with the two source areas previously suggested,[116] later workers proposed a third, representing an emergent landmass in east-central Pennsylvania or New Jersey.[117]

The depositional environments of the Oriskany Sandstone are varied but always fall within the broad category of shallow marine. A high-energy beachface environment for the Oriskany in the Valley and Ridge Province (corresponding to central Pennsylvania) has been suggested.[118] Other proposed environmental interpretations include nearshore, shallow water,[119] tidal ridges and submarine dunes,[120] shallow to deeper subtidal,[121] and marine shelf bar.[122]

3.3.6 Geologic Structure and Trapping Mechanisms

As a natural-gas reservoir, the Oriskany is affected by three types of traps – stratigraphic (updip permeability pinchout),[123] structural,[124] and combination stratigraphic and structural.[125] In the areas of pinchout (Figures 3.3-2 and 3.3-3), fluids migrated updip (westward and northward) to where the sandstone pinched out against overlying and underlying impermeable rocks (typically tight carbonates or shales), creating a stratigraphic trap.[126] Brine often is trapped between the actual sandstone pinchout and the zones or belts of gas production. Where the trapping mechanism is structural (from central-western Pennsylvania and West Virginia eastward), structural complexity increases from west to east. To the west and north, anticlinal structures with rifted cores originated through detachment in incompetent Silurian salt beds. Salt water typically occurs in the cores of these anticlines. To the east, multiple east-dipping thrust sheets (duplexes), resulted from tectonic thrusting.[127] Combination traps occur in a narrow band across easternmost Ohio into western Pennsylvania and western West Virginia where moderate structures enhance trapping in updip porosity pinchout situations.[128] Figure 3.3-2 shows the areas of structural complexity within Pennsylvania and surrounding areas. The few faults shown imply much more simplicity and generalization than actually occur, owing to the scale of the map. Studies of individual structures and gas fields indicate much more complexity than can be shown on a map at this scale.

The Atlas of Major Appalachian Gas Plays[129] classifies four natural gas plays for the Oriskany based on these trapping mechanisms (Figure 3.3-4). Moving from east to west across the Appalachian Basin, they are: (1) ***Dop***: Lower Devonian Oriskany Sandstone updip permeability pinchout; (2) ***Dho***: fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone; (3) ***Dos***: Lower Devonian structural play; and (4) ***Doc***: Lower Devonian Oriskany Sandstone combination structural and stratigraphic traps. The play boundaries are important in delineating the areas of Pennsylvania that are most suitable for CO_2 injection into the Oriskany Sandstone. The ***Dop*** play is characterized by stratigraphic trapping updip from Oriskany "no-sand" areas in northwestern Pennsylvania. This play occurs where the Oriskany Sandstone is relatively shallow and in some cases even above the 2,500-ft (762-m) minimum depth for sequestration. Plays ***Dho*** and ***Dos*** are defined by structural trapping, and natural-gas production is closely related to faulting and fractures in the rocks. Extending from Greene County in the southwest to Susquehanna County in the northeast, the combined areas of the two plays cover much of Pennsylvania. Play ***Doc***, defined by both structural and stratigraphic trapping mechanisms, covers the smallest geographic area in Pennsylvania. It extends from the western border of Pennsylvania east to southern Jefferson County.

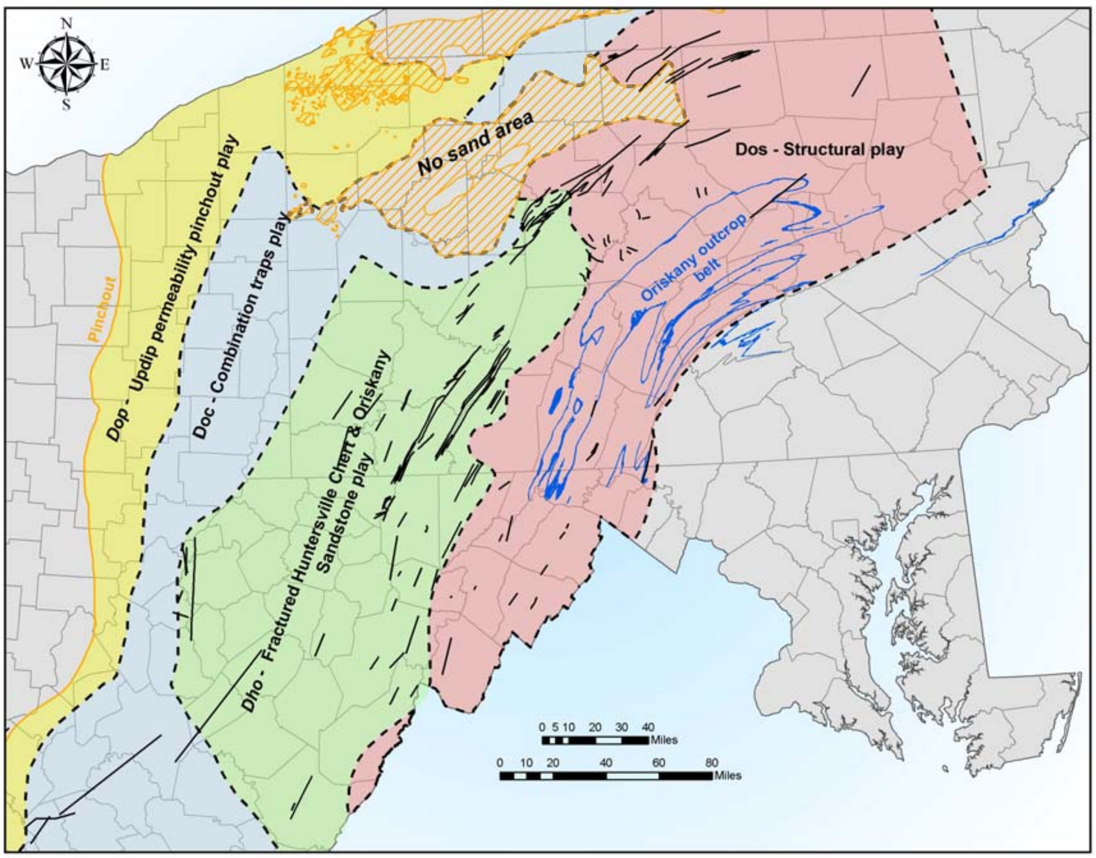

Figure 3.3-4. Oriskany natural gas plays in the Appalachian Basin.[F13]

Salient characteristics of these four individual plays are summarized as follows:[130]

- The highest porosities in the Oriskany Sandstone are observed in the updip permeability pinchout, ***Dop***, and the fractured Huntersville Chert and

Oriskany Sandstone, ***Dho***. Intergranular porosity, and to a lesser extent dissolution porosity, are observed in the ***Dop***. Porosity is controlled by fracturing in ***Dho***, with only minor secondary porosity from dissolution.

- The Oriskany Sandstone shows little variation in porosity and permeability in the ***Doc*** play, based on existing data. Additional data, however, are required to determine if the interpretation is correct, before extending this conclusion elsewhere, or if it is simply an artifact of the available, limited data.
- The tightest Oriskany Sandstone occurs in the ***Dos*** play, having calculated and measured porosities of less than 2 percent from Pennsylvania sample locations.
- Porosity in the ***Dho*** and ***Dos*** plays is largely controlled by fractures. Consequently, appropriate geophysical and seismic methods should be employed to evaluate fracture porosity and conduct fracture analyses at any potential injection sites in these play areas.

3.4 Upper Devonian Sandstone Reservoirs

3.4.1 Lithostratigraphy

The modern petroleum industry began in Pennsylvania in 1859 with the successful drilling of the Drake well in Venango County, where “Colonel” Edwin Drake and his partners produced oil from sandstone in the Upper Devonian Venango Group. The Upper Devonian sandstones have served as the “bread and butter” rocks of Pennsylvania’s oil-and-gas industry ever since. Literally hundreds of thousands of wells now penetrate these rocks in western Pennsylvania and so the general stratigraphy of the Upper Devonian strata is well known. Nevertheless, the complex lithologies and discontinuous nature of coarser grained sediments (sandstones and conglomerates) in this stratigraphic interval continue to challenge geologists who endeavor to correlate and map these rocks in fine detail at the local scale. Figure 3.4-1 shows a subsurface correlation diagram of the Upper Devonian rocks in western Pennsylvania. Figure 3.4-2 is a map showing the thickness and distribution of sandstones within this Upper Devonian stratigraphic interval.

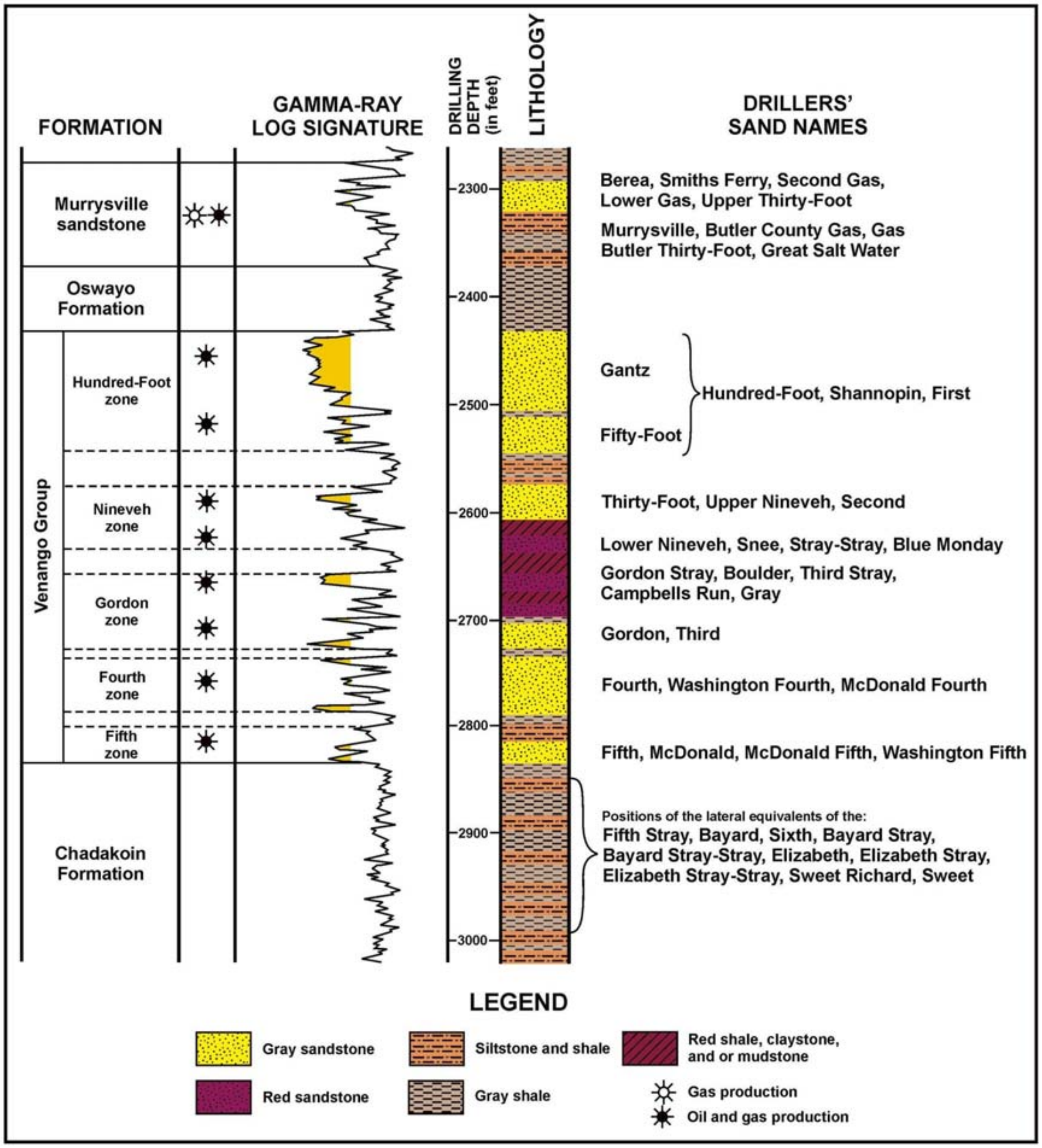

Figure 3.4-1. Generalized stratigraphic correlation diagram of Upper Devonian rocks in western Pennsylvania.

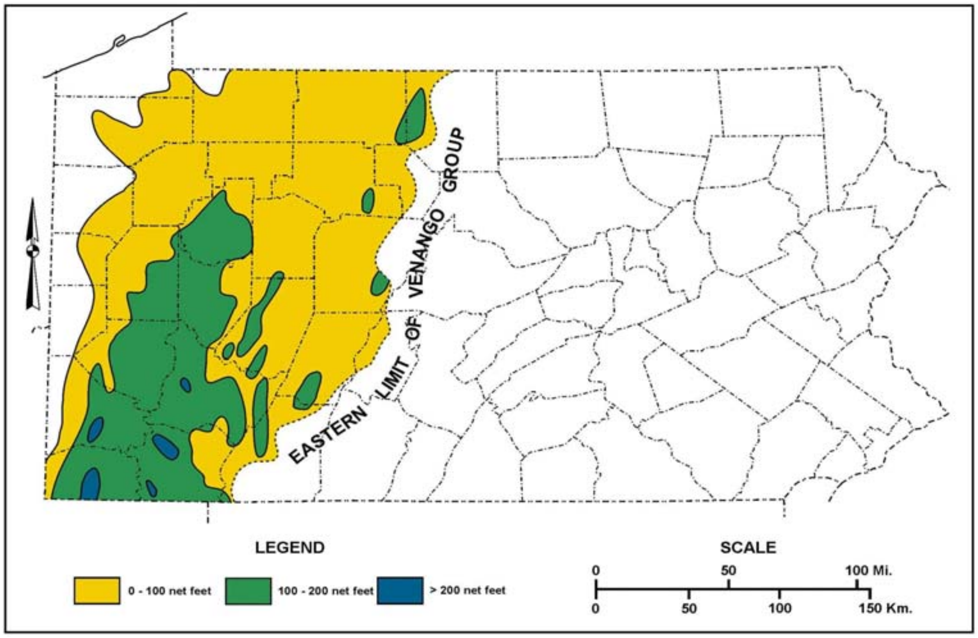

Figure 3.4-2. Thickness and distribution of Upper Devonian sandstones in western Pennsylvania.

Because of the wedge-shaped geometry of the Appalachian Basin, the Upper Devonian section is thinner in northwestern Pennsylvania than in the south-central areas. Based on gamma-ray geophysical log correlation, the Upper Devonian clastic interval ranges from 0 to over 5,000 ft (1,525 m) thick between Erie and Somerset Counties.[131] The net-feet thickness of actual sandstone within the Upper Devonian, however, ranges from 0 to just over 700 ft (215 m) in the same area. The sandstones and conglomerates occur as discrete, but widespread bundles or packages of coarser sediment interbedded with finer-grained siltstones, shales, and minor carbonate rocks. These bundles are mapped in the subsurface as the Venango, Bradford, and Elk Groups. The potential targets for geologic CO_2 sequestration in Pennsylvania include sandstones of the Venango Group in southwestern Pennsylvania, specifically in portions of Allegheny, Washington, Westmoreland, Greene, and Fayette Counties.

The Venango Group has the greatest westward expanse of the three sandstone-bearing Upper Devonian intervals and contains most of the coarser clastics. In southwestern Pennsylvania, the Venango Group comprises interbedded conglomerates, sandstones, siltstones, and shales in varying quantities. In most of southwestern Pennsylvania, the

Venango Group consists of four to seven distinct sandstone sub-groupings that are correlatable over long distances. The seven sandstone zones include, from top to bottom, the Hundred-Foot, Nineveh, Gordon, Fourth, Fifth, Bayard, and Elizabeth.[132]

3.4.2 Significant Earlier Studies on this Interval

The most recent comprehensive work on the subsurface geology of southwestern Pennsylvania's oil-and-gas fields was published in the 1980s.[133] Other useful reports from the 1940s through the 1970s.[134] Harper and Laughrey[135] provided background on the history of subsurface studies in southwestern Pennsylvania and a comprehensive bibliography of previous geological work in the study area.

3.4.3 Nature of Lower and Upper Contacts

The contact between the Upper Devonian Venango Group and the overlying Riceville and Oswayo Formations is considered conformable in lithostratigraphic correlations.[136] The stratal patterns within the Venango Group, however, indicate that it is a type-1 stratigraphic sequence.[137] The abrupt change from coarse-grained, aggradational to progradational parasequence sets of the Hundred-Foot sandstone interval to predominately fine-grained strata of the Oswayo Formation occurs near the upper boundary of the highstand systems tract. The Oswayo Formation may represent truncated portions of the highstand systems tract. It contains evidence for marine deposition (very fossiliferous sandstones, siltstones, and shales), waning highstand progradation (flagstones), and subaerial exposure (red shale and claystone). The Oswayo Formation might be more properly considered an upper portion of the Venango Group and its upper contact with the Murrysville Sandstone, another type-1 sequence boundary (an upper bounding unconformity). Detailed sequence stratigraphic work is needed to resolve these ideas.

