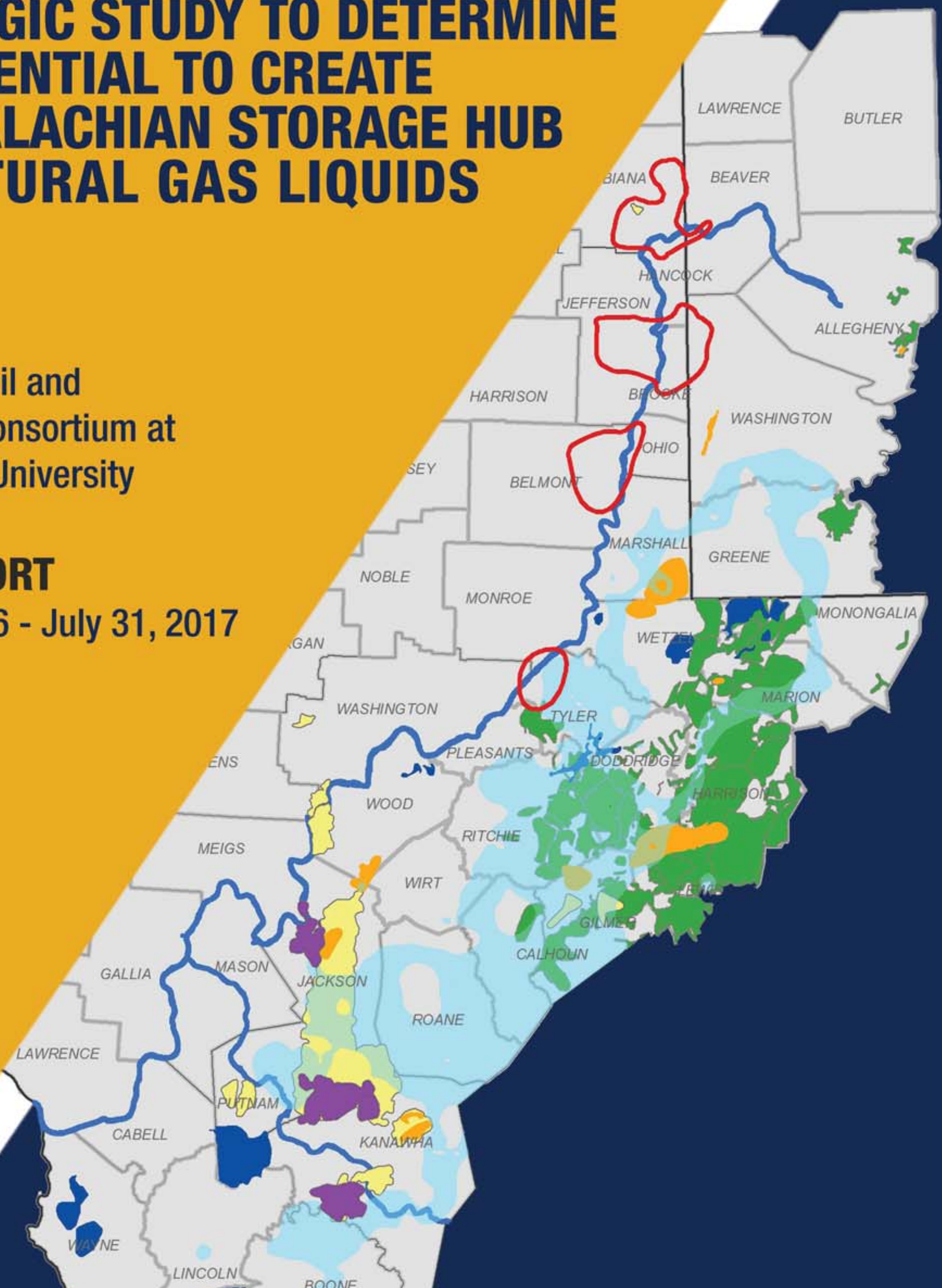
# A GEOLOGIC STUDY TO DETERMINE THE POTENTIAL TO CREATE AN APPALACHIAN STORAGE HUB FOR NATURAL GAS LIQUIDS




Coordinated by:

Appalachian Oil and Natural Gas Consortium at West Virginia University

## FINAL REPORT

August 1, 2016 - July 31, 2017

West Virginia University

# A GEOLOGIC STUDY TO DETERMINE THE POTENTIAL TO CREATE AN APPALACHIAN STORAGE HUB FOR NATURAL GAS LIQUIDS

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Project Start Date: August 1, 2016
Project End Date: July 31, 2017