The lower contact of the Venango Group and subjacent Chadakoin Formation is also considered conformable in published lithostratigraphic correlations.[138] The contact between the Chadakoin Formation's transgressive marine strata and the fluvial/deltaic deposits of the basal Venango Group (Lower Sandy, Fifth, and Bayard zones), however, meet the criteria of an unconformable type-1 sequence boundary.[139] Incised valley-fill deposits in the Lower Sandy zone of the Venango Group, onlap of overlying strata onto the margins of the incised valley, coastal onlap, and a basinward shift in facies have been documented.[140] All of these features are criteria for recognizing a type-1 sequence boundary.

3.4.4 Discussion of Depth and Thickness Ranges

The upper contact of the Venango Group in southwestern Pennsylvania occurs at depths of 1,750 ft (533 m) to 2,900 ft (884 m). The Venango Group has a variable thickness in this area, exceeding 600 ft (180 m) along the Monongahela River and tapering to less than 100 ft (30 m) in the western portion of this region. Where the Venango Group thins to the west, it does so rapidly by the termination of identifiable sandstones. We selected an arbitrary cutoff between the Venango Group and the Chagrin Member of the Ohio Shale where the amount of sandstone in the section constitutes less than fifty net feet as measured on gamma-ray logs. Actual net sandstone thickness in this area ranges from 0 to 200 ft (61 m). The thickest net sandstone intervals are concentrated within linear pods that are normal or parallel to the Devonian depositional shoreline. The individual sandstones in the Venango Group average between 15 and 20 ft (4.6 and 6 m) in thickness. They rarely exceed 50 ft (15 m). The Hundred-Foot sandstone zone at the top of the Venango Group is an important exception. The Gantz sandstone, which comprises the upper part of the One Hundred Foot zone, locally exceeds 75 ft (23 m) (Figure 3.4-1). Individual sandstone bodies are lenticular, multistory, and highly variable in aerial extent.

3.4.5 Formative Processes

The depositional setting of the Venango Group sandstones has been interpreted as a complex system of coastal and shallow marine environments that existed along the margin of the Late Devonian epeiric sea.[141] The vertical sequences of sandstone, siltstone, and shale sedimentary facies indicate that this depositional setting was probably characterized by intermediate wave energy, tides, and low littoral drift such as is seen today in the Burdekin Delta of northeastern Australia. The vertical stacking patterns of these sedimentary facies in the Venango Group also resemble those of the modern inner continental shelf off Maryland. This comparison suggests that the Venango Group may have originated, in part, as seaward-accreting, transgressive coastal sequences. This interpretation is especially compelling for the Hundred-Foot zone and equivalents which comprise much of the highstand systems tract deposits.

Specific interpreted depositional environments and their associated lithologies in the Venango Group include: (1) fluvial-deltaic environments, with sandy bedload channel-fill deposits, conglomeratic bedload channel-fill deposits, and sandstone, siltstone, and shale that originated as distributary-mouth-bar deposits; (2) tidal flat environments, with fine-grained sandstones and interbedded shales; and (3) foreshore and shoreface environments, with very fine- to fine-grained sandstones having intercalated layers and lenses of coarser sandstone and conglomerate and fossiliferous siltstones and shales. All of these disparate sedimentary rocks occur within the Venango Group. Various sandstone bodies were deposited and subsequently reworked and partially destroyed during eustatic sea level changes during Late Devonian time. As a result, the lithologies encountered in the subsurface during drilling are highly heterogeneous and can vary greatly over a few tens to hundreds of feet both laterally and vertically. Porous and permeable reservoir rocks under consideration for geologic CO_2 sequestration have variable thickness and variable lateral extent. The porous and permeable zones are erratic in occurrence.

3.4.6 Geologic Structure and Trapping Mechanisms

Southwestern Pennsylvania lies on the Allegheny Plateau on the western periphery of the central Appalachian Basin. The area has undergone relatively mild tectonic distortion over time. This mild distortion is due to recurrent movement of Precambrian basement rocks, Upper Silurian Salina salt tectonics, and detachment within the Lower Paleozoic shales. Except for a dozen or so small-scale folds, the overall regional dip, and joints, the surface rocks present little evidence of major orogenic influence. This holds generally true for the relatively shallow rocks of the Venango Group, but the intensity of folding and faulting do increase markedly at greater depths.[142]

Fold structures in southwestern Pennsylvania – anticlines and synclines – have relatively little to do with oil-and-gas production in the shallow Venango Group reservoirs,[143] except for a discussion of hypothetically possible subtle structural effects on petroleum distribution in these rocks. The reservoir traps are stratigraphic, that is, formed by porosity and permeability contrasts at lithologic contacts (sandstone pinching out against shale) or diagenetic contacts where mineral cements seal in subsurface fluids.

Porosity and permeability in the Venango Group sandstones range from lows of 2.5 percent and 0.2 millidarcy (md), respectively, to measured highs of 27 percent and 300 md, respectively (Figure 3.4-3).

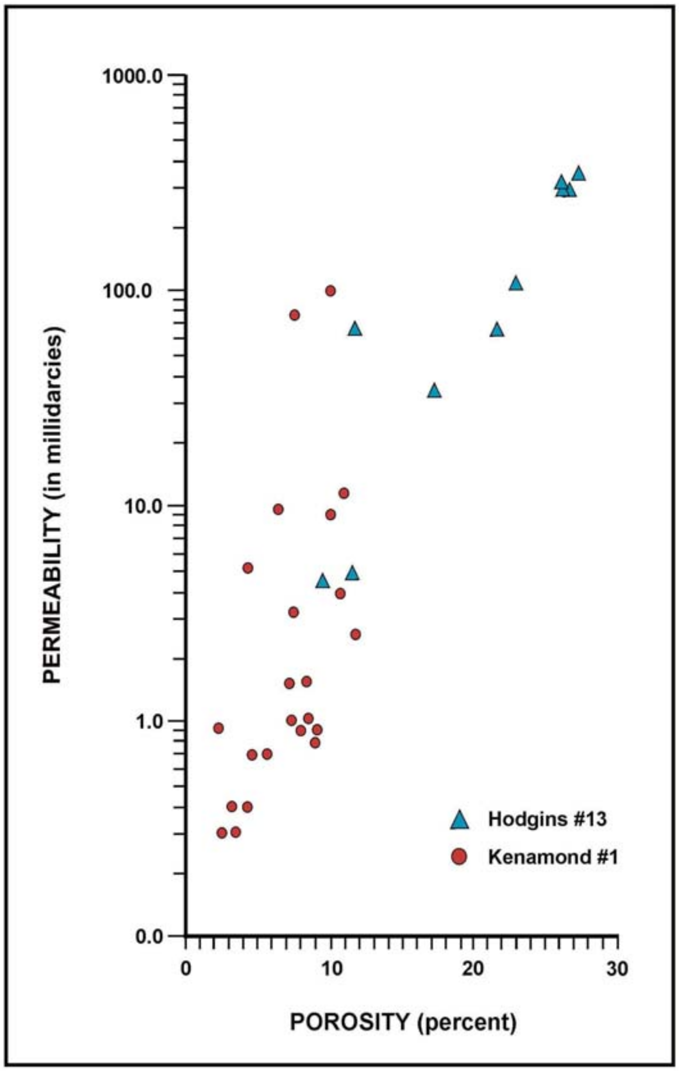

Figure 3.4-3. Crossplot of porosity versus permeability (determined from core analysis) in Venango Group sandstones from Washington County, Pennsylvania.[F14]

Three principal types of porosity in the sandstones have been documented: (1) reduced primary intergranular porosity; (2) secondary intergranular porosity; and (3) intraconstituent porosity.[144] Primary porosity in the sandstones originally existed as space between sand grains when the sediments were deposited. This original porosity probably was on the order of 26 to 48 percent, depending on the initial grain size, sorting, and packing of the sand in the depositional setting.[145] This original porosity was significantly reduced in the Venango sandstones during burial by two processes: (1) compaction, which packed the grains tighter together and forced ductile grains and clay minerals into the intergranular void space; and (2) cementation by the precipitation of secondary minerals, specifically silica, calcite, dolomite, smectite, chlorite, and sericite.

In the first instance, intergranular porosity was largely destroyed, and the sandstones are poor reservoirs today. In the second instance, porosity was reduced but not rendered totally ineffective. These sandstones could still transmit fluids, which subsequently entered the rocks to dissolve minerals, create secondary voids, and deliver hydrocarbons.

Secondary porosity in the Venango Group sandstones is mainly the result of dissolution of carbonate cement and, to a lesser extent, of feldspar and chert grains. The effective available porosity is a hybrid of reduced primary pore space and secondary void space of dissolution origin. This interpretation of the porosity in the Venango sandstones is based on microscope studies of the rocks and is supported by the observed scatter in permeability when plotted against porosity (Figure 3.4-3). Variations in porosity and permeability in these sandstones that are controlled by the depositional environment in which the rocks formed have been documented.[146]

4.0 SUMMARY OF STATEWIDE GEOLOGIC ASSESSMENT FOR CARBON SEQUESTRATION

The Survey has examined the subsurface geology of the Commonwealth of Pennsylvania and delineated the most promising geologic CO_2 reservoirs (sinks) via literature review, data interpretation, and digital mapping in a GIS environment. These data and maps are presented as a first approximation of the state's geologic CO_2 sequestration potential in accordance with Act 129, and to further develop the state's carbon sequestration network. The suitability of the four potential reservoirs assessed herein for geologic sequestration of CO_2 is discussed below.

4.1 Suitability for Injection Purposes

4.1.1 Medina Group/Tuscarora Sandstone

The Medina Group/Tuscarora Sandstone is considered an injection target, particularly for its prevalence throughout the Appalachian Basin as a reliable oil- and gas-producing reservoir, its sandstone lithologies, and the presence of less permeable confining rocks above and below the interval. Even so, factors such as the variability in lithology, the tight nature of this reservoir (with respect to both porosity and permeability), and the discontinuity of sandstone lenses in the northwestern portion of the basin, may limit the overall success of this as a CO_2 sequestration target.

The Medina Group and equivalent units consist of interbedded sandstones, mudrocks, and some carbonate rocks that were deposited under variable conditions.[147] This mixture of lithologic type results in a heterogeneous reservoir that contains internal variations such as grain size, type and degree of cementation, clay content, and pore geometry,[148] and is evidenced in the three major facies of this interval, the Grimsby Formation, Cabot Head Shale, and Whirlpool Sandstone as previously discussed. Thus, detailed characterization of this sequence for injection potential must be performed at each prospective site.

The porosity and permeability of the Medina Group varies due to both depositional and diagenetic processes. The deposition of mudrocks isolated sandy and silty layers within the Grimsby Formation and the upper Cabot Head Shale, creating permeability barriers between these reservoir rocks. Diagenesis has altered the relatively tight, primary porosity in the northern portion of the basin, creating two major types of secondary porosity – intergranular and moldic. The secondary intergranular porosity is the result of dissolution of primary calcite cement and grain edges, and moldic porosity is due to the corrosion of silica cement and dissolution of feldspar minerals.[149] Diagenesis does not always enhance porosity in this reservoir, however. Secondary cementation by authigenic silica has been observed to reduce porosity, in some cases surrounding entire grains to destroy the primary porosity.[150]

Work performed in the Athens Field of Crawford County, Pennsylvania, identified several porosity types in the Medina Group.[151] These varied from relict primary porosity, to microporosity, intraconstituent porosity, and fracture porosity. The occurrence of fracture porosity in the Medina Group and equivalent units has been documented also, to a limited extent, in other parts of the basin.[152] In northwestern Pennsylvania, the highest porosity zones are associated with those areas influenced by both depositional environment and diagenetic phenomena.[153]

Figure 4.1-1 illustrates typical gamma-ray and porosity curves for the Medina Group in the northern portion of the Appalachian Basin. The gamma-ray signature demonstrates the abrupt, sandy signature of the Whirlpool Sandstone as it overlies the Queenston Formation, the increasing-upward occurrence of siltstone/sandstone laminations within the Cabot Head Shale, and the relatively thick, sandy nature of the Grimsby. The crossover between density-porosity and neutron-porosity curves is shown with light-gray shading, and indicates a gas effect in the porous zones in the Grimsby Formation, the transitional silty sandstones of the Cabot Head Shale, and the Whirlpool Sandstone. Medina Group porosities range from 2 to 23 percent across the basin and average 7.8 percent.[154]

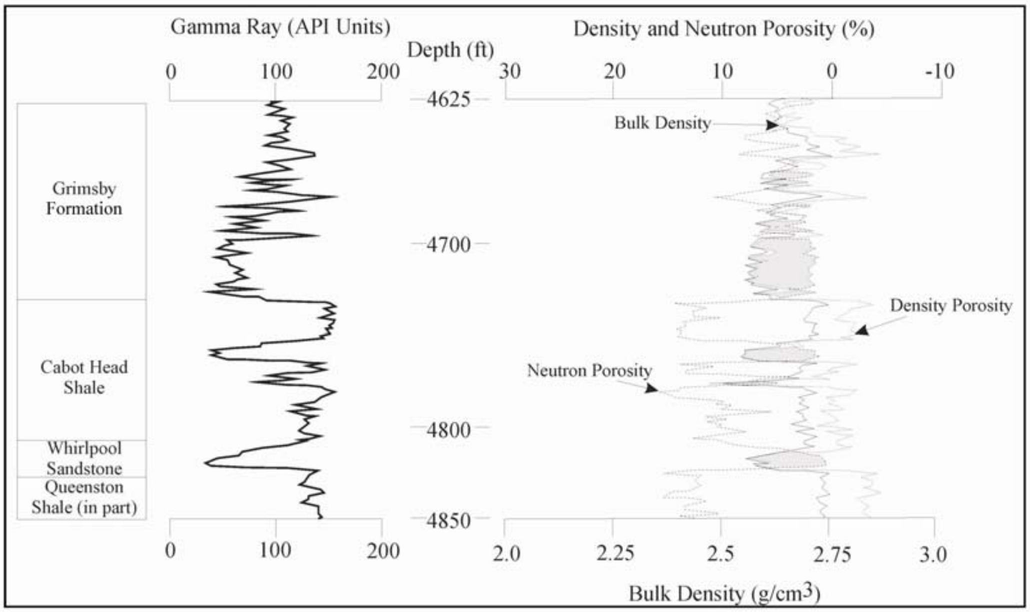

Figure 4.1-1. A typical geophysical-log profile for the Medina Group in the northern Appalachian Basin.

Medina Group permeability values are widely variable, ranging from less than 0.1 md to 40 md.[155] In northwestern Pennsylvania, Medina permeabilities occur on the lower end of this range.[156]

As a sequestration target, the Medina Group/Tuscarora Sandstone is overlain by limestones, dolostones, and shales of the Clinton Group, and underlain by the Queenston Formation (Medina) and Juniata Formation (Tuscarora) (Figure 4.1-2). These units should serve as effective seals above and below the Medina target based on their lithology and low-permeability characteristics, just as they currently serve as components of the stratigraphic trapping mechanism of this reservoir. Furthermore, the presence of extensive, mostly tight carbonate and evaporite rocks immediately above the Clinton Group contributes to the ability of this interval to prevent any vertical migration of gas out of the Medina Group.

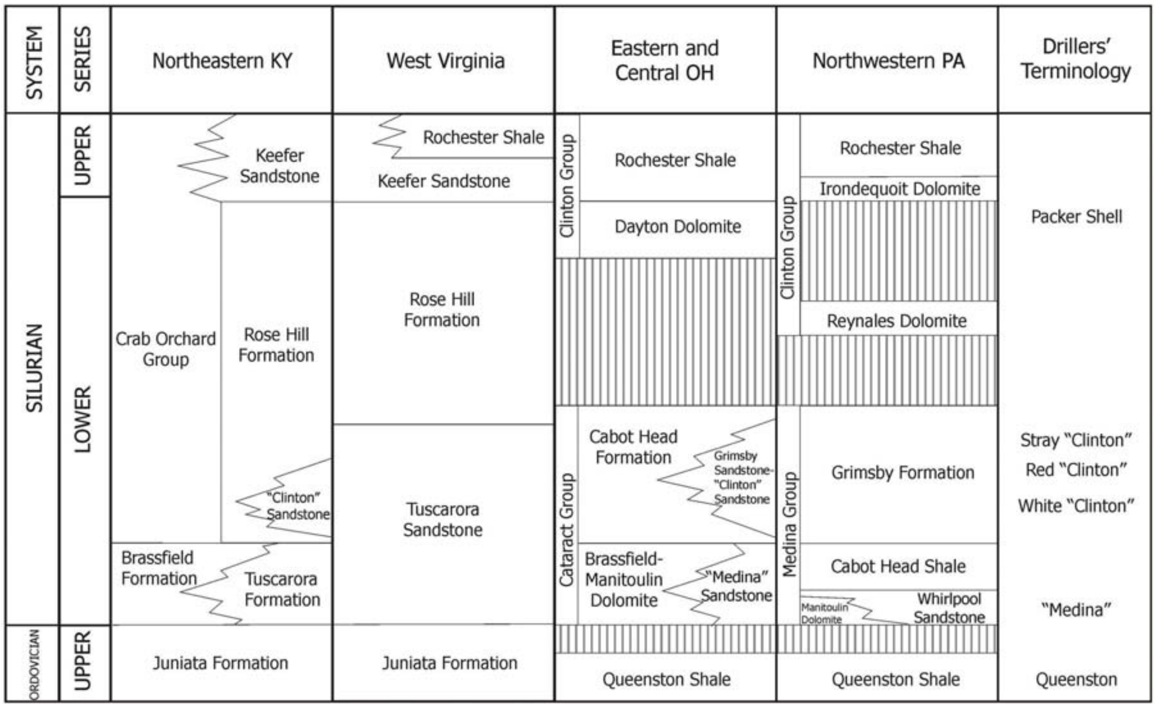

Figure 4.1-2. Stratigraphic correlation chart of the Medina Group in the northern Appalachian Basin.

In Pennsylvania, only one Medina Group field has been converted to natural-gas storage. The Corry Storage field, situated in Wayne Township, Erie County, Pennsylvania, was discovered in 1947 and first underwent gas injection in 1955.[157] The average producing depth and thickness of Medina sandstones in this field were 4,520 and 13 ft (1,378 and 4 m), respectively. Maximum storage pressure was reported at 1,200 psi (8.3 MPa). The total capacity of the Corry Storage field is 600 million cubic feet (MMCF) of gas.[158]

Medina Group oil fields typically do not respond well to normal waterflooding for EOR. This is thought to be due to the relatively low permeability and heterogeneity of the reservoirs. Nonetheless, CO_2 enhanced recovery may prove to be much more effective in these reservoirs because of the ability of CO_2 to solubilize in the native oil and brine, thereby lessening their viscosity and allowing better flow through this low-permeability heterogeneous system. If this potential can be proven via a pilot project, a vast area of the Appalachian Basin becomes available for CO_2 sequestration with the potential to produce hundreds of millions of barrels of additional oil from reservoirs of this interval.

4.1.2 Salina Group

Storage of fluids in solution-mined (leached) salt cavities is a well-known and accepted method, even within the Appalachian Basin. Salt cavern storage was first conceived in Canada during World War II; by the early 1950s, many salt caverns were being used in North America and Europe for storage of liquid petroleum gas.[159] Since that time, thousands of salt caverns have been created throughout the world for storage of crude oil (for example, the U.S. Strategic Petroleum Reserve), natural gas, and disposal of waste materials from the manufacturing and oil-and-gas industries (produced brines). Most of the national cavern storage capacity occurs in salt domes where the salt can be tremendously thick, allowing for caverns over several thousand feet high and hundreds of feet wide. Salt caverns also occur in bedded salt formations similar to the Salina Group in northeastern, midwestern, and southwestern states.[160] Bedded salts tend to be thinner, but are more widespread. As a result, salt caverns would be smaller but provide greater surface area for a multiple-cavern system. A 1997 Gas Processors Association survey found that locations of light hydrocarbon storage in salt caverns in North America included New York, Ohio, and Ontario, indicating that Salina salt beds are already being used for fluid storage, and at significantly shallower depths than would occur in Pennsylvania. Although figures are not available for Ontario and Ohio, New York stored 2,340 MMCF of natural gas in salt caverns in 2007.[161]

As stated previously, NE Hub Partners had proposed storing natural gas in leached caverns in Tioga County, Pennsylvania in the 1990s.[162] Although the project was terminated before leaching could begin, Dominion Resources, Inc. has recently revived the concept of this project and is proposing to develop salt caverns for natural gas storage in Clinton and Tioga Counties starting in 2009.[163]

The use of salt caverns for fluid storage has both advantages and disadvantages over storage in depleted oil-and-gas fields or in saline formations. Advantages include: (1) individual caverns have the ability to store large quantities of fluids per unit area; (2) they are essentially impermeable (fluids cannot escape through the surrounding rock salt), making them ideal for storing high pressure fluids; (3) they allow very little injected fluid to escape unless it is specifically extracted, as in natural gas or crude oil storage caverns; and (4) the walls of a salt cavern have the structural strength of steel, making salt very resistant to degradation over the life of the storage facility.[164] Some disadvantages include: (1) leaching a salt cavern can be quite expensive;[165] (2) because salt beds, unlike salt domes, are wide and thin, they are more prone to deterioration;[166] (3) salt caverns typically take up only 1/100th of the acreage expended by a typical depleted gas reservoir, so a single cavern cannot hold as much fluid volume as can a traditional sandstone reservoir; and (4) the produced brine has to be properly treated (if to be sold as a commodity) or disposed, which could impose environmental issues and/or incur a large expense.

In addition, salt leaching a storage cavern is a water-intensive process – the volume of water required to leach a cavern is 7 to 10 times the total cavern volume.[167] NE Hub Partners had planned to use 3,456,000 gallons (gal) per day (gpd) [13,082,383 liters (l) per day(lpd)] for a period of greater than two years; the proposed source was the Cowanesque Reservoir in Tioga at a withdrawal rate of 2,400 gal per minute (gpm) [9,085 l per minute (lpm)].[168] Depth could be an issue also. Six thousand ft (1,829 m) was considered to be the maximum depth for leaching salt caverns in bedded salt owing to salt properties, expenses, operating temperatures and pressures, and other factors.[169] Technology changes quickly, so this might no longer be an issue.

To be an effective candidate for storage of large fluid volumes, the salt storage site would have to be a large area with many caverns controlled by a central storage facility. An example from the oil-and-gas industry is the NE Hub Partner's planned Tioga project; they called for 10 salt storage caverns, each with a capacity of 2.5 to 3 billion cubic feet (BCF) of working natural gas storage capacity, on a 900-acre (1.4 mi^2 or 3.6 km^2) tract.

In order to evaluate the prospective capacity of a salt cavern for storage of supercritical CO_2, some rudimentary calculations have been prepared. For a hypothetical cylindrical cavern 500 ft (152 m) high and 350 ft (107 m) wide, the volume of void space is calculated to be 48,081,250 ft^3 (1, 361,509,380 l). The density of supercritical CO_2 is 0.0265 tons/ft^3 (849 g/L), so the mass of supercritical CO_2 that could be stored in such a cavern is roughly 1.3 million tons (1.2 million t). Supercritical CO_2 has a density similar to that of crude oil (750 to 1,050 g/L), as well as similar buoyancy characteristics (Burrus and others, 2009) [170]. We prepared similar capacity calculations for crude oil in the same cylindrical volume, and they provide estimates between 1.1 and 1.5 million tons of crude oil, values that are consistent with that obtained for supercritical CO_2.

The CO_2 would be stable at the depths and confining pressures of the Salina salt beds. Supercritical CO_2 has a specific gravity of 1.03, whereas any brine in the cavern will have a specific gravity of approximately 1.18. This would allow the CO_2 to remain stable by the confining pressures of the brine column in the cavern. Then, as the CO_2 is injected, the brine can be withdrawn and disposed.

Although there are significant advantages to a multiple-cavern storage field, such a project would not be without potential safety problems, as there would be with any other fluid storage concept. The Solution Mining Research Institute has published hundreds of technical papers dedicated to leached cavern, including many on safety factors.[171] Analyses of numerous salt cavern storage problems have been produced,[172] but in all cases the problem was related to flammable hydrocarbons, which would not be applicable to storage of supercritical CO_2.

The leaching process is relatively simple. Once the site has been chosen, a well is drilled into the salt formation following all DEP and U.S. EPA requirements. The well would contain multiple strings of casing for safety, with two internal strings used for the solution mining process. Water is injected through the injection string to dissolve the bedded salt, and the resulting brine is produced through the production string. Solution mining proceeds initially by direct circulation of water entering at the base of the proposed cavity and exiting at the top. This creates and enlarges the lower portion of the cavern. Reverse circulation then creates and enlarges the upper portion, with water entering the top of the cavern and exiting at the bottom. The leaching company can control the rate of cavern growth and the disposal of insoluble materials. The resulting cavern might look approximately like Figure 4.1-3, based on data submitted to DEP by NE Hub Partners in 1996 (the thickness of the salt in the roof of the cavern should be at least 1/3 the diameter of the cavern).[173]

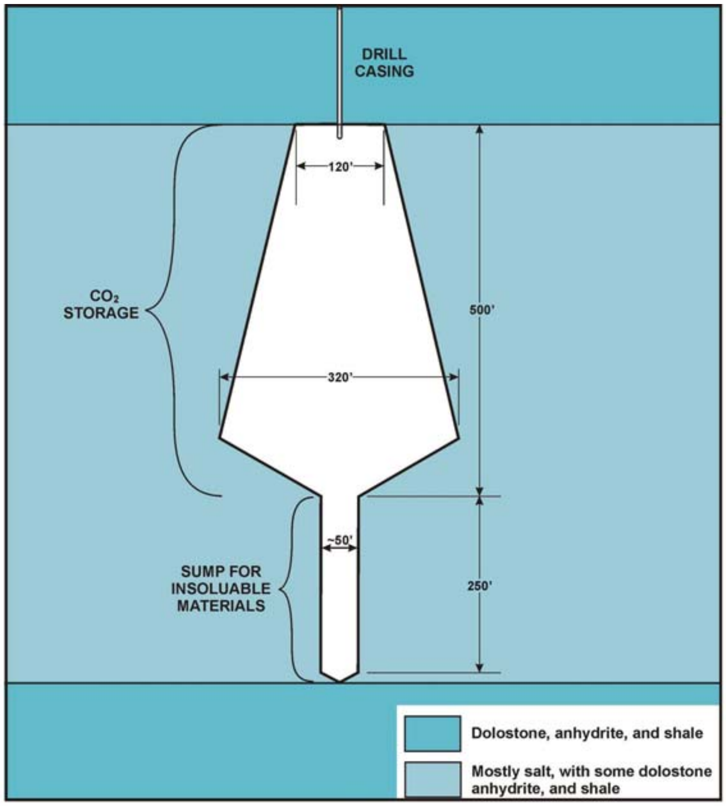

Figure 4.1-3. Schematic diagram of a potential leached salt cavern in north-central Pennsylvania.[F15]

This inverted cone shape minimizes stress concentrations near the roof of the cavern. The long, narrow opening at the bottom of the cavern is designed to capture insoluble materials such as anhydrite and dolostone during leaching. Once the cavern has been excavated, the well string can be withdrawn to the top of the salt bed to maintain its integrity in the event of an unforeseen structural problem such as cavern collapse.

NE Hub Partners drilled a test hole in the Salina salt of the Tioga gas storage field prior to submitting their proposal to DEP and U.S. EPA for leaching the salt. They recovered numerous cores and submitted them to several testing laboratories for physical and chemical analysis. Based on the results of these test analyses, the Salina salt has compressive strength that is considered to be typical of salt, and a slightly higher than typical tensile strength. The stress needed to start the process of generating microfractures in the salt is significantly greater, making the Salina more resistant to dilation damage than other salts.

The core penetrated more than 2,200 ft (671 m) of salt-bearing Salina Group. The top of the salt was at 4,398 ft (1341 m), with about 250 ft (76 m) of interbedded anhydrite, limestone, and dolostone in the section above it. The salt is dark grey to black with interbeds of limestone, dolostone, anhydrite, and black shale that range in thickness from a few feet to nearly 100 ft (30 m). Salt color is a function of grain size plus type and amount of impurities. Salt dissolution data indicate impurity contents of four to 72 weight percent insoluble residue, including quartz, dolomite, anhydrite, and clay minerals. Grain size was highly variable, from granule and coarse sand to silt and clay sizes, which is consistent with the non-salt stringers being broken up and disseminated by salt flowage. Most of the soluble material consists of halite with some calcium and sulfate impurities. No potassium or magnesium salts were detected in the samples examined by X-ray diffraction.

The arrangement of multiple caverns within a specified area of storage should follow the guidelines published by the Interstate Oil and Gas Compact Commission for minimum thickness between caverns to avoid pressure influences when they are operating at full storage pressures.

4.1.3 Oriskany Sandstone

The results of our current work suggest that the Oriskany Sandstone is a viable target for geologic sequestration of CO_2, but stratigraphic and structural variations within the unit make statewide assumptions unreliable. Site-specific studies are necessary before any injection of CO_2 can be considered.[174] The reservoir characteristics of this prospective sequestration reservoir are summarized below.

The Oriskany Sandstone consists mostly of quartz and calcite, with minor amounts of pyrite, dolomite, and other minerals.[175] The most common pore-filling cements are quartz and calcite. Clay minerals that formed in place have also been observed.[176] Cements and clay minerals may partially or completely obscure the pore space available for sequestering CO_2, so the relative proportions of these components must be carefully evaluated at each prospective site. In addition to these compositional changes, variations in texture are also important. Overall, the Oriskany is a coarsening-upward sequence,[177] but vertical and lateral variations within the unit require that each prospective injection point be studied for sequestration potential prior to development.

The Oriskany Sandstone is typically a “tight” rock – that is, one of low porosity and permeability. Primary intergranular porosity, which is the original porosity that developed during deposition of the sediments that became rock, is present only locally. Even so, secondary porosity, which is porosity that developed in rock after its deposition by fracturing and/or dissolution, is common in this formation. Its development depends directly on mineralogy, changes in the rock after deposition and burial (diagenesis), and amount of fracturing.[178] Fracture porosity, where it occurs, aids greatly in fluid storage within the Oriskany.

The most porous zones in the Oriskany Sandstone are found in the ***Dop*** and ***Dho*** plays, with average porosities of 10 percent and 14 percent, respectively. Intergranular porosity and subordinate dissolution porosity occur in ***Dop*** (Figure 4.1-4), whereas porosity is controlled by fracturing in ***Dho*** (Figure 4.1-5). Porosity averages less than 2 percent in the ***Dos*** play and is controlled by rare open fractures in the rock and minor associated dissolution. The difference in porosities between the two structural plays, ***Dos*** and ***Dho***, is related to the timing of fracturing – early fractures generally healed during diagenesis (***Dos***), whereas late-stage fractures commonly remained open (***Dho***). A combination of primary intergranular porosity and dissolution porosity, averaging 5 percent, are observed in the ***Doc*** play. These average values are based on both geophysical log calculations and core analyses.

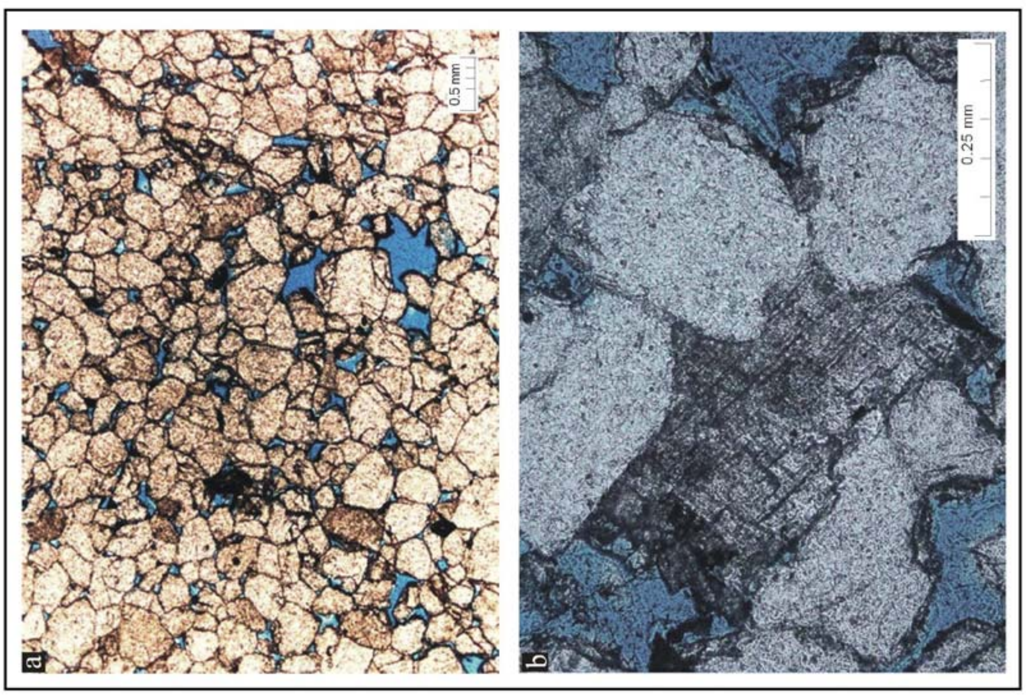

Figure 4.1-4. Porosity types in the Oriskany Sandstone *Dop* Play.

Figure 4.1-5. Fracture porosity in the Oriskany Sandstone *Dho* Play.

Permeabilities in the Oriskany Sandstone range from less than 0.1 to almost 30 md.[179] Highly fractured rocks tend to have higher permeabilities, as do rocks in which carbonate dissolution has occurred. Permeabilities are lower where fractures have been healed by secondary mineralization, or where secondary dissolution of cements has been minimal. Injection of fluids, therefore, would be more favorable in areas close to an updip pinchout or along structures where fractures have not healed.

The Oriskany Sandstone has been used for the injection of industrial wastes in several wells in the basin, and for injection of natural gas for gas-storage purposes in numerous depleted gas fields. One injection project, a waste disposal well in Pennsylvania, had an injection rate of about 20 gpm (76 lpm) at an intake pressure of 1,400 psi (9.7 MPa) during the initial investigation stage.[180] The Oriskany in this well ranged in depth from 5,250 to 5,426 ft (1,600 to 1,654 m). Average porosity and permeability were 5.2 percent and 2.2 md, respectively. Following hydraulic fracture, the injectivity increased to 55 gpm (208 lpm) at 1,700 psi (11.7 MPa). These data clearly indicate that, even in areas of low porosity and permeability, the Oriskany can be used for sequestration of fluids as long as hydraulic fracturing or acidizing is applied prior to injection.