## APPALACHIAN OIL & NATURAL GAS RESEARCH CONSORTIUM

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**July 31, 2017**

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## ACRONYMS USED IN THIS REPORT

AOI – Area of Interest

AONGRC – Appalachian Oil and Natural Gas Research Consortium

API – American Petroleum Institute

ASH – Appalachian Storage Hub

B5-B1 – Bradford sandstones

CATG – Cataract Group (Clinton/Medina Group)

DPHI – Density porosity

E4-E1 – Elk sandstones

FERC – Federal Energy Regulatory Commission

FTP – file transfer protocol

GIS – Geographic Information Systems

GR – Gamma ray

GRNB – Greenbrier Limestone

GWPC – Ground Water Protection Council

ILM – Medium induction log

IOGCC – Interstate Oil and Gas Conservation Commission

KENR-BERE – Keener to Berea sandstones

LPGs – Liquid Petroleum Natural Gases

MRCSP – Midwest Regional Carbon Sequestration Partnership

MSL – Mean Sea Level

NBRG – Newburg sandstone

NGLs – natural gas liquids

NPHI – Neutron porosity

OGS – Ohio Geological Survey

ORSK – Oriskany Sandstone

PAGS – Pennsylvania Geological Survey

Pe – Photoelectric factor

RHOB – Bulk density

ROM – Rough order of magnitude

RSRN – Rose Run-Gatesburg sandstones

SLNF – Salina F4 Salt

SSL – secure socket layer

V5-V1 – Venango sandstones

WVGES – West Virginia Geological and Economic Survey

## UNIT ABBREVIATIONS USED IN THIS REPORT

| | |
|---|---|
| ***Length*** | |
| inch | in |
| feet | ft |
| mile | mi |
| ***Area*** | |
| acre | ac |
| ***Density*** | |
| grams per cubic centimeter | g/cc |
| ***Pressure*** | |
| pounds per square inch | psi |
| ***Volume*** | |
| cubic feet | $ft^3$ |
| barrel | BBL |
| thousand cubic feet | MCF |
| million cubic feet | MMCF |
| billion cubic feet | BCF |
| trillion cubic feet | TCF |
| ***Permeability*** | |
| Darcy | D |
| millidarcy | mD |
| ***Concentration*** | |
| Weight percent | % |
| Parts per million | ppm |
| Parts per billion | ppb |

## ACKNOWLEDGEMENTS

The members of the Appalachian Oil & Natural Gas Research Consortium would like to express our gratitude to the Benedum Foundation for their financial support for this Study. We also would like to thank those companies and organizations in the private sector who contributed matching funds to fully fund the Study. These Study Partners are: AEP, Antero Resources, Blue Racer, Charleston Area Alliance, Chevron, Dominion, EQT, First Energy/Team NEO, Mountaineer NGL Storage LLC, Noble Energy, Southwestern Energy, XTO Energy and the West Virginia Oil & Natural Gas Association (WVONGA). We also would like to acknowledge the efforts of the WVU Foundation for taking the lead in obtaining these matching funds, the WVU Research Corporation and National Research Center for Coal and Energy for their administrative support, and the WVU Corporate Relations Office for their administrative and hospitality support over the course of the Study, particularly during the kickoff and semi-annual Partners meetings. Last but not least, we thank our Advisory Group members for their helpful guidance and support, and for the thoughtful reviews and commentaries prepared by Advisory Group members and Study Partners that improved the content of this final report.

# EXECUTIVE SUMMARY

The Marcellus and Utica shale plays continue to lead the way in an ever-expanding shale revolution with average daily production, growing from about 3 billion cubic feet (BCF) in 2010 to more than 24 BCF today. Forecasts suggest that this could grow to as much as 40 BCF in the next 5 years. Fortunately, sweet spots in the Utica in eastern Ohio and in the Marcellus in northern West Virginia and southwestern Pennsylvania are areas of wet gas production, downdip from oil production and updip from dry gas. Production in these regions represents about 40 percent of the total from the Marcellus and Utica shales and is expected to represent a disproportionate share of future production growth. Because of the amount of natural gas liquids (NGLs) contained in this production, development of these shale plays has the potential to have a large impact on the petrochemical industry.

In the United States, petrochemical projects are expanding. Industry investment and jobs have increased; the value of NGLs has increased; and fractionation capacity has increased as new processing plants come on line.

The great, untapped resource from the Marcellus and Utica play areas is ethane. Due to the lack of a local market providing a higher value alternative, most of the ethane from the Marcellus and Utica is rejected, that is, left in the gas stream for sale. For the ethane that is recovered, it is all leaving the area and going to Canada, Texas, Louisiana and export markets in Europe to support the petrochemical industry in those locations.