The largest single storage problem for sequestration of CO_2 in the Oriskany is the possibility of seal failure. Cap rock integrity problems have been cited as the single most important constraint on long-term sequestration in all target storage sites.[181] Mechanical seal problems would probably be more likely to occur in areas where the structural complexity places a porous or highly fractured rock in juxtaposition (vertical or lateral) with open fractures or high-porosity zones in the sandstone. The integrity of Oriskany reservoir cap rocks and fracture seals needs to be evaluated thoroughly for mechanical and, possibly, chemical alteration potential before any project would begin.

4.1.4 Upper Devonian Sandstone Reservoirs

The excellent petroleum production history of the Venango Group sandstones in the subsurface of southwestern Pennsylvania suggests that these rocks might be suitable for the geological sequestration of CO_2. More than 155 MMBO and an unknown quantity of natural gas have been produced from relatively shallow fields and pools in southwestern Pennsylvania, and most of that oil production is from Venango Group sandstones.[182] This production history provides us with reasonably good capacity estimates and a proven pre-drilling seal. The high reservoir heterogeneity documented in the rocks[183] can be a good choice for injecting and storing CO_2.[184] This is because the fluid flow path is tortuous, creating a longer migration path for the CO_2. The longer the migration path, the more CO_2 is trapped as an immobile residual fluid.

Venango Group sandstone reservoirs at depths greater 2,500 ft (762 m) in southwestern Pennsylvania are restricted to the lowermost sandstones (Gordon through Bayard and Lower Sandy zone) in pools developed along and adjacent to the border of Allegheny and Washington Counties, eastern and southern Washington County, and most of Greene County. Indeed, all of the Venango Group reservoirs, including the thicker Hundred-Foot zone sandstones, are suitably deep for CO_2 sequestration. The sandstone depths here range from 2,500 to 3,000 ft (762 to 914 m).

Porosity and permeability in the Venango Group sandstones of southwestern Pennsylvania range from 2.5 to 27 percent and 0.2 to 300 md, respectively (Figure 3.4-3). The porosity is a hybrid of reduced primary pore space and enlarged secondary voids that formed through dissolution of mineral cements. Further petrographic analyses will be imperative, however, if the Venango Group sandstones are considered for CO_2 sequestration. While the present pore size distribution is both suitable and desirable for sequestration, it is critical to note that this distribution is time-dependent for CO_2 due to chemical reactions in the reservoir. The variable amounts of carbonate cement, clay minerals, and feldspar in the rocks pose some risk for inducing changes in the initial pore size distribution. Carbon dioxide injected into these sandstones would mobilize residual oil, dissolve into brine, and promote dissolution of the carbonates, feldspars, and clays. The brine could become supersaturated with dissolved solids. The kinetics of dissolution and precipitation, and the potential changes in pore size distribution will require further petrographic study, geochemical modeling, and testing.

We have no idea of the present distribution of fluids in the Venango Group sandstones. The long history of petroleum production in these rocks assures us that considerable amounts of brine and residual oil occupy most of the pore space. Much of the natural gas has been produced, but serious methane migration problems in the area[185] indicate that gas phases still move between and leak from wells in the region. Further evaluations of the Venango Group rocks for CO_2 sequestration will require extensive geophysical well logging to determine relative fluid saturations in the reservoirs.

There is a lack of fundamental information regarding the integrity of the post-petroleum-production cap rocks. Reliable knowledge about present day capillary sealing mechanisms of the cap rock and height of gas column that the seal can withstand is critical, especially given the shallow depths (2,500 to 3,000 ft; 762 to 914 m) of these rocks. For this reason, it will be necessary to obtain old and new cores of the potential CO_2 reservoir rocks. The very long history of petroleum production in southwestern Pennsylvania, which includes various artificial stimulation and secondary recovery efforts, requires us to consider the probability that the integrity of reservoir cap rock and lateral seals have been compromised. Consequently, porosity, permeability, and capillary-pressure measurements of reservoirs and cap rocks are essential before injecting large amounts of CO_2 into these rocks. Further, the high density of oil-and-gas wells in the region poses moderate and real risk for migration and leakage in this area; a detailed evaluation of plugging and abandonment techniques would have to be conducted for those wells known to have been abandoned, and a thorough field reconnaissance for orphaned and/or improperly plugged wells, followed by proper plugging and abandonment activities, would have to be completed to minimize or eliminate this risk.

In summary, the Venango Group sandstone reservoirs in southwestern Pennsylvania are feasible targets for CO_2 sequestration, but offer limited storage capacity in that: (1) not all of the reservoirs occur at depths in excess of 2,500 ft (762 m); and (2) lateral/vertical variations in thickness and extent are expected for these reservoirs. The viability of these prospective sequestration formations is also limited by the unknown integrity of post-production cap rock and the high density of oil-and-gas wells in this area, which poses a real risk for CO_2 migration and leakage.

4.2 Building a Digital Database of Statewide Sequestration Opportunities

The Survey is building a Carbon Sequestration Network (CSN) database as a means of managing and evaluating prospective sequestration sites relative to available geologic reservoir data. The CSN database will consist of two component parts, a digital database and a statewide GIS. Together, these tools will allow us to perform initial analyses of prospective sites based on geographic location and geologic data readily available to the Survey. The CSN database is expected to evolve over time with respect to both the number of potential sequestration sites archived in the database component and the type and volume of geologic data that will be available in the GIS component for site analysis. The overall intent is to provide the Commonwealth with a digital archive of geologic sequestration opportunities that may be utilized, as needed, to match CO_2 sources to sinks.

5.0 NEXT STEPS

The foregoing preliminary assessment indicates that geologic formations in the Commonwealth of Pennsylvania can support the development of a geologic sequestration network in the Commonwealth (Figure ES-1; subject to detailed characterization to be performed at each prospective sequestration site). In addition, there are opportunities, in conjunction with the development of this network, to develop EOR opportunities in portions of western Pennsylvania (Figure ES-2). In light of these opportunities, we present the following next steps necessary to implement a carbon sequestration project. These include a business plan, risk assessment, insurance, outreach, site characterization, monitoring, and regional studies for future site development, as discussed below.

5.1 Business Plan

Significant scale economies can potentially be created by deploying CCS in an orchestrated and staged large-scale network approach that will help mitigate initial high cost levels. Combined with savings from shared infrastructure and the longer term investment horizon of a scaled network (versus discrete and finite pilot projects), the development of such networks offer the Commonwealth the opportunity to optimize funding requirements while building a substantial infrastructure asset.

A complete project would represent an integrated network of CO_2 emitters (such as power plants or other large industrial sources with deployed technologies to facilitate the capture and compression of the CO_2), pipeline companies (to transport the CO_2) and owners/operators of the wells and geologic strata (in which the CO_2 will ultimately be sequestered).

It is anticipated that a business plan would be instrumental in securing public and private funding for the development of a CCS network.

5.2 Risk Assessment

Risk is a matter of both perceived and real potential impacts to or on a wide variety of issues. While costs and benefits can be discussed in somewhat abstract terms, risk is a personal, as well as a financial, matter. The preliminary risk assessment required by Act 129 will be conducted jointly and transparently by a group that will include representatives from DCNR, academia, and engineering firms with expertise in a long list of the elements of the overall project. This is quite likely the most complicated, as well as the most critically important, of the steps described in this report. The feasibility of the entire project rests on this assessment, and it must be thorough and comprehensive. Failure to consider all risk could imperil the entire project if this risk assessment is inadequate. Chapter 6 addresses this aspect in greater detail.

5.3 Insurance

The type and extent of insurance necessary for the geologic sequestration project will rely heavily on the risk assessment component of the plan, as described herein, and will be discussed in greater detail in the report that DCNR will submit pursuant to Act 129 by November 1, 2009.

5.4 Outreach

Because of the scope, expense, risks, pioneering nature, and potential nationwide benefits of a geologic sequestration network project in the Commonwealth, extensive public education is essential in this process. Chapter 8 discusses this topic in further detail.

5.5 Site Characterization

After preliminary data collection has been completed and a review of each potential sequestration site's geological characteristics is conducted, a more detailed analysis of the proposed site(s) will be required. A significant component of this review will be the cultural and demographic aspects of the site(s) and how the development of the site(s) may impact, or be impacted by, non-geologic features. If the site(s) is (are) deemed acceptable, a more detailed geologic analysis will begin.

Detailed characterization will require more intensive seismic reflection data. Previous seismic data were two-dimensional (2-D), giving an indication of structure along a profile and the presence/absence of problematic geologic features. 3-D seismic reflection will be required to develop a complete picture of the site(s). Additional near-surface seismic data will be collected to search for shallow geologic features that might compromise the integrity of the storage area.

Careful non-seismic analysis of all surficial features will also be required. This will include mapping using remote sensing data; "on-the-ground" mapping; and near-surface rock and soil sample collection and analyses.

The deeper features, those that intimately describe the reservoir and all its elements, must be examined by drilling into the target formation(s) and performing in-situ testing. Samples must be collected to examine both the strata that will contain the CO_2, and those strata that will confine it. In-situ tests will illuminate the critical parameters affecting the size of the storage reservoir, the ease with which it can be filled, the probability of loss, and numerous other project engineering aspects. This invasive step is both expensive and time-consuming, but will be a necessary component of an investigation.

Each of these geologic steps, as well as others not listed, is critical to the understanding of the site(s), and vital to the development of a complete risk assessment.

While the time required for a thorough evaluation is dependent on numerous factors including money, availability of equipment and talented human resources, the geologic efforts will likely require at least three years to fully describe each site selected for sequestration.

5.6 Monitoring

Chapter 7 indicates some of the monitoring activities required at a potential sequestration site. Monitoring must include a pre-development phase that gathers and evaluates the stability and parochial nature of the area, pre-injection. This will allow us to assess the performance of the reservoir during and following injection. Accurate monitoring will also allow for remedial measures to be applied in a timely and effective manner, should some problem arise. Monitoring also provides data necessary to periodically calibrate the models used to predict reservoir performance.

Monitoring is a scientific necessity, but also a critical outreach element. The public must recognize the scale of the monitoring, understand its intent, and believe that it is appropriate to address any risk elements.

5.7 Regional Studies for Future Site Development

The full development of a state geologic sequestration network that encompasses most/all of the major point sources of CO_2 emissions will require the development – over time – of multiple sequestration sites, sized and located according to network needs, geologic conditions, regulatory frameworks, advancing technology, and the other factors described in this report. Furthermore, should the primary site be found to have a disqualifying flaw, additional sites will be required to begin network development. In addition, based on the amount of CO_2 produced, there will be a continuing need for additional sites. A regional study to develop prospects will require seismic reflection lines, additional LiDAR, and statewide aeromagnetic surveys. Basic geologic mapping, much of which needs to be done anew, will help define additional prospects. Most importantly, the large amount of existing geologic data needs to be entered into a database for ease of use by the Commonwealth and industry. Additional deep wells in previously unexplored regions of the state could produce information that transforms the economic potential of the state.

6.0 RISKS ASSOCIATED WITH CO_2 IN GEOLOGIC RESERVOIRS

The potential risks associated with a CCS project employing geologic sequestration are many. A thorough review of all aspects of a given project site will be required to appropriately assess its risks as well as demonstrate to the public that the full project, from CO_2 capture, to transportation to the sequestration site, to long-term storage, has been evaluated and quantified. Items to be addressed include, among others: (1) environmental issues ranging from land disturbance and habitat infringement to air quality permits for compressor stations water withdrawals; (2) purchasing rights-of-way, land surface, and mineral estates; (3) liability for leaks and related surficial damage; (4) potential for vandalism to pressurized pipelines and/or electrical equipment; and (5) backup sequestration sites in the event of primary site failure.

From a purely geological standpoint, the primary risks associated with a CCS project include: (1) CO_2 and/or methane leakage out of the reservoir through faults and fractures, or through unplugged or improperly plugged wells; (2) seismic events (earthquakes) associated with fault slippage or stressed cap rock; (3) ground movement, particularly surface uplift resulting from overpressuring the reservoir; (4) contamination of groundwater supplies; and (5) displacement of brine and/or CO_2 into non-saline formations or adjacent formations (pore space) owned by third parties (Figure 6.0-1). Each of these is described in further detail below.

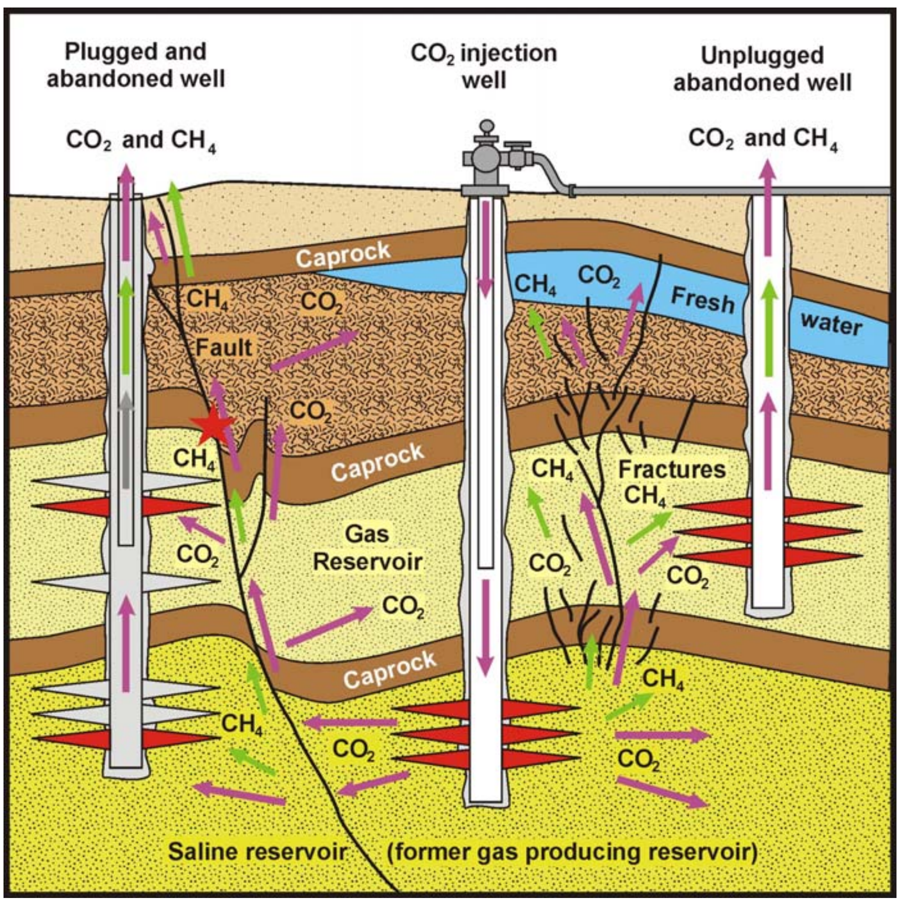

Figure 6.0-1. Potential risks associated with geological sequestration of CO_2.

Leakage of CO_2 that has been injected into a reservoir and/or methane that is native to the reservoir can occur from a variety of factors. Although not all faults and major fracture systems pose a risk to CO_2 leakage, open (non-mineralized) faults and fracture systems passing through reservoir seals can act as migration pathways for reservoir fluids, including any native or injected gases or liquids. The integrity of the injection and monitoring wells, and any other wells in the vicinity, are vital to a safe, reliable sequestration system. The injection well must be properly constructed and inspected during all phases of drilling, casing, cementing, and perforation of the casing and cement prior to injection. It is also imperative that any active or abandoned oil-and-gas wells in the vicinity of the injection well either be plugged or established to have no connection with the injection reservoir. Injecting CO_2 into an area occupied by unplugged or improperly plugged wells invites leakage, especially if the injection reservoir formerly acted as an oil and/or natural-gas producing or gas-storage reservoir. In Pennsylvania's older oil-and-gas fields, many drill holes exist that can constitute a leakage pathway for reservoir gases, including injected CO_2. The safest course of action would be to avoid the oldest of these oil fields, such as those in the northwestern counties (especially Venango, Warren, and McKean), because those areas contain large numbers of oil wells drilled in the late 19th century for which no completion records currently remain.

Although not of great concern in an area as seismically stable as Pennsylvania, storing large amounts of fluids in a rock formation could conceivably alter the rock's mechanical state and change the existing stress fields to the extent that earthquakes might occur. An assessment of the seismic risk at the proposed injection site must occur prior to injection in order to avoid any potential damages.

Injecting CO_2 into a reservoir at a pressure greater than the native rock pressure might result in sinking or uplift at the surface that will damage buildings and other infrastructure. Several situations have occurred in Pennsylvania in the past where a gas storage reservoir was overpressured, resulting in damage to structures at the surface and/or to the other wells in the area. Such cases are rare, but they illustrate some of the risks associated with storing gases under high pressure in a geologic reservoir.

Leakage of injected CO_2 and/or native methane through faults, fractures, or wells can affect potable groundwater supplies. Even small amounts of CO_2 in groundwater can cause significant deterioration in water quality by decreasing pH, which in turn will dissolve calcium, increase water hardness, and potentially change trace element concentrations to levels that exceed drinking water standards. Small amounts of methane in groundwater have been known to find their way into houses through water wells, so it is possible that CO_2 could experience the same fate.

Injection of CO_2 into a deep saline formation could cause displacement of native brine and/or the CO_2 itself into adjacent rock formations. Such an occurrence would not likely affect drinking potable groundwater formations, since these are typically are very shallow (a few tens to hundreds of feet) in comparison to deep saline formations used for geologic sequestration (those that are at least 2,500 ft (762 m) deep). Migration of brine or CO_2 beyond the footprint of the CCS project – that is, beyond the limits of the sequestration reservoir(s) dedicated for CO_2 injection and owned by the Commonwealth or project partners – would, however, impact adjacent mineral/oil-and-gas rights owners. Specifically, the migration of CO_2 or brine could displace hydrocarbons in the pore space owned by third parties, thereby affecting the overall value of such mineral/oil-and-gas ownership.

Additional risks may be posed at the pore-scale level in the sequestration reservoir itself. These include: (1) porosity changes due to precipitation of minerals at or near the injection site; (2) permeability changes due to swelling of in-situ minerals, deposition of contaminants within the injectate, and/or precipitation of minerals in reduced pressure zones away from the injection zone; and (3) solution of soluble minerals and redeposition as the solution becomes saturated with respect to CO_2 or other constituents.

7.0 MEASUREMENT, MONITORING, AND VERIFICATION (MMV)

It is important to recognize that the CO_2 injection performance at a sequestration site must be measured and monitored to demonstrate that the models, studies, and assumptions used to choose the site are valid, and that the guarantees given to the public (at large) and neighbors (in particular) relative to safety are met throughout the life of the project. Similarly, a CCS facility may face financial exposure under a federal cap and trade program or other carbon regime if CCS credits are used to meet carbon constraint standards and the sequestration site fails to some degree and the carbon leaks, financial penalties would result from the release of stored CO_2.[186] To these ends, any sequestration site requires monitoring prior to, during, and after injection of supercritical CO_2 for various reasons for the lifetime of the storage project. Further, the results from MMV should be used in an iterative process in conjunction with modeling to inform site selection, construction, operation, closure, and long-term stewardship or mitigation of leakage should the need arise.[187]

Pre-injection monitoring must be begun prior to site disturbance to ensure that the baseline characteristics of the site are known; this will facilitate the identification of any post-injection variations at the site. While injection is proceeding, monitoring allows the operator to chart the movement of CO_2 through the sequestration reservoir and identify any anomalies that may indicate potential risk. After injection is complete, post-injection monitoring should be employed for several years (as many as 50 years according to some sources) to ensure the injected CO_2 remains sequestered and does not migrate back to the surface. The remainder of this section details some MMV methods that could be employed by the Commonwealth.[188]

7.1 Seismic Activity

Pre-injection baseline data are required to demonstrate that the CCS site is not currently seismically active. This will require placement of seismometers at the site as far in advance of the beginning of injection activity as possible, preferably years in advance. As injection begins, seismic monitoring will allow mapping of the progress of any small rock movement at depth associated with the injection. This may also be useful as a means of determining the progress of the CO_2 front as it moves through the reservoir. Small changes in pressure may make the reservoir rocks move, even a small amount, creating a seismic wave recorded at the surface. These seismic waves may be so small that they could not be detected at any great distance, nor felt by humans.

7.2 Topographic Change

As CO_2 is injected, the land surface will be raised from its original elevation. Therefore, it is possible to map the progression of the injection front as it moves through the reservoir by repeatedly making highly precise topographic measurements. DCNR, through its PAMAP program, acquired a baseline LiDAR coverage of the entire state in 2005-2008. LiDAR is a technique that uses thousands of laser beams, which are shot upward and outward from the ground surface and timed as they bounce back to Earth, resulting in a very detailed topographic map. Injection of CO_2 at any CCS site should be preceded by a local LiDAR acquisition and periodic LiDAR measurement thereafter as long as the site is considered active.

An alternative to LiDAR is to utilize Interferometric Synthetic Aperture Radar (InSAR) on a continuing basis, relying on repeated coverage to show changes in ground elevation without necessarily determining exact elevations. InSAR utilizes the difference in elevation between repeated radar flights to generate a map showing where change is occurring. This could be accomplished using Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR), a NASA instrument on a fixed wing platform, or Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI), a NASA satellite proposed for launch in the near future.[189]

Both LiDAR and InSAR would require a minimum of one year of acquisition before injection to establish earth-tide variation and seasonal variation in groundwater flow. After injection, monthly measurements would be required until the frequency of land change can be established, and thereafter, at such frequency until the site is no longer considered active.

Tiltmeters would also be useful in determining rates of land deformation. Tiltmeters measure tiny changes in orientation of the ground. This approach would provide continuous real-time data at a single point, as opposed to monthly data collected for a wide area.

7.3 CO_2 Measurement

Sensitive CO_2 monitors should be emplaced in boreholes to monitor any CO_2 concentration variations that could be associated with injection. Recent research at MIT's Draper Lab[190] indicates that it is also helpful to flood the region with many small detectors to detect real CO_2 variations in what may be a noisy CO_2 environment (seasonal changes, atmospheric pressure, plant decay, and other activities may contribute to a "noisy" background). Any leakage that may occur is likely to be localized along fractures. Therefore, a carefully planned system of monitors, crossing known fractures, will most likely provide early warning of any leakage.

When injecting CO_2 into a saline formation, CO_2 leakage would likely be preceded by migration of native brines; therefore, a groundwater geochemistry sampling program would be necessary at such a CCS site. Injection of known isotopes could serve as tracers, which could be used to determine the source of the brine(s) and whether they may have originated from the sequestration reservoir(s) used in the project.

7.4 Pressure Monitoring

Reservoir pressure should be monitored for the life of the sequestration reservoir. Variations in pressure will be used to document the movement of supercritical CO_2 through the reservoir, and pressure drops will assist with the identification of CO_2 leakage during or after. This effort would require numerous monitoring wells.

7.5 Seismic Reflection

Seismic reflection data can be used to monitor the location of CO_2 in the subsurface. By sending a seismic wave into the ground and recording its reflected energy, it is possible to map different rock layers (and their characteristics) in the subsurface. Rocks filled with CO_2 will have a different reflectivity (shown as bright spots in a seismic survey) than those filled with brine. This is similar to a technique that has been used for many years in the oil industry to detect gas in a reservoir prior to drilling. Repeated reflection seismic acquisition (preferably 3-D) will allow mapping of CO_2 flow through the reservoir over time.

7.6 Seismic Tomography and Vertical Seismics

Seismic tomography is analogous to a Computerized Axial Tomography (CAT) scan in the medical field, except that it uses seismic energy rather than X-rays. By utilizing boreholes and placing the seismic source at depth, it is possible to create a 3-D seismic picture of the subsurface. In this regard, existing or new boreholes could be used for geophysical monitoring using either a surface or down-hole source combined with down-hole receivers.

7.7 Drilling

A series of boreholes should be drilled outward from the point of CO_2 injection. These will act as geophysical measuring points and subsequently as geochemical sampling points as the CO_2 pressure front advances through the subsurface.

7.8 Hyperspectral Imagery

An airborne scanner with 256 channels of visible and near infrared (NIR; the same frequency as a remote controller for a television) coverage would allow mapping of vegetation stress and change over time to indicate any CO_2 leakage to the surface. Vegetation is highly responsive in the NIR; in fact, stressed vegetation shows a response in the NIR well before it is discernable by the human eye. This technique could be combined with LiDAR data for an effective means of biomass mapping, the important issue here being that a significant change in biomass could be an indicator of CO_2 leakage.

7.9 Thermal Hyperspectral Imagery

An airborne thermal scanner would allow remote mapping of methane and CO_2. By having many channels, discrete absorption features would be detectable in the thermal region, just beyond the NIR spectral region. This portion of the spectrum can measure gas absorption bands. Extensive ground-based observations are required in order to differentiate signal from noise.

7.10 Resistivity and Self-Potential

Electrical geophysical techniques can be used to measure resistivity change in the subsurface.[191] This may be useful in detecting brine movement in the near surface should a leak occur, since salt water would have a higher conductivity.

In summary, Pennsylvania should utilize a combination of the various techniques presented in this section as part of a comprehensive, ongoing MMV program at a sequestration site. Each technique selected, based upon the unique characteristics of the site, should be employed prior to the development of a CCS site so that proper baseline conditions can be documented. To this end, preliminary work has already started with respect to seismicity monitoring and LiDAR measurements on a regional basis across the state. In addition, InSAR, hyperspectral imagery, and seismic reflection data (at a minimum) should be acquired prior to site development.

8.0 PUBLIC OUTREACH, EDUCATION, AND ACCEPTANCE

No assessment of the feasibility of a state CO_2 sequestration network would be complete without some preliminary consideration of the necessity of public involvement in the myriad decisions that will be required as this work moves forward. Although the American public’s awareness of CCS has grown recently – due in large part to the federal government’s focus on global warming impacts and carbon cap and trade considerations

– there still remains an enormous lack of understanding of CCS technologies and the issues surrounding its implementation and potential impact.

Developing an education and outreach program for a Commonwealth CCS initiative must first start with a solid understanding of the communication challenges that surround CCS, global warming, and the Pennsylvania audiences for which the information is intended.

Because the geologic sequestration of carbon emissions has yet to be demonstrated at commercial scale, it brings with it many unanswered questions, all of which could significantly complicate or impede Pennsylvania's efforts to combat global warming through a thorough evaluation, consideration and implementation of CCS. As the Commonwealth studies the geologic, economic, and technologic feasibility for developing a carbon sequestration network, it, too, must analyze and plan for the social science behind such an issue.

Some of the communications obstacles that this effort may face include:

- complexity of sequestration and climate change issues;
- general skepticism or lack of understanding of new technology;
- negative experiences with or distrust in government;
- safety perception or reality;
- perceived resource competition with renewable energy or energy efficiency;
- spending very large amounts of money in a time of fiscal crisis;
- short timeline/urgency; and
- local siting conflicts with tourism/environment.

As Pennsylvania moves forward with the feasibility analysis and, eventually, potential siting of CCS facilities, involved partners must be certain information is provided in an unbiased, open and transparent manner, with the various publics engaged in constructive dialogue. Without this communication process, siting a CCS network in Pennsylvania could prove to be difficult.

The goals of a comprehensive CCS outreach, education, and acceptance strategy should be to:

- increase awareness and understanding of global warming and its effects on

Pennsylvania;

- increase the awareness, understanding, and acceptance of CCS as a safe and effective technology to mitigate carbon's impact on our environment;
- engage stakeholders in a two-way dialogue about the benefits and shortcomings of CCS and its impacts on citizens and the environment; and
- create an open, accessible public process and record of activities.

As with any comprehensive communications strategy, Pennsylvania must quickly and fully engage various audiences as the CCS work begins. Identifying those key stakeholders and understanding their knowledge and acceptance of CCS should be the first step in the process. Focus groups, interviews, research review, and meetings will be key to gauging the current level of understanding of the technology, issues, and concerns of these audiences.

A suite of materials and messages will need to be developed and/or gathered, and tailored in way that will speak to the various audiences. These may include fact sheets, newsletters, displays, and videos, among other, that would all be accessible on a website. The website should serve not only as a clearinghouse of information, but a place where the public can track and comment on specific progress of Pennsylvania's CCS initiative.

Much of the education and outreach should be conducted by a qualified team who is credible, knowledgeable, and trusted. Formation of this team and development of their roles and responsibilities should be a top objective in the communications strategy. These experts will be the face of CCS in the Commonwealth, and will be the core communicators with identified constituencies. This group of scientists, government officials, respected community and environmental leaders, and academics will require set themes, messages and presentations from which to work.

Much of the CCS outreach and education work will need to be through face-to-face communications – briefings and detailed presentations to community organizations, policy makers, environmental groups, associations, and other identified stakeholders. Larger forums and events – perhaps developed through national and international CCS work – should play into the overall mix of public outreach and education.

Even though face-to-face communications will be central to gaining a public acceptance of CCS, the media will play an important role in helping to widely disseminate information about Pennsylvania's work. A media plan that targets key reporters and media outlets, and works with editorial boards to ensure factual and unbiased information, will help raise the general public's awareness of this issue. It will be important to closely monitor media coverage of CCS, particularly in smaller communities, or those targeted for development. Misinformation should not go unchallenged.

Throughout every step of the Commonwealth's CCS work, there needs to be opportunities for those leading the project to hear from citizens. Those in leadership roles should be willing and able to respond and react to questions and concerns. Citizens must believe they are not being shut out of the work, particularly those identified as being most impacted by this technology.

Pennsylvania is not alone in the need to educate affected stakeholders about CCS. Worldwide focus on CCS has prompted international organizations, companies, and consortiums to begin development of public education and outreach strategies. While faced with its own communications challenges and circumstances, Pennsylvania should capitalize on the explosion of international focus on this issue. By joining forces with global organizations, scientists and experts, the Commonwealth can leverage expertise to produce a credible and integrated communication program.

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11.0 GLOSSARY

3-D seismic: A method of displaying a three dimensional-image of the Earth's subsurface as created by the interpretation of the seismic data that have been collected through numerous seismic surveys run in a grid pattern. 3-D seismic surveys display more detailed information on the subsurface than do conventional surveys and contribute significantly to field appraisal, exploitation, and production.

Acidizing: A process used by the oil-and-gas industry to help make a well begin to produce by pumping acid down the well bore. This is used to: (1) remove mud injected during drilling; or (2) injected into limestones and dolostones, and in sandstones cemented with carbonate cement, to dissolve some of the rock or cement, thereby increasing permeability and allowing hydrocarbons to flow more readily.

Adsorb: Pertaining to the accumulation of a substance on a surface through adsorption. Adsorption: A process that occurs when the molecules of a fluid accumulate on the surface of a solid or a liquid, forming a film.

Adsorption storage: The retention of CO_2 molecules onto the fracture faces and matrix of organic-rich rocks such as coal or black shale.

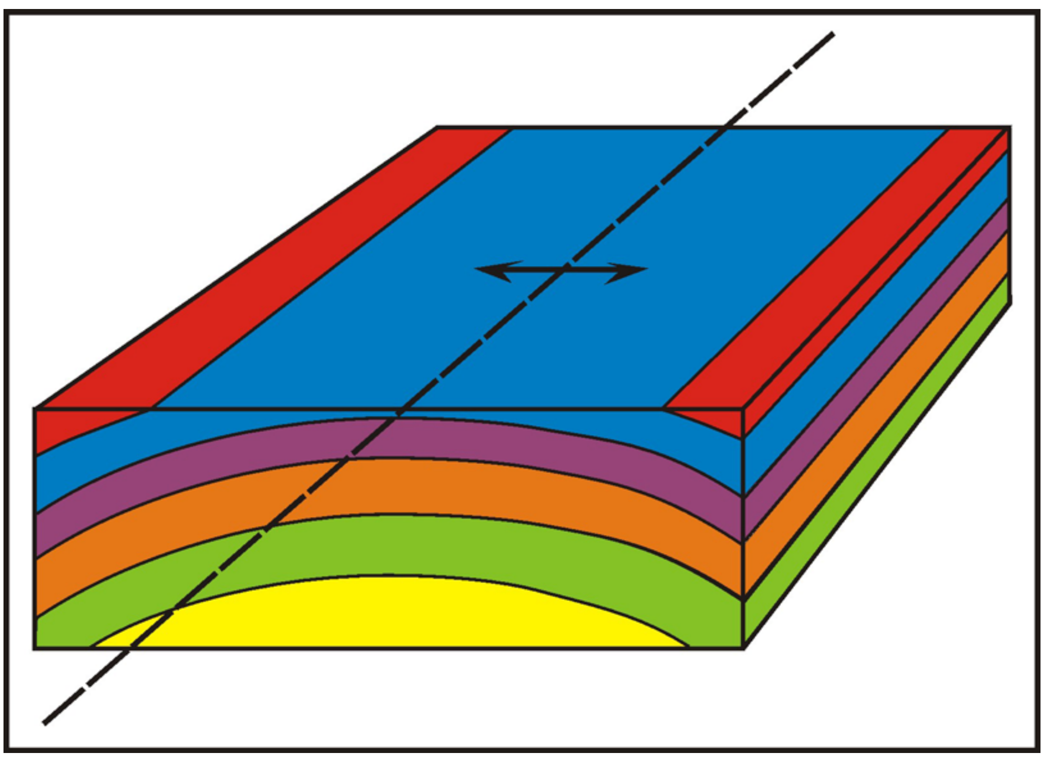
Aeromagnetic: Pertaining to the natural magnetic signature of the Earth, as detected by sensitive instruments flown over the area of interest by aircraft, and displayed as a map of the variations or anomalies they detect.

Aggradational: Building up through deposition. For example, a pond will be filled with mud and sand as the result of aggradation.

Anhydrite: A mineral consisting of calcium (Ca), sulfur (S), and oxygen (O), with the chemical formula $CaSO_4$. It is akin to gypsum, but differs in having no water molecules in the chemical matrix.