To seize the opportunity presented by this valuable resource in this area, state officials in Ohio, Pennsylvania and West Virginia are promoting a high-technology program to enhance economic development by expanding the market for ethane production from the liquids-rich Marcellus and Utica shale plays. The vision is to create a robust infrastructure supporting the creation of value from the prolific NGL production in the Appalachian basin, including NGL storage and trading, plus pipeline infrastructure.

A critical first step in the development of infrastructure and expanded industrial growth would be to prepare a geologic investigation of the potential to develop adequate subsurface storage along the pipeline route. Such a study would provide data essential to decision-makers intent on supporting the development of an Appalachian Storage Hub (ASH) and the petrochemical industry.

The Appalachian Oil and Natural Gas Research Consortium (AONGRC) has been tasked with evaluating the storage potential of subsurface stratigraphic units along the pipeline route (the Study). Individual formations and intervals of interest include the Greenbrier Limestone for subsurface mining; the Salina salt for the creation of cavities through brine extraction; and depleted gas fields and gas storage fields in sandstone reservoirs in the Lower Mississippian (Keener to Berea interval); Upper Devonian (Venango, Bradford and Elk intervals); Lower Devonian (Oriskany Sandstone); Upper Silurian (Newburg sandstone); Lower Silurian (Clinton/Medina Group); and Lower Ordovician (Rose Run Formation) - Upper Cambrian (Gatesburg Formation).

The Study was funded by a grant from the Benedum Foundation to the West Virginia University Foundation, with matching funds from Industry Partners and cost share provided by the state geological surveys in Ohio, Pennsylvania and West Virginia (OGS, PAGS and WVGES, respectively), who collectively comprised the ASH Research Team.

The goal of the Research Team was to complete a geologic study of all potential options for subsurface storage of NGLs along and adjacent to the Ohio River from southwest Pennsylvania to eastern Kentucky, with a similar study along the Kanawha River in West Virginia. This involved the mapping and identification of areas where the Salina F Salt is at least 100 feet (ft) thick and suitable for solution mining; mapping and identification of areas of the Greenbrier Limestone that are at least 40 ft thick and suitable for hard-rock mining; and mapping the thickness and extent of sandstone reservoirs in depleted gas fields and gas storage fields that could be converted to NGL storage.

The Research Team defined an Area of Interest (AOI) on both sides of the Ohio River that extends from southwestern Pennsylvania in the north as far as the Kanawha River Valley in southern West Virginia, and conducted a regional stratigraphic study of all potential storage candidate formations and reservoirs in this area. Each of the individual stratigraphic units or intervals was defined in the subsurface based on well-log patterns that marked the top and bottom of each. These log tops were then correlated throughout the AOI, enabling the construction of regional stratigraphic cross sections as well as thickness and structure maps. Individual sandstone reservoirs were identified within this regional stratigraphic framework, as appropriate.

Using this stratigraphic framework, the Research Team found the best candidates for each of the following types of storage container: salt caverns, mined-rock caverns and sandstone reservoirs in depleted gas fields and gas storage fields. Detailed reservoir characterization and field-level studies were then performed on the best candidates.

Potential mined-rock cavern locations must meet several criteria for consideration. The host unit must be relatively homogeneous and at least 40 ft thick to accommodate the storage gallery. The interval must have the necessary mechanical integrity and compressive strength to support a mined-cavern opening. For these reasons, lithology is particularly important. Limestone, dolomite and sandstone generally possess adequate compressive strength, but shale typically does not. In addition, rock units with high clay mineral content should be avoided, due to the likelihood of gas adsorption onto the clay particles, thereby hindering extraction of NGLs.

Developing salt caverns for ethane storage requires the identification of salt formations that are relatively clean and have adequate thicknesses to support both product storage and allow for residual insoluble materials that may accumulate at the base of the caverns over time. The presence of high-quality salt is preferred to maintain cavern integrity and eliminate the likelihood of weak zones and lateral migration pathways. Based on these criteria and with a view to minimize construction and operation costs, Nelson and others (2011) recommended a minimum thickness of 100 ft and subsurface depths ranging from 1,500 to 3,000 ft for solution-mined salt caverns, although it considered cavern depths of as much as 6,700 ft as a viable storage option.

Whereas regional mapping efforts went a long way toward identifying those geographic areas with the best mined-rock and salt cavern opportunities, the Research Team found that performing a preliminary assessment of the more than 2,700 depleted gas fields was necessary to focus characterization work for the multitude of siliciclastic reservoirs within the AOI. Of these, approximately 1,500 fields occur at a depth of 2,000 ft or more, considered to be the minimum depth for adequate liquid storage. Using this dataset, the Research Team screened each field by assigning preliminary rating values (ranging from 0 to 3) for each of a limited list of criteria. These values were then summed to generate an overall rating value for each field; the higher the rating, the more promising the siliciclastic storage opportunity. Following the initial screening, 113 depleted gas fields and 12 natural gas storage fields were determined to have favorable reservoir characteristics for storage.