Ankerite: A mineral consisting of calcium (Ca), carbon (C), oxygen (O) and iron (Fe), magnesium (Mg), and/or manganese (Mn) in the matrix, with the chemical formula $Ca(X)(CO_3)_2$ where (X) represents iron, magnesium, and/or manganese.

Anticline: An upward fold in rocks, typically caused by mountain-building pressures.



Arbitrary cutoff: The boundary between two different intergrading rock units, based on geologic preferences such as rock color, bedding changes, or lithologic changes.

ArcGIS: A suite of geographic information system software products produced by ESRI, a commercial company.

Argillaceous: Largely containing clay-size material. A synonym for "shaly."

Artificial stimulation: Any method used to increase production in a well. Examples include hydraulic fracturing, shooting with nitroglycerine, and acidizing.

Authigenic: Formed or generated in place, generally referring to portions of a rock that were not transported as sediment to the site where the rock was formed. For example, in some sandstones, minerals are formed by precipitation long after the sediments has been hardened.

Basalt: A dark-colored igneous rock, generally created by volcanic activity.

Basement: The undifferentiated complex of, generally, igneous and metamorphic rocks that underlies.

Basin: A depression in rocks. In the structural sense, a basin is a downward fold that dips inward in all directions.

Beach face: The section of a beach exposed to the action of waves.

Bedding: The arrangement of a sedimentary rock in beds or layers of varying thickness and character.

Biochemical sequestration: The process of using microbes to convert CO_2 into useful products such as methane (natural gas).

Braided: A type of stream that has a channel consisting of a network of smaller, interweaving channels separated by small and often temporary low islands or bars, giving it an aspect roughly reminiscent of braided hair or rope.

Brine: Salt-saturated water that that occupies the pore spaces of sedimentary rocks. Essentially, concentrated sea water.

Calcareous: Containing more than 50% calcite. A synonym for "limey."

Calcite: A common mineral composed of calcium (Ca), carbon (C), and oxygen (O) with the chemical formula $CaCO_3$. Calcite is the primary constituent in limestone and marble, and commonly acts as cement in sandstone and conglomerate.

Capillary pressure: The difference in pressure across the interface between two immiscible fluid phases within the pore space of a sedimentary rock.

Cap rock: A comparatively impermeable rock layer overlying a reservoir rock that keeps the reservoir fluids from escaping upward.

Carbonaceous shale: A dark-gray or black shale with a significant carbon content. Also called organic-rich shale.

Carbonate: A rock originally formed by precipitation of calcareous minerals such as calcite or dolomite. Examples of carbonate rocks include limestone and dolostone.

Carbon capture: The first step in carbon sequestration, involving capturing carbon dioxide at its source before it is pressurized and turned into a supercritical fluid for sequestering.

Carbon dioxide: A chemical compound, usually in a gaseous form, composed of carbon (C) and oxygen (O), and having the chemical formula CO_2. It is considered to be one of the major greenhouse gases that contribute to global warming.

Carbon sequestration: Disposing of carbon dioxide through oceanic, chemical, biochemical, terrestrial, or geological means.

Casing: Heavy metal pipe that is put into a borehole following drilling and cemented in place. The pipe serves multiple purposes: (1) it keeps the rock in the wall of the borehole from caving in and filling the hole; (2) it prevents drilling fluids from invading the rocks being drilled; and (3) it prevents fluids within the rocks from entering the borehole.

Cement: Mineral material, such as calcite or silica, which fills the pore spaces in a sedimentary rock and helps holds the grains together.

Cementation: The process by which sediment grains are bound together and solidified into solid rock through the deposition and/or alteration of minerals within the pore spaces of the rock.

Chalcedony: A very hard mineral that is composed of silicon (Si) and oxygen (O), and has the chemical formula SiO_2. It is essentially the same as quartz, but has an extremely small crystal structure. Common names, depending on elemental impurities and gemstone quality, include agate, carnelian, flint, jasper, onyx, and sard among many others.

Chemical sequestration: Mixing CO_2 with an element or mineral that results in a stable compound that has value in manufacturing, chemicals, agriculture, and other industries.

Chert: (1) A common chalcedony mineral found in sedimentary rocks; (2) a common sedimentary rock, usually a limestone or siltstone, with a substantial amount of the mineral chert distributed throughout the rock.

Chlorite: A form of clay mineral commonly found in sedimentary rocks and composed of aluminum (Al), silicon (Si), oxygen (O), hydrogen (H), and iron (Fe) or magnesium (Mg). The chemical formula is $(Mg, Fe^{+2}, Fe^{+3})_6AlSi_3O_{10}(OH)_8$.

Clastic: Pertaining to a rock or sediment composed of broken fragments derived from pre-existing rocks. For example, quartz sand is a clastic sediment, and quartzose sandstone is a clastic rock.

Clay mineral: Any of a complex group of very finely crystalline minerals typically composed of aluminum (Al), silicon (Si), and oxygen (O) in combination with other elements. Clay minerals typically are formed by the deterioration of other minerals such as feldspar. Examples of clay minerals include chlorite, illite, and smectite among many others.

CO_2 front: The moving contact between injected supercritical CO_2 and the natural fluid (brine, oil, gas) content of the sequestration reservoir formation.

Coal: A combustible rock composed primarily of carbonaceous material derived from ancient plants. Two main varieties occur in Pennsylvania – bituminous (soft coal) is prevalent in western Pennsylvania and anthracite (hard coal) occurs exclusively in eastern and northeastern Pennsylvania.

Coalbed methane: Natural gas produced from coal seams.

Coarsening-upward sequence: A sequence of rocks in which the sizes of the grains of sediment gradually become larger from the bottom to the top of the sequence.

Coarse sand: Sand composed of grains that have diameters in the range of 0.5 to 1 millimeter. A rock composed of coarse sand is called a coarse-grained sandstone.

Combination trap: A type of trap for oil and gas that has elements of both structural traps and stratigraphic traps.

Compaction: The process that reduces the bulk volume and the pore space of fine-grained sediment by the weight of overlying sediment, turning it into rock.

Compressive strength: The maximum pressure applied through compression that a material can withstand before it fails.

Conductivity: The ability of a fluid-filled rock to conduct an electric current.

Confining layer: A layer of impermeable rock that is vertically and/or laterally adjacent to a reservoir, and is able to keep fluids from escaping.

Conformable: A term applied to a vertical sequence of rocks in which the layers formed by regular, uninterrupted deposition.

Conglomerate: A sedimentary rock composed largely of grains larger than 2 millimeters in diameter (including pebbles, cobbles, and boulders). Most conglomerates are sandstones containing a large percentage of gravel.

Conglomeratic: Pertaining to a sedimentary rock having the composition and qualities of a conglomerate. For example, a conglomeratic sandstone.

Continental shelf: The wide, flat underwater regions at the edges of many continents.

Contour line: A line drawn on a map connecting points of equal value. The most readily recognizable contour lines are those on a topographic map indicating elevation. Other examples include maps that have contour lines indicating drilling depth, thickness of a formation, or net feet of a specific rock type within a formation.

Core: A cylindrical section of rock, typically anywhere between 1 and 6 inches in diameter and between 1 inch and several tens of feet long, cut in a borehole using specialized drilling tools. There are two basic types of cores, full-barrel core and sidewall core.

Craton: A portion of the Earth's crust that has attained stability and has not been deformed for a long time.

Cratonic: Pertaining to the craton.

Creep: The slow movement of a mineral, rock, or soil under stress. Creep generally occurs as a result of gravitation (for example, soil creep on a slope), but vertical and lateral stresses can also affect rocks and minerals as a result of small, constant stresses acting over a long period of time.

Crop line: A line shown on a map indicating the surface expression of the boundary between two rock units.

Crossover: On a geophysical log, the place at which two log signatures cross. For example, where the density and neutron log signatures cross, the rock being logged is considered to have relatively good reservoir potential.

Crystalline rock: A rock consisting of interlocking mineral crystals, rather than discrete grains. The term generally is used to distinguish igneous and metamorphic rocks (crystalline) from sedimentary rocks (non-crystalline).

Deltaic: Pertaining to a delta.

Density log: A type of geophysical log generated by recording the back scatter of gamma rays into to the rock of the borehole. The density log measures the bulk density of the rock and its contained fluids.

Density porosity: On a geophysical log, the calculated percentage of pore space in a rock as measured by the density log.

Depleted: Pertaining to an oil-and/or-gas field that has reached its economic limit of productivity. Even when all available technology has been exhausted, a field will still contain as much as 70 or 80 percent of the original hydrocarbons in the reservoirs within the area of the field.

DESDynI: A dedicated NASA satellite mission to study geologic hazards and global environmental change. It is an acronym for Deformation, Ecosystem Structure and Dynamics of Ice.

Detachment: Pertaining to a large section of rock strata that has been separated along faults and moved away from its original location.

Diabase: A type of igneous rock that formed dikes and sills in southeastern Pennsylvania.

Diagenesis: All of a large variety of physical and chemical changes that take place within sediment and the sedimentary rock it becomes from the time it is deposited to the time it is exposed to erosion.

Dike: A body of igneous rock that intrudes into and cuts across the bedding of the surrounding rock.

Dilation: Deformation to a rock caused by a change in its volume without a change in its shape.

Dip: The angle that a bedding plane or fracture plane makes relative to horizontal. For example, beds dipping at 90^o are vertical whereas those dipping at 0^o are flat-lying.

Dipmeter log: A type of geophysical log that can be used in conjunction with other geophysical logs to determine and measure the dip and strike of rocks in the subsurface.

Disconformable: A term applied to a break in a vertical sequence of rocks where the layers were interrupted during deposition.

Discontinuity: An interruption in deposition within a vertical sequence of rocks.

Dissolution: The process of dissolving a solid substance in a solvent.

Dissolution porosity: An increase in porosity within a rock caused by the dissolution of grains, cement, or matrix.

Distal: Situated farthest away from the center or point of interest.

Dolomite: A common carbonate mineral composed of calcium (Ca), magnesium (Mg), carbon (C), and oxygen (O) with the chemical formula $CaMg(CO_3)_2$. Dolomite is the primary constituent in dolostone, and commonly acts as cement in sandstone and conglomerate.

Dolostone: A carbonate rock composed primarily of the mineral dolomite.

Drill cutting: Rock chips cut by a drill bit during the drilling of a borehole and retrieved in order to provide a record of the rock layers penetrated by the drill.

Drill-stem pressure test: A procedure for measuring the natural pressure in a reservoir while the drill string is still in the borehole.

Drill string: An assemblage of connected pipes, collars, and bits used to drill a well. Also called drill stem.

Dual induction log: A type of geophysical log that consists of two separate measurements of electrical conductivity from different depths within the rock wall of a borehole.

Ductile: The physical quality of a material, such as rock, that allows it to undergo 5 to 10% deformation before failing.

Duplex: A system of overlapping thrust faults that branch off from a single fault below and merge with a separate thrust fault above. This process forms stacks of fault-bounded rock bodies that are bounded above and below by thrust faults.

Earth-tide: The variable 12-hour, or longer, motion of the Earth caused by the gravitational effects of the sun and moon.

Effective permeability: The ability of a rock to conduct one fluid, for example natural gas, in the presence of other fluids such as oil or water.

Enhanced coalbed methane recovery (ECBM): An artificial method of producing large quantities of coalbed methane from a coal seam by injecting another gas such as carbon dioxide into the seam to drive off the methane.

Enhanced oil recovery (EOR): A method of stimulating crude oil production in a "depleted" reservoir by injecting another fluid such as water, steam, chemicals, or carbon dioxide into the reservoir. The injected fluid helps loosen the oil from pore spaces in the rock and flushes the oil to a nearby borehole while taking the place of the oil in the pores.

Epeiric sea: A sea or ocean situated within the interior of a continent.

Estuarine: Pertaining to an estuary, the seaward end of a river valley where fresh river water meets and mixes with sea water.

Eustatic: Pertaining to worldwide changes in sea level, affecting all oceans simultaneously. For example, increasing water volume in the oceans by melting the ice caps causes a eustatic rise in sea level.

Evaporite: A type of sedimentary rock formed by precipitation of minerals produced in saline water as a result of evaporation.

Facies: Characteristics of a rock unit that reflect the conditions of its origin. These characteristics may change relative to the same rock unit or to other rock units that are deposited at the same time, reflecting changes in the depositional environments.

Fault: A fracture in rocks along which movement has taken place.

Fault slice: A rock mass that is bounded on at least two sides by faults.

Feldspar: A general name for a group of common rock-forming minerals composed of aluminum (Al), silicon (Si), oxygen (O), and one of several other elements.   The chemical formula is $[X]AlSi_3O_8$, where [X] stands for potassium (K), sodium (Na), calcium (Ca), barium (Ba), rhubidium (Rh), strontium (Sr), or iron (Fe).

Fining-upward deposit: A sequence of rocks in which the sizes of the grains of sediment gradually become smaller from the bottom to the top of the sequence.

Flagstone: A hard form of thin-bedded, fine-grained sandstone that splits fairly uniformly into thin slabs suitable for use in flooring, retaining walls, as decorative stone facades, etc.

Fluid saturation: The measure of the gross pore space in a reservoir rock that is occupied by a fluid, expressed as a percentage.

Fluvial: Pertaining to streams and their processes.

Fluvial-deltaic: Pertaining to streams associated with deltas and their processes.

Fold: A bend in rock layers caused by deformation. The two primary types of folds are anticlines and synclines.

Foreshore: The outer, seaward-sloping part of a shore or beach lying between the tide levels.

Formation: A body of rock identified by its character and position within a rock sequence that allow it to be mapped as a unit.

Formation microimager (FMI):   A type of specialized geophysical log produced by Schlumberger that generates an electrical image of the borehole from numerous measurements of fluid resistivity in the rock.

Fracture face: The surface of a fracture.

Fracture porosity: The pore space within a rock that results from the presence of fractures.

Framework grains: Particles (grains) within a sedimentary rock that support one another in a rigid arrangement because they are in direct contact.

Gamma-ray log: A type of geophysical log that measures the natural gamma radiation emitted by subsurface rocks. The gamma-ray log is used to determine the type of rock penetrated in the borehole and to establish formation boundaries in the subsurface.

Gas absorption band: The the wavelength range over which electromagnetic energy is absorbed by a particular gas.

Gas column: The vertical producing zone of a gas-producing formation.

Gas drive: A form of secondary recovery method in which air or natural gas is injected into a reservoir to help reestablish the rock pressure and loosen the oil in the pore spaces of the rock so that it can be flushed to a nearby borehole.

Gas effect: An effect methane gas has on neutron and density logs that causes them to be misinterpreted. Because gas is less dense than liquids, a gas reading on the density log translates into porosity that is too high; however, gas has much less hydrogen per unit volume than oil and water, so the gas reading on the neutron log translates to porosity that is too low. The use of a combination of neutron and density logs is advantageous because the average of neutron and density porosity values is usually close to the true porosity, regardless of the type of rock in the borehole.

Gas phase: The state of an element or compound with relatively low density and viscosity and without a specific shape or volume. H_2O has three phases: solid (ice), liquid (water), and gas (steam or water vapor).

Geodatabase: a database designed to store, query, and manipulate geographic information and spatial data. Also called a spatial database.

Geographic Information System (GIS): A sophisticated computer mapping system that captures, stores, analyzes, manages, and presents digital geographic data, allowing users to create interactive queries, analyze spatial information, create and edit data and maps, and present the results in easily understood formats.

Geologic map: A map that records some aspect of geology such as the location, distribution, thickness, or attitude of surface and subsurface rocks.

Geologic province: An extensive region that is characterized by similar geologic history, or by similar geological features such as folds and faults, rock types, or topography.

Geologic sequestration: Storing CO_2 underground in saline formations, coal seams, carbonaceous shales, salt caverns, depleted oil-and-gas reservoirs, or other rock units.

Geologic structure: Layers of rocks that have been displaced from their normal horizontal position by the forces of nature. Common geologic structures include folds, faults, and joints.

Geophysical log: A graphic record of the physical characteristics of the rock in a borehole measured by various instruments and plotted by depth. A suite of geophysical logs can give valuable information on formation boundaries, rock type, amount of pore space, type and amount of fluids in the rock, temperature, direction and angle of dip, presence of and offset along faults, and other important features. Some of the more common geophysical logs used in Pennsylvania include gamma-ray, caliper, neutron, density, resistivity, temperature, photoelectric, sonic, and dipmeter.

Geothermal gradient: The rate of increase in temperature in the Earth with depth.

Gigatonne: One billion metric tonnes, a mass equal to 2,204,626,600,000 pounds (1.1023 billion tons).

Glauconite: A name usually given to a group of greenish minerals composed of aluminum (Al), silicon (Si), oxygen (O), hydrogen (H), and potassium (K) or iron (Fe). The chemical formula is $[X]Al_2Si_4O_{10}(OH)_2$, where [X] is either potassium or iron.

Gneiss: A metamorphic rock composed of bands of minerals that formed by the application of heat, pressure, or chemical changes to a sedimentary or igneous rock.

Granule: A sediment grain larger than coarse sand (0.5 to 1 millimeter) but smaller than a pebble (4 to 64 millimeters).

Gravity: The gravitational force of the Earth, as measured by very sensitive instruments at the Earth's surface, and displayed as a map of the gravitational variations or anomalies they detect.

Greenhouse gas: Any gas, such as carbon dioxide, water vapor, or methane, which traps heat and causes an increase in temperature.

Grid data: Raster-based GIS data formats composed of square grid cells each with an associated X, Y, and Z value. The X and Y points give the grid a geographic location and the Z-value represents the information being mapped, for example elevations, depths, or thicknesses.

Group: A rock unit consisting of one or more formations.

Gypsum: A common mineral composed of calcium (Ca), sulfur (S), oxygen (O), and hydrogen (H). The chemical formula is $CaSO_{4+}{\cdot}2H_2O$. Gypsum is popularly known as Epsom salts and is the main ingredient in plaster of Paris.

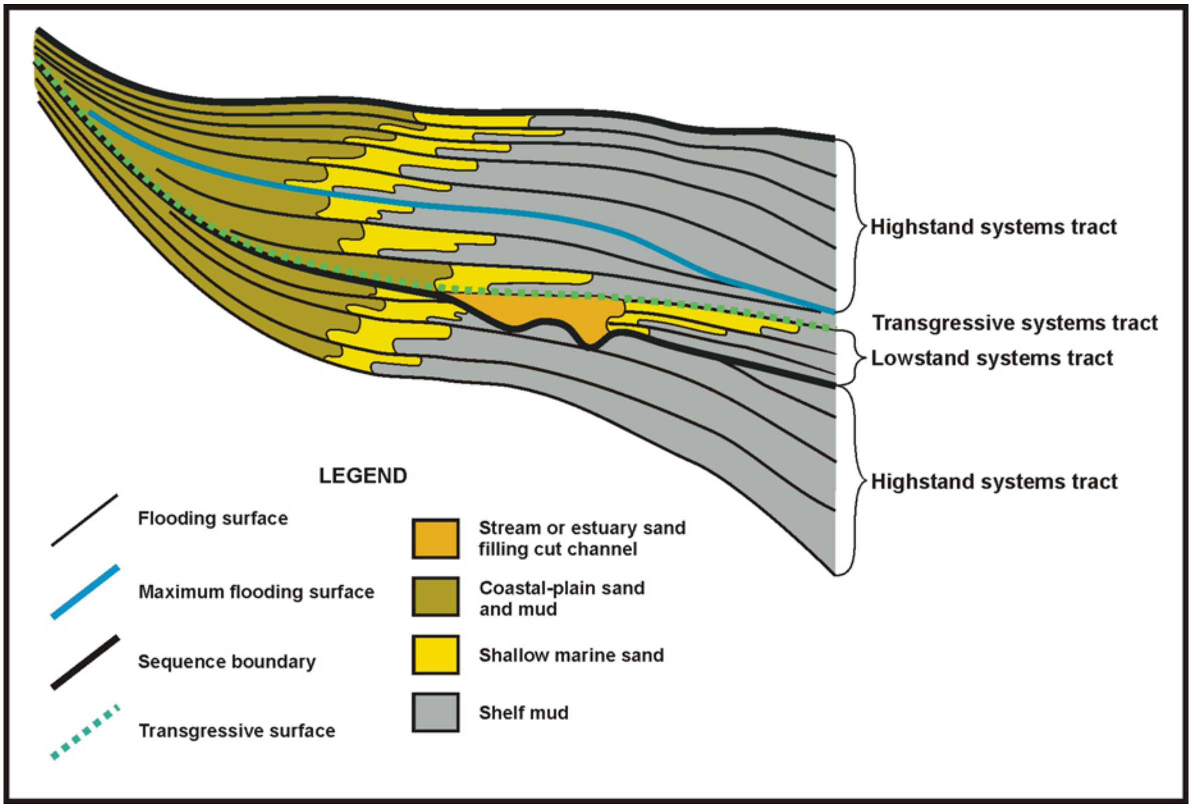
Halite: A common mineral composed of sodium (Na) and chlorine (Cl), with the chemical formula NaCl. In large accumulations it is called rock salt. In its unrefined state it is used for road salt, and when refined it is table salt.

Hematite: A common mineral composed of iron (Fe) and oxygen (O), with the chemical formula Fe_2O_3. In large amounts, it is a valuable iron ore. In minute amounts, it often occurs as a cement in sedimentary rocks.

Heterogeneity: The measure of how parts of a rock sample are different from one another.

Heterogeneous: Pertaining to the aspect of a rock that consists of multiple characteristics having a large number of variations.

Highstand systems tract: An aggradational to progradational set of genetically related beds that overlie the maximum surface of marine flooding during sea level rise.



Hydraulic fracturing: Also called "fracing" (pronounced "fracking"), the process of creating porosity and permeability in a reservoir by injecting large amounts of fluid into the rock of a borehole under high pressure. The pressurized fluid fractures the rock, and the fractures are propped open with sand or some other granular material that is injected with the fluid. This allows gas or oil trapped in the reservoir to flow to the borehole.

Hydrocarbon: Any of a large variety of chemical compounds in which carbon (C) and hydrogen (H) are the primary ingredients. Methane (CH_4) is the simplest hydrocarbon compound. Other well-known examples include propane and butane.

Hydrodynamic flow regime: A range of fluid flows having similar flow form and resistance.

Hyperspectral: Pertaining to information collected from across the electromagnetic spectrum. For example, infrared, ultraviolet, and visible light.

Igneous rock: A rock that cools and crystallizes out of a molten state. There are two broad categories of igneous rocks: (1) those that cool at or close to the Earth's surface (volcanic or extrusive). Examples include basalt, pumice, and obsidian or volcanic glass; and (2) those that cool at some depth below the Earth's surface (plutonic or intrusive). Granite is an example of a plutonic igneous rock.

Immiscible: Pertaining to the relationship of two or more fluids that, at equilibrium, will not completely dissolve into one another. For example, oil and water are immiscible.

Impermeability: An aspect of rock in which the pore spaces are not connected, keeping fluids from being transmitted from one place to another under pressure.

Incised valley-fill deposit: An accumulation of sediment that fills all or part of a valley that has been cut down into the surrounding landscape.

Injectate: A fluid that is injected into a borehole. Examples include water, brine, and carbon dioxide.

Injection string: That portion of the casing in a well through which a fluid is injected into the rock within the borehole for the maintenance of pressure or for enhanced recovery of hydrocarbons.

Injectivity: The rate and pressure at which fluids can be pumped into a formation without fracturing the rock.

In-situ: In the original place or site.

Insoluble residue: The material remaining after a rock sample has been dissolved in acid.

Interbedded: Pertaining to beds lying between, or alternating with, beds of a different character. For example, where thin beds of sandstone alternate with beds of shale.

Interferometric synthetic aperture radar (InSAR): A remote sensing technique that uses two or more synthetic aperture radar images to generate maps of surface deformation or digital elevation using differences in the phase of the radar waves bouncing off the Earth's surface and returning to the satellite or aircraft carrying the instruments. This technique can potentially measure centimeter-scale changes in deformation over time spans of days to years.

Intergranular porosity: The accumulated pore space in a sedimentary rock that occurs between adjacent grains, expressed as a percentage of the rock volume.

Intergranular void: An open space between the grains of a sedimentary rock.

Interstitial fluid: A fluid that occurs within the pore space of a sedimentary rock.

Intraconstituent porosity: The pore spaces developed within sediment grains as a result of irregularities within or leaching of the grains.

Island arc: A generally curved belt of volcanic islands.

Isoline: The general name for a line on a map that connects points of equal value. For example, the lines of elevation on a topographic map are isolines.

Isopach map: A type of map that uses isolines to indicate the thickness of a rock unit.

Isotope: Any of the different types of atoms of the same element, each having a different atomic mass as a result of different numbers of neutrons in the nucleus. For example, the nucleus of hydrogen most commonly has one proton but no neutrons. The hydrogen isotope called deuterium has one proton and one neutron, and the isotope called tritium has one proton and two neutrons.

Joint: A fracture in rock along which movement has not taken place.

Kinetics: The rates of chemical reactions, the factors that affect those rates, and the reaction mechanisms associated with the formation or dissolution of minerals in a rock.

Lagoonal: Pertaining to a lagoon, a shallow body of seawater that is separated from the open sea by an elongate strip of land, such as a sand bar, barrier island, or reef.

Lamination: The thinnest recognizable layer of deposition in a sedimentary rock, typically shale or very fine-grained sandstone.

Leaching: The act of creating a cavity in a salt bed or salt dome by flushing water into the rock to dissolve the salt.

Legacy data: Geological data already in existence. For example, known outcrops and structures in a particular area.

Lens: A body of sedimentary rock that is thick in the middle and thin at the edges (that is, lens-shaped).

LiDAR: A remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target. The term is an acronym for Light Detection And Ranging.

Limestone: A carbonate rock composed primarily of the mineral calcite.

Lithologic: Pertaining to the physical character of the rocks.

Lithology: The study, description, and physical character of rocks. Also often used as a synonym for rock type.

Lithostratigraphic: Pertaining to the organization of rock strata.

Lithostratigraphy: The study, description, and organization of rock strata.

Littoral: Pertaining to the bottom of the ocean that lies between high and low tides.

Longshore bar: An low sand ridge build by wave action that occurs parallel to, and at a distance from, the shoreline.

Lower shoreface: The portion of the seafloor along a coast that is deeper than the area affected by normal wave action.

Marble: A metamorphic rock composed primarily of calcite that was formed by applying heat and pressure to a limestone.

Marine shelf bar: A submerged (or partly submerged) ridge occupying seafloor between the shoreline and the deep ocean.

Matrix: Fine-grained material in a sedimentary rock that encloses, or fills the interstices between, larger grains.

Metamorphic rock: A rock formed from a pre-existing rock by the chemical or physical actions of heat, pressure, or chemical alteration. Common metamorphic rocks include marble, slate, and gneiss.

Methane: A flammable compound composed of carbon (C) and hydrogen (H), and having the chemical formula CH_4. Methane is the primary ingredient in natural gas.

Microfracture: A very small or fine fracture in rock.

Microporosity: The pore space in a rock that is has diameters of less than 2 nanometers (billionths of a meter).

Migration: The movement of a fluid, such as oil or gas, from the place where it is formed (source rock) to a reservoir.

Millidarcy: A measurement unit of permeability; one thousandth of a darcy. A darcy is defined as the measure of the flow of 1 cubic centimeter per second of a fluid with a viscosity of 1 centipoise under a pressure gradient of 1 atmosphere per centimeter acting across an area of 1 square centimeter.

Mineralogy: The study of the formation, occurrence, properties, composition, and classification of minerals.

Mineral storage: The storage of carbon dioxide through the chemical reaction of the CO_2 with the minerals and brine in the rock unit being used for sequestration.

Miscible: Pertaining to the relationship of two or more fluids that, at equilibrium, will mix with one another to form a single fluid.

Moldic porosity: Pore space in rock formed by the preferential dissolution of grains, cement, or other materials, resulting in a void or empty mold that bears the shape of the former material.

Monitoring well: A well used to monitor the hydraulic head or sample the groundwater for chemical constituents.

Monocrystalline: Pertaining to a mineral formed as a single crystal-unit so all parts have an identical crystal orientation.

Mud log: A continuous description of the drilling mud and drill cuttings produced from a borehole that permit analysis of subsurface rocks and their potential for oil-and -gas production during drilling.

Mudrock: A general term for any sedimentary rock composed of clay- and silt-size particles.

Multicycled sediment: Sediment that has undergone more than one stage of deposition and erosion. For example, the Oriskany Sandstone is the end product of deposition, lithification, and erosion of at least two older formations.

Multistory: Pertaining to rock units that contain numerous layers of a particular lithology, separated by other lithologies. For example, a formation that has five or six thick sandstone beds separated by tens of feet of shale.

Net feet: The total thickness of a particular lithology in a formation, determined by adding together the individual thicknesses of all layers of that lithology.

Neutron log: A type of geophysical log generated by recording the intensity of neutron or gamma radiation produced when the rock in a borehole is bombarded by neutrons. The neutron log indicates the presence of fluids in the rock, and can be used with the gamma ray log to calculate porosity.

Neutron porosity: On a geophysical log, the calculated percentage of pore space in a rock as measured by the neutron log.

Normal: Formed at right angle to; perpendicular.

Oceanic sequestration: Using the ocean to sequester carbon dioxide, either by injecting liquefied CO_2 directly into the deep ocean where the increased pressures and decreased temperatures would keep it in its supercritical phase, or by stimulating the growth and reproduction of phytoplankton that remove CO_2 from the atmosphere during photosynthesis.

Offshore bar: A low, elongate body of sand in the ocean, either submerged or above water level, situated some distance from the shoreline.

Onlap: The phenomenon of successively younger layers of rock extending progressively further across an erosion surface in older rocks.

Organic-rich: Containing a large amount of material derived from once living organisms; carbonaceous.

Orogeny: The process of mountain building.

Orthophotography: Photography of the Earth's surface from the air or space that has been geometrically corrected so that the scale is uniform and the photograph has the same lack of distortion as a map of the same region.

Orthoquartzite: A quartzose sandstone so thoroughly cemented it has the appearance of quartzite, a type of metamorphic rock.

Outcrop: That part of a rock formation that appears at the surface.

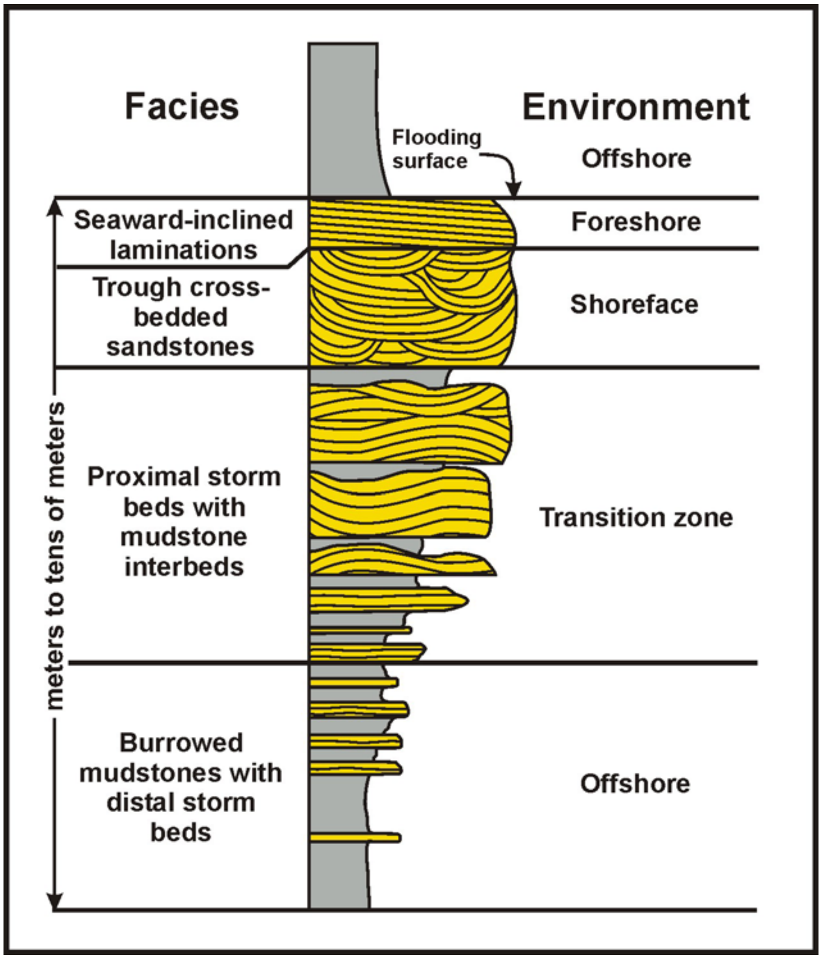
Overburden: The geological material (rock and soil) that lies above the area or rock formation of interest.

Overpressured: Pertaining to a rock unit in which the pore pressure is greater than normal pore pressure for a rock unit at that depth.

Paleotopographic high: An elevated portion of land surface, such as a hill, that existed in the geologic past and has been preserved within the rock record.

PAMAP: An electronic map of Pennsylvania that is currently being created as a seamless, consistent, high-resolution set of digital geospatial data products. The map is being compiled from new high-resolution aerial photography and elevation data, and from existing digital map resources developed by state and federal agencies, counties, regional agencies, and municipalities.

Parasequence: An asymmetrical shallowing-upward sedimentary cycle in which all parts were deposited in lateral continuity to one another, and bounded by marine flooding surfaces and their lateral correlative surfaces.



Pay: That part of a rock unit that produces or is capable of producing oil, gas, water, or other economic product.

Perforation: A hole punched through the steel casing and cement in a well into the producing formation so that fluids can flow from the formation into the well.

Permeability: The capacity of a reservoir rock to allow fluids to pass through it, expressed in millidarcy.

Permeable: Pertaining to a rock that will allow fluids to pass through it.

PETRA: A sophisticated suite of software products from IHS, a commercial oil-and-gas information company, that provides integrated applications in database management, geological mapping, construction of cross-sections, analysis of geophysical logs, production and reservoir analysis, and 3-D modeling.

Petrographic: The branch of petrology that focuses on detailed descriptions of rocks.

Petrology: The study of rocks and the conditions in which they form.