The Research Team's preliminary assessment led to the conclusion that there are multiple storage opportunities for each category of storage container in the AOI. These include four areas where the net thickness of the Salina F4 Salt is greater than 100 ft; multiple areas throughout southwestern Pennsylvania and western West Virginia where the Greenbrier Limestone occurs at depths ranging from 1,800 to 2,000 ft; and 12 natural gas storage fields and 66 depleted gas fields that were selected for further evaluation based on favorable reservoir attributes.

Detailed rating efforts involved the assignment of numeric rating values (ranging from 0 to 3) to a set of criteria developed for each type of storage container. Rating values were then summed to provide an overall rating value for each storage opportunity for comparison purposes. Once again, the higher the rating, the more promising the storage opportunity. These rating efforts were used to generate a short list of 30 locations with the greatest potential to facilitate underground storage of ethane and other NGLs (Table 1).

***Table 1. Detailed rating results for the top 30 opportunities, summarized by storage container type and geologic interval.***

| Container Type | Field/Location | Geologic Interval | Rating Result |
|---|---|---|---|
| Mined-Rock Cavern | 5 | Greenbrier | 19 |
| | 4 | Greenbrier | 16 |
| | 2 | Greenbrier | 15 |
| Salt Cavern | 1 | Salina F4 Salt | 15 |
| | 2 | Salina F4 Salt | 15 |
| | 4 | Salina F4 Salt | 15 |
| Natural Gas Storage Field | RIPLEY | Oriskany | 24 |
| | RACKET-NEWBERNE (SINKING CREEK) | Venango | 22 |
| Depleted Gas Reservoirs | MAPLE-WADESTOWN | Keener to Berea | 23 |
| | BURDETT-ST. ALBANS | Keener to Berea | 22 |
| | CONDIT-RAGTOWN | Keener to Berea | 22 |
| | ABBOTT-FRENCH CREEK | Venango | 25 |
| | WESTON-JANE LEW | Elk | 24 |
| | CAMPBELL CREEK | Oriskany | 25 |

| | | | |
|---|---|---|---|
| Depleted Gas Reservoirs | ELK-POCA (SISSONVILLE) | Oriskany | 24 |
| | NORTH RIPLEY | Newburg | 27 |
| | ROCKY FORK | Newburg | 27 |
| | KANAWHA FOREST | Newburg | 27 |
| | COOPER CREEK | Newburg | 25 |
| | CANTON CONSOLIDATED | Clinton/Medina | 25 |
| | CANTON CONSOLIDATED | Clinton/Medina | 24 |
| | CANTON CONSOLIDATED | Clinton/Medina | 24 |
| | RAVENNA-BEST CONSOLIDATED | Clinton/Medina | 24 |
| | DUMM RIDGE | Rose Run-Gatesburg | 18 |
| | DUMM RIDGE | Rose Run-Gatesburg | 18 |
| | FRAZEYBURG | Rose Run-Gatesburg | 18 |
| | RANDOLPH | Rose Run-Gatesburg | 18 |
| | KIRKERSVILLE | Rose Run-Gatesburg | 17 |
| | DUMM RIDGE | Rose Run-Gatesburg | 17 |
| | ROCKBRIDGE | Rose Run-Gatesburg | 17 |

Three areas of thick Salina F4 salt are situated in the northern and central areas of the AOI along the Ohio River. The top-rated areas where the Greenbrier's lime mudstone facies was at least 40 ft thick and has a substantial acreage were identified in West Virginia. In addition, the top two natural gas storage fields and highest ranked depleted gas reservoirs are located in West Virginia.

Because the rating criteria applied to each category of storage were not identical, the Research Team could not use the rating values for ranking purposes as they were. The Research Team decided to normalize these rating criteria by using only those criteria common to each container type – specifically, distance to infrastructure, acreage, average depth, net thickness, trap integrity, legacy well penetrations and stacked opportunities. Using these data, nine of the 30 fields/locations yielded rankings of 1, 2 or 3 (Table 2). One of the parameters considered to be very important in this process is stacked opportunities.