Petrophysics: The study of the physical and chemical properties that describe the occurrence and behavior of rocks.

pH: The measure of the acidity or alkalinity of a fluid. The pH scale ranges from 0 to 14, where values from 0 to <7 are called acidic, values equal to 7 are called neutral, and values from >7 to 14 are called basic. The term is an acronym for potential of Hydrogen.

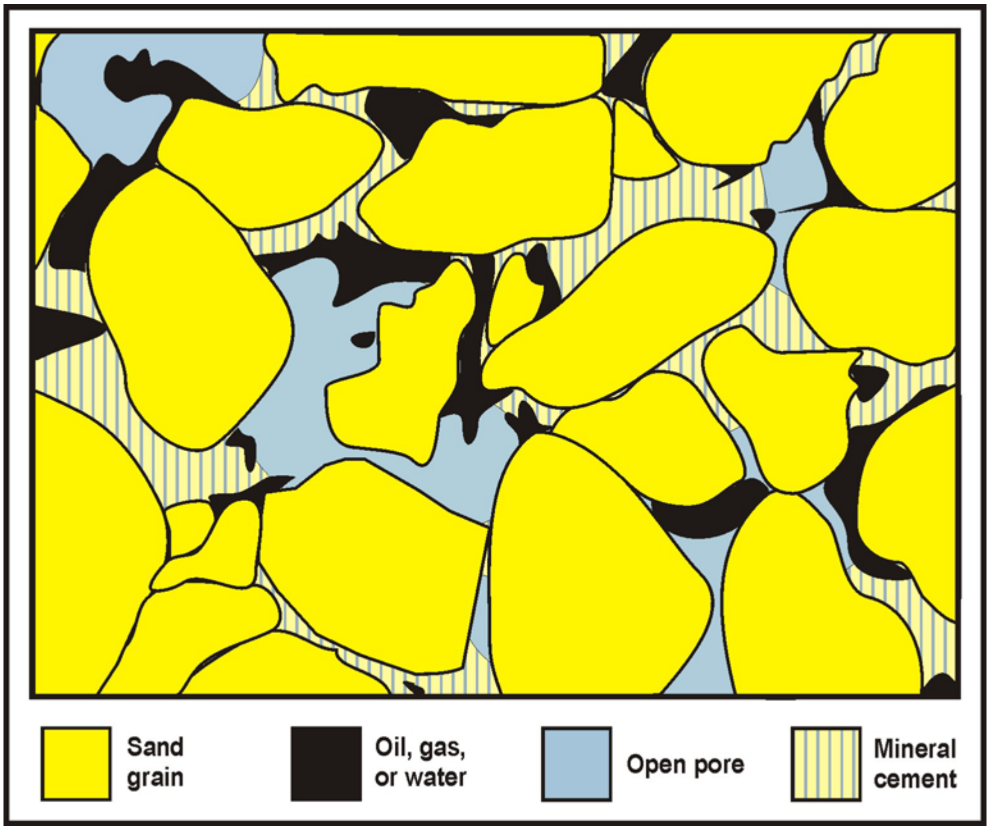
Phase: A distinct state of matter in a system. For example, the three phases of H_2O are ice (solid), water (liquid), and steam (gas).

Pinchout: The progressive thinning of a rock unit to the point where it disappears.

Plutonic: Pertaining to a body of igneous rock that has cooled and crystallized from a molten state below the surface of the Earth. Granite is an example of a plutonic rock.

Pore geometry: The size, shape, and relative position of a pore space in rock.

Porosity: The ratio of the volume of the pore space within a reservoir rock to the volume of the whole rock, generally expressed as a percentage.



Porous: Pertaining to a rock that has open pore spaces.

Precipitation: The formation of a solid mineral from a supersaturated solution.

Primary porosity: The original pore space in a rock that survived the process of lithification.

Production string: The last string of casing set in a well prior to production.

Progradational: Building outward through deposition. For example, a delta will prograde out into the ocean as mud and sand continue to be carried by the river currents through the channels.

Proximal: Situated nearest to the center or point of interest.

Pyrite: A mineral consisting of iron (Fe) and sulfur (S), and having the chemical formula FeS_2. It is commonly called "fool's gold."

Quartz: A mineral consisting of silicon (Si) and oxygen (O), and having the chemical formula SiO_2.

Quartzite: A metamorphic rock derived from a quartzose sandstone.

Quartzose: Having a composition rich in quartz.

Ramping up: Pertaining to a fault slice that is torn from the crust of the Earth and thrust upward 10° to 30° (or more).

Reflectivity: The ability of a rock or fluid surface to reflect seismic energy.

Regression: The retreat of the sea from land, occurring as a result either of sea level drop or tectonic uplift of the shoreline or seafloor.

Remote sensing: The acquisition of data about one or more aspects of the physical, chemical, or biological makeup of the Earth by the use of devices that are not in physical contact with the Earth. For example, towing the devices behind an airplane or ship, or housing them in a satellite.

Repressurizing: Pumping a fluid into a reservoir through a borehole in order to return the rock pressure to its original state.

Reservoir: A subsurface rock unit that has sufficient porosity and permeability to contain fluids such as oil, gas, and water.

Reservoir pressure: The pressure recorded in a borehole in a reservoir rock.

Residual fluid: The fluid that remains on the walls of a previously saturated pore after the critical pressure for the fluid in the pore has been reached.

Rifted core: The depressed center of a fault-bounded anticline, formed when the flanks of the anticline are thrust over the center.

Resistivity: The fundamental measure of a material that represents how strongly a material opposes the flow of an electric current.

Rutile: A mineral composed of titanium (Ti) and oxygen (O), and having the chemical formula TiO_2.

Saline formation: An underground reservoir rock that contains salt water.

Salinity: The total quantity of dissolved solids in brine, measured by weight in parts per thousand (o/oo).

Salt: The general term for naturally occurring sodium chloride (NaCl), or halite.

Sandstone: A sedimentary rock composed of sand-sized particles, regardless of composition.

Schist: A metamorphic rock that has been altered from a fine-grained sedimentary rock such as shale by heat or pressure or both, so that minerals occur in roughly parallel layers.

Seal: An impervious rock adjacent to a reservoir rock in the subsurface that acts as a barrier to the passage of migrating fluids.

Secondary porosity: The total pore space developed in a rock after its deposition and emplacement, which results from processes such as dissolution of minerals and fracturing.

Secondary recovery: An artificial method of restoring or increasing production from a reservoir after the natural producing mechanism and reservoir pressure declines as a result of depletion. Gas injection and waterflooding are examples of secondary recovery.

Secondary void: A pore space developed in a rock after its deposition and emplacement that results from processes such as dissolution of minerals and fracturing.

Sedimentary basin: A depression, created through subsidence, that fills with sediment.

Sedimentary rock: A rock that forms from sediment that has accumulated through the actions of wind, water, ice, or gravity. Common sedimentary rocks include coal, shale, limestone, and sandstone.

Seismically stable: Pertaining to an area that is not prone to earthquakes.

Seismic reflection: The process of bouncing seismic (sound) waves off various rock layers within the Earth and recording the time they take to return to the surface in order to determine depth and composition of the layers of interest.

Seismic survey: The process of gathering seismic data in an area.

Seismic tomography: A technique comparable to that of the CAT scan that is used to image the interior of the Earth with pressure waves that are generated by seismic surveying equipment.

Seismic wave: A pressure or sound wave that travels through the Earth as the result of an earthquake, explosion, or other strong vibration.

Seismometer: An instrument that measures and records motions of the Earth's crust generated by earthquakes, explosions, or other strong vibrations.

Self-potential: A naturally occurring electric potential difference in the Earth, measured by an electrode relative to a fixed reference electrode. Also called spontaneous potential.

Sequence boundary: A significant erosional unconformity, the product of a fall in sea level that erodes the exposed sediment of an earlier sequence. See sequence stratigraphy graphic under "Highstand systems tract."

Sequence stratigraphy: A branch of stratigraphy that subdivides sedimentary rock deposits into units of varying scales bounded above and below by unconformities that are assumed to represent time lines within the sedimentary sequence.

Sequestration capacity: The volume of a rock that is capable of storing carbon dioxide.
Sericite: A fine grained mica mineral formed by alteration of feldspar.

Serpentinite: A green metamorphic rock composed of hydrated magnesium silicates formed by the alteration of other minerals.

Shale: A very fine-grained sedimentary rock composed of clay minerals that have been compacted to a finely laminated structure.

Shoreface: The narrow, shallow part of the inner continental shelf adjacent to shore in which waves regularly agitate the bottom.

Sidewall core: A small, cylindrical sample of rock cut from the wall of a borehole by a specialized tool.

Silica: A generic term for silicon dioxide (SiO_2).

Sill: A body of igneous rock that intrudes parallel to the bedding of the surrounding rock.

Siltstone: A sedimentary rock composed of silt-sized (between 1/256 and 1/16 millimeters in diameter) particles.

Sinkhole: A depression or open hole in the ground that was formed either by dissolution of limestone or by collapse of a subsurface void like a mine opening.

Smectite: A type of clay mineral.

Solubilize: To make something soluble.

Solution-mining: The process of dissolving a salt bed by circulating water, thus forming a void in the bed.

Sorting: The distribution of grain sizes in sedimentary rock.

Specific gravity: The density of a substance relative to the density of water.

Sphalerite: A mineral composed of zinc (Zn) and sulfur (S), and having the chemical formula ZnS.

Stratal: Pertaining to a stratum (rock layer).

Stratigraphic: Pertaining to the study, description, and organization of strata (layers of rock).

Stratigraphic trap: A trap for oil, gas, or water that involves changes in the rock, rather than in structural deformation.

Stratigraphy: The study, description, and organization of rock strata.

Strike: The orientation of the plane of a fold, fault, fracture, or bedding where it intersects the horizontal.

Structural: Pertaining to rock deformation or the features that result from it.

Structural closure: In an anticline, dome, or other structural trap, the vertical distance between a geologic structure's highest point and lowest closed structure contour.

Structural elevation: The depth above or below sea level of the mapped surface of a rock layer or formation.

Structural trap: A trap for oil, gas, or water that is the result of folding, faulting, or other deformation.

Structure contour: A line drawn on a map connecting points of equal elevation of a surface of a rock unit that indicates depth, showing the structural deformation of the rock unit.

Subaerial: Pertaining to conditions occurring in the open air.

Sublittoral: Pertaining to conditions occurring in the ocean between low tide and a depth of about 300 feet.

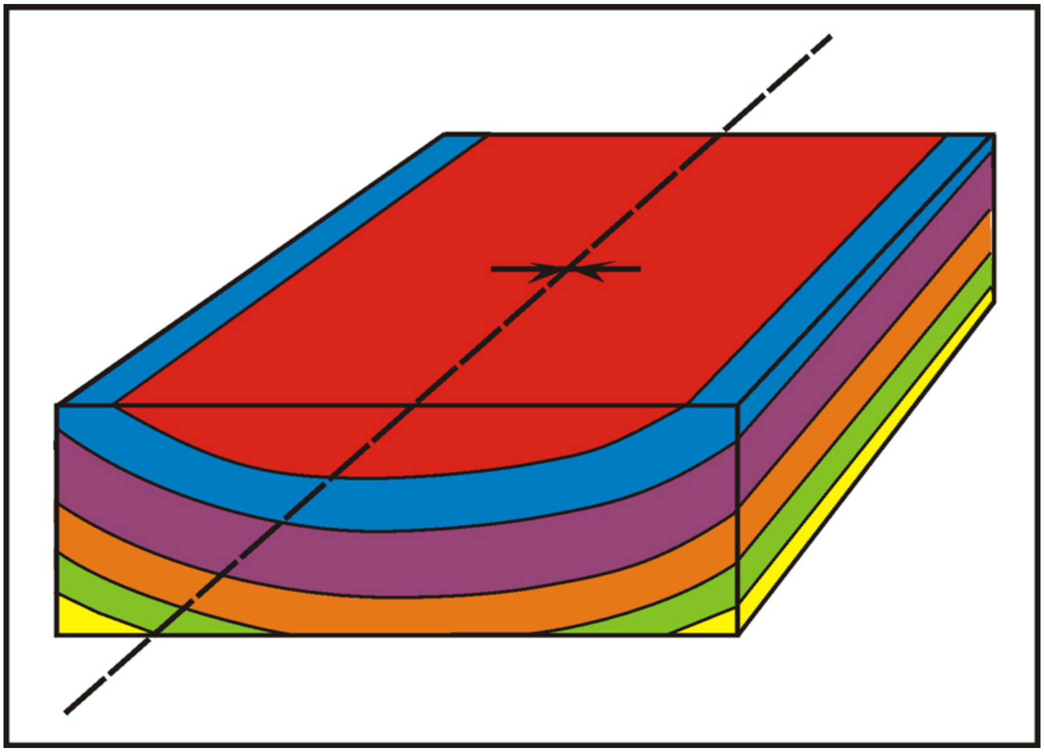
Subsea elevation: Depth below sea level, generally referenced relative to the mean elevation of the ocean surface.

Subsurface: Pertaining to anything beneath the surface of the Earth.

Sulfate: A mineral compound containing, along with other elements, sulfur (S) and oxygen (O), and having the chemical formula $(X)SO_4$, where (X) represents an element such as calcium (Ca) or barium (Ba).

Supercritical: Pertaining to a fluid, existing at a temperature and pressure above where the density of the gas and liquid phases equal, that can move through solids like a gas and dissolve materials like a liquid.

Syncline: A downward fold in rocks, typically caused by mountain-building pressures.



Tectonic: Pertaining to the forces involved in deformation of the Earth's crust.

Tectonism: A general term for all movement of the Earth's crust produced by tectonic process.

Tensile strength: The maximum stress applied perpendicular to rock body that the rock can withstand before it breaks.

Terrestrial sequestration: Using plants and soils to store carbon dioxide.

Thermal hyperspectral imagery: Imagery collected from near infrared spectral region of the electromagnetic spectrum.

Thermal region: That part of the electromagnetic spectrum considered solely with reference to their heating effects, such as infrared radiation.

Thermal scanner: A detector that is sensitive to infrared (heat) radiation.

Thin section: A fragment of rock or mineral that is ground to a thickness of about 3 millimeters, thin enough to be transparent or translucent, and viewed through a microscope in order to study its composition and properties.

Thrust fault: A type of fault in which one side is pushed up and over the other side.

Thrust sheet: A body of rock above a large-scale thrust fault that is nearly horizontal in orientation.

Tidal channel: A channel extending from offshore to a lagoon or salt marsh that the tidal currents follow.

Tidal creek: A small estuary.

Tidal ridge: A sand bar within a tidal channel oriented parallel with the tidal current.

Tight: Pertaining to a rock with very low permeability.

Tiltmeter: An instrument used to measure small changes in the tilt of the Earth's surface, usually in relation to a liquid-level surface or to the resting position of a pendulum.

Topographic: Pertaining to the configuration of the surface of the Earth.

Topography: The general configuration of a land surface or any part of the Earth's surface.

Tortuous: Pertaining to rock having many twists and turns within its pore space.

Transgressive: Pertaining to the spread of sea over land as a result of sea level rise or tectonic subsidence of the land area.

Type-1 sequence boundary: An unconformity characterized by deep stream cutting and an abrupt shift of deposition toward the sedimentary basin.

Type-1 stratigraphic sequence: A sequence of strata that originated during a relative fall in sea level below the position of the present shoreline.

Unmineable coal seam: A coal seam that is too deep and/or too thin to be considered economically mineable.

Trap: Any barrier to the movement of oil, gas, or water, thus allowing the fluid to accumulate in a reservoir.

UAVSAR: A specifically designed NASA radar system used to acquire airborne repeat track synthetic aperture radar data for differential interferometric measurements. It is an acronym for Uninhabited Areal Vehicle Synthetic Aperture Radar.

Unconfined rock unit: A rock unit without specific structural or stratigraphic traps.

Unconformable: Pertaining to two strata that are separated by an obvious hiatus in deposition.

Unconformity: A surface within a rock sequence that separates younger from older strata, displaying evidence of erosion or non-deposition over a significant period of time.

Unconventional gas reservoir: A rock unit that, until recently, was not considered to contain commercially producible quantities of natural gas. For example, coal, carbonaceous shales, and very low-permeability sandstones.

Underpressured: Pertaining to a rock unit in which the pore pressure is less than normal pore pressure for a rock unit at that depth.

Updip: In the general direction of highest elevation on an inclined rock layer.

Upper shoreface: The portion of the seafloor that is shallow enough to be agitated by normal wave action.

Upland: A general term for land having higher elevation than the surrounding or regional land areas.

Viscosity: A property of a material that makes it resistant to flow.

Volumetric storage: Storage of carbon dioxide in which the CO_2 is occurs throughout the three-dimensional pore volume of the rock, rather than merely on the surface (as in adsorption storage).

Vug: A small cavity in a rock, typically lined with crystals of a different mineral composition than the enclosing rock.

Waterflood: A secondary recovery operation in which water is injected into the producing formation in order to maintain reservoir pressure and force oil towards the producing wells.

X-ray diffraction: An analytical technique used to determine the structures and compositions of materials by passing X-rays through the material.

Zircon: A mineral composed of zirconium (Zr), silicon (Si), and oxygen (O), and having the chemical formula $ZrSiO_4$.