***Table 2. Final ranking results for the top 30 ethane storage opportunities in the AOI.***

| Ranking | Container Type | Field/Location | Geologic Interval | Normalized Rating |
|---|---|---|---|---|
| 1 | mined-rock cavern | 5 | Greenbrier | 19 |
| 2 | depleted gas reservoir | NORTH RIPLEY | Newburg | 16 |
| 2 | depleted gas reservoir | ROCKY FORK | Newburg | 16 |
| 2 | depleted gas reservoir | KANAWHA FOREST | Newburg | 16 |
| 2 | mined-rock cavern | 4 | Greenbrier | 16 |
| 3 | depleted gas reservoir | CAMPBELL CREEK | Oriskany | 15 |
| 3 | mined-rock cavern | 2 | Greenbrier | 15 |
| 3 | salt cavern | 1 | Salina F4 Salt | 15 |
| 3 | salt cavern | 2 | Salina F4 Salt | 15 |

Stacked opportunities are defined as multiple subsurface geologic formations or intervals that occur at different depths within a given geographic footprint. Stacked opportunities provide many benefits, most notably flexibility with respect to the amount and kind of products that could potentially be stored at a site and the actual placement of pipeline infrastructure relative to a site's footprint. In addition, stacked opportunities may reduce risks related to site acquisition and/or access to subsurface mineral rights and pore space, and could offer economies of scale relative to site preparation, number of wells to be drilled and logistics. Finally, the availability of multiple storage options in a given area allows an operator to tailor its underground storage portfolio to suit its business needs, financial position and any potential environmental safety concerns.

The Research Team identified three storage prospects in the AOI that contain top-rated geologic intervals/reservoirs and exhibit varying degrees of stacked potential. These prospects have been identified by their general geographic area – northern, central and southern – and are shown in Figure 1.

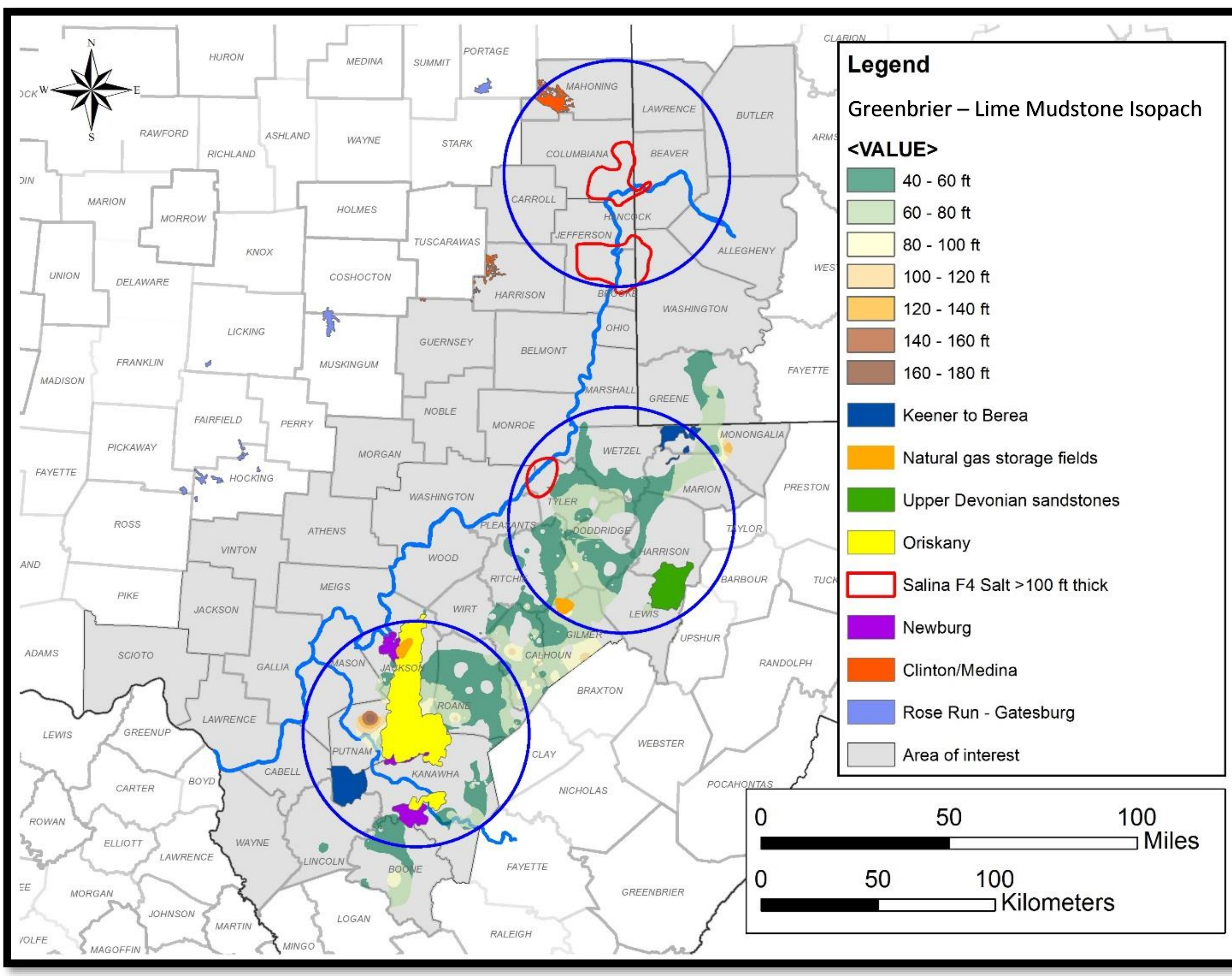



**Figure 1. Three prospects evaluated using reservoir characterization data prepared for this Study.**

The Northern Prospect encompasses the northern panhandle of West Virginia and adjacent portions of eastern Ohio and western Pennsylvania, presenting storage opportunities in the Clinton/Medina sandstones of Ohio's Ravenna-Best Consolidated Field and two Salina F4 Salt cavern opportunities straddling the Ohio River. In addition, the Oriskany Sandstone occurs throughout this portion of the Appalachian basin, overlying both intervals, and offers a potential stacked opportunity based on available subsurface data.

The Central Prospect includes portions of southeastern Ohio, southwestern Pennsylvania and north-central West Virginia and contains five storage opportunities: Greenbrier Limestone mined-rock cavern options; depleted gas reservoirs in the Keener to Berea interval in and between the Maple-Wadestown and Condit-Ragtown fields; a depleted gas reservoir in the Upper Devonian Venango Group in the Racket-Newberne (Sinking Creek) gas storage field; depleted gas reservoirs in in Upper Devonian sandstones in the Weston-Jane Lew field; and a Salina F4 Salt opportunity near Ben's Run in West Virginia. Despite the number of storage options here, stacked opportunities are somewhat limited and restricted to the outer edges of the prospect area.

The Southern Prospect is situated in the Kanawha River Valley of West Virginia and comprises the most storage opportunities of any prospect evaluated for this Study, including mined-rock caverns in the Greenbrier interval; an Oriskany Sandstone natural gas storage field; and various depleted gas fields in the Keener to Berea, Oriskany Sandstone and Newburg sandstone intervals. What's more, many stacked and adjacent opportunities are available within a relatively small geographic area. The number, variety and stacking of storage opportunities in the Southern Prospect shows its potential to support a thriving petrochemical industry.

All legacy data compiled for this Study, as well as all new data developed by the Research Team, were uploaded to a project website that was accessible to the Research Team and Partners during the twelve-month project period. Following a workshop during which the results of the study will be released to the public, the data will be made available through the West Virginia Geological Survey website.

In conclusion, this Study has confirmed that there are multiple storage options with in the AOI that can be exploited. In addition, the Study has produced three main products: (1) a regional subsurface geologic investigation of all geologic intervals of interest; (2) a detailed reservoir characterization effort, including field-level studies, rating criteria used to screen candidate fields, the final ranking of storage candidates and presentation of three prospect areas; and (3) the publicly accessible website in which all of the above reside. These deliverables are intended to guide the future site investigations conducted by any operators interested in developing the Appalachian Storage Hub.

# A GEOLOGIC STUDY TO DETERMINE THE POTENTIAL TO CREATE AN APPALACHIAN STORAGE HUB FOR NATURAL GAS LIQUIDS

## 1.0 INTRODUCTION AND PURPOSE

State officials in Pennsylvania, Ohio and West Virginia, with the support of their respective Governors, are promoting a high-technology program to enhance economic development by expanding the market for ethane production from the liquids-rich Marcellus Shale gas fields in southwestern Pennsylvania and Utica Shale fields in eastern Ohio and northern West Virginia. Their vision is to link these gas fields to end users in southern West Virginia and northeastern Kentucky via a pipeline that essentially follows the Ohio and Kanawha rivers. However, because the production of ethane may not occur at a consistent rate, and the need by consumers is for a steady, dependable supply, underground storage for ethane and other natural gas liquids (NGLs) at some point along the pipeline route is essential. NGLs can then be injected into storage at irregular rates, but withdrawn at consistent volumes and rates for transportation to the end users. Without this underground ethane storage facility, the entire program cannot go forward.

To this end, the Appalachian Oil & Natural Gas Research Consortium (AONGRC, or the Consortium) was engaged to conduct a one-year geologic study (the Study) to determine the potential to create an Appalachian Storage Hub (ASH) for NGLs to identify potential reservoirs for the secure, long-term storage of ethane and other products derived from the liquids-rich Marcellus and Utica shale plays. The main goal of the Study has been to locate the best options for storage in close proximity to a proposed pipeline from the areas of shale production in southwestern Pennsylvania to end users in southern West Virginia and northeastern Kentucky. This Area of Interest (AOI) comprises 50 counties located in the Ohio River Valley corridor of Ohio, Pennsylvania and West Virginia. This report presents the details of this investigation and the results and conclusions of the Study.

The project was funded by a grant from the Benedum Foundation to the West Virginia University Foundation, with matching funds from industry partners and cost share from the state geological surveys in Ohio, Pennsylvania and West Virginia (OGS, PAGS and WVGES, respectively).

Individual formations and intervals of interest included the Greenbrier Limestone for subsurface mining; the Salina salt for the creation of cavities through brine extraction; and depleted gas fields (some of which have been converted to natural gas storage fields) in siliciclastic reservoirs of the Keener to Berea interval; Venango, Bradford and Elk intervals; Oriskany Sandstone; Newburg sandstone; Clinton/Medina Group; and Rose Run-Gatesburg sandstones (see Table 1-1).

*Table 1-1. Geologic intervals of interest investigated for the Study.*

| System/Age | Interval | Description | Storage Type |
|---|---|---|---|
| Mississippian | Greenbrier Limestone | Limestone comprised of multiple carbonate facies | Mined-rock cavern |
| Lower Mississippian-Devonian | Keener to Berea | Multiple sandstones of variable location, thickness and extent | Depleted gas reservoirs |
| Upper Devonian | Venango, Bradford and Elk groups | Multiple sandstones of variable location, thickness and extent | Depleted gas reservoirs |
| Lower Devonian | Oriskany Sandstone | Regionally persistent sandstone | Depleted gas reservoir |
| Upper Silurian | Salina Group | Bedded salt formations | Salt cavern |
| Upper Silurian | Newburg sandstone | Localized sandstone equivalent to Salina C interval | Depleted gas reservoir |
| Lower Silurian | Clinton/Medina Group | Multiple sandstones of variable location, thickness and extent | Depleted gas reservoirs |
| Lower Ordovician - Upper Cambrian | Rose Run-Gatesburg sandstones | Regionally persistent sandstone | Depleted gas reservoirs |

The Study evolved into three main areas, including a regional subsurface study of all geologic units of interest, including formation descriptions, inter-state correlations and mapping; developing criteria with which to rate and eventually rank the candidate formations and reservoirs as safe and secure storage containers; and a project database and website in which all of the data and research findings are located and can be accessed by the public and all companies who are interested in developing a storage hub. Detailed descriptions or the methodology employed in each of these three areas are documented in this report. The results of these areas of investigation are the three main products of this one-year research effort.

## 1.1 Research Team

The Study Research Team included the following AONGRC personnel: from the OGS, Mohammad Fakhari, Kyle Metz, Michael Solis, Julie Bloxson, Erica Schubert and Michael Angle; from the PAGS, Kristin Carter, Brian Dunst, Katherine Schmid, Robin Anthony, Antonette Markowski, Stephen Shank, Ellen Davis, Lindsey Ditzler, Irma Drndar and Eric Hirschfeld; and from the WVGES, Jessica Moore, Gary Daft, Philip Dinterman, Michael Hohn, John Saucer and John Bocan. Project management was provided by Douglas Patchen of AONGRC.

## 1.2 Scope of Work

The scope of work for the Study was divided into eight strategies, nomenclature preferred by the funding entity (see Table 1-2).

*Table 1-2. Research efforts by strategy.*

| Strategy | Team Lead |
|---|---|
| 1. Data Collection | West Virginia Geological and Economic Survey (WVGES) |
| 2. Stratigraphic correlation of key units | Ohio Geological Survey (OGS) |
| 3. Map the thickness, extent and structure of potential storage units in the study area | OGS |
| 4. Conduct studies of reservoir character | Pennsylvania Geological Survey (PAGS) |
| 5. Develop ranking criteria for potential storage zones | PAGS |
| 6. Recommendations | Douglas Patchen, WVGES, PAGS |
| 7. Suggestions for engineering follow-up study | Douglas Patchen, WVGES, PAGS |
| 8. Project management and technology transfer | Douglas Patchen |

Whereas previous Study progress reports were organized relative to these strategies, this final report has been structured differently to provide for more logical development of the Study's findings. Specifically, this report is organized along the lines of the three areas of research described above that culminated in the definition of three prospect areas and a description of options for NGL storage in each, including the potential for stacked storage.

## 2.0 DATA DELIVERABLE ACCESS, ORGANIZATION AND MANAGEMENT

This Study provides three valuable products for end users considering subsurface storage of ethane and other NGLs: (1) the raw datasets, analyses and derived data utilized by the Research Team to complete the Study; (2) the rating and ranking methodologies specifically developed by the Research Team to evaluate subsurface storage prospects in the Study area; and (3) this final report, complete with subsurface geology and reservoir characterization findings, storage recommendations, and tables, figures and appendices that corroborate the Study findings. All project-specific data, whether compiled from legacy (i.e., pre-existing) sources or derived specifically for this work, have been organized and assimilated into the project website, which was a major deliverable product for the project.

Due to the iterative nature of the research tasks, modification and addition of data to the project database continued throughout the twelve-month project duration, and final additions and edits will continue to be made as final deliverables are submitted by the Research Team. Access to the database (https://gisonline.wvgs.wvnet.edu/ASH) will continue to be password-protected and encrypted by a secure socket layer (SSL) license until August 31, 2017. After that date, the project information will be available to the public via the Oil and Gas section of the WVGES website (www.wvgs.wvnet.edu; Figure 2-1).

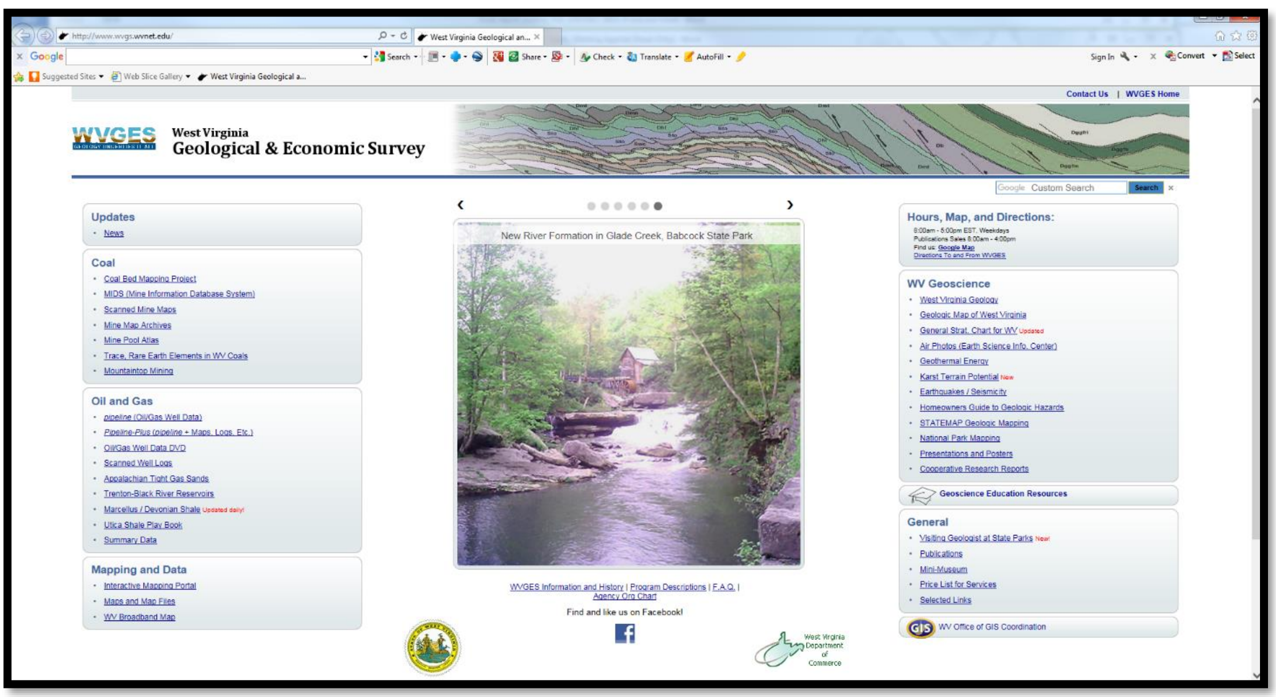



**Figure 2-1. The Study database will continue to be password-protected until the end of the project and will be served via the WVGES website beginning September 1, 2017.**

## 2.1 Study Website

The Study website serves as the primary method of technology transfer between the Research Team and Industry Partners. It is designed for use by a wide range of user groups from policy makers and their constituents to the geoscientists and engineers who will continue the research into subsequent phases of development.

The website is divided into three main sections (Figure 2-2). The header bar contains links to the *Project Overview and Summary*; *Quarterly and Final Reports* and *Presentations*; and a description of the *Stratigraphic Intervals* examined.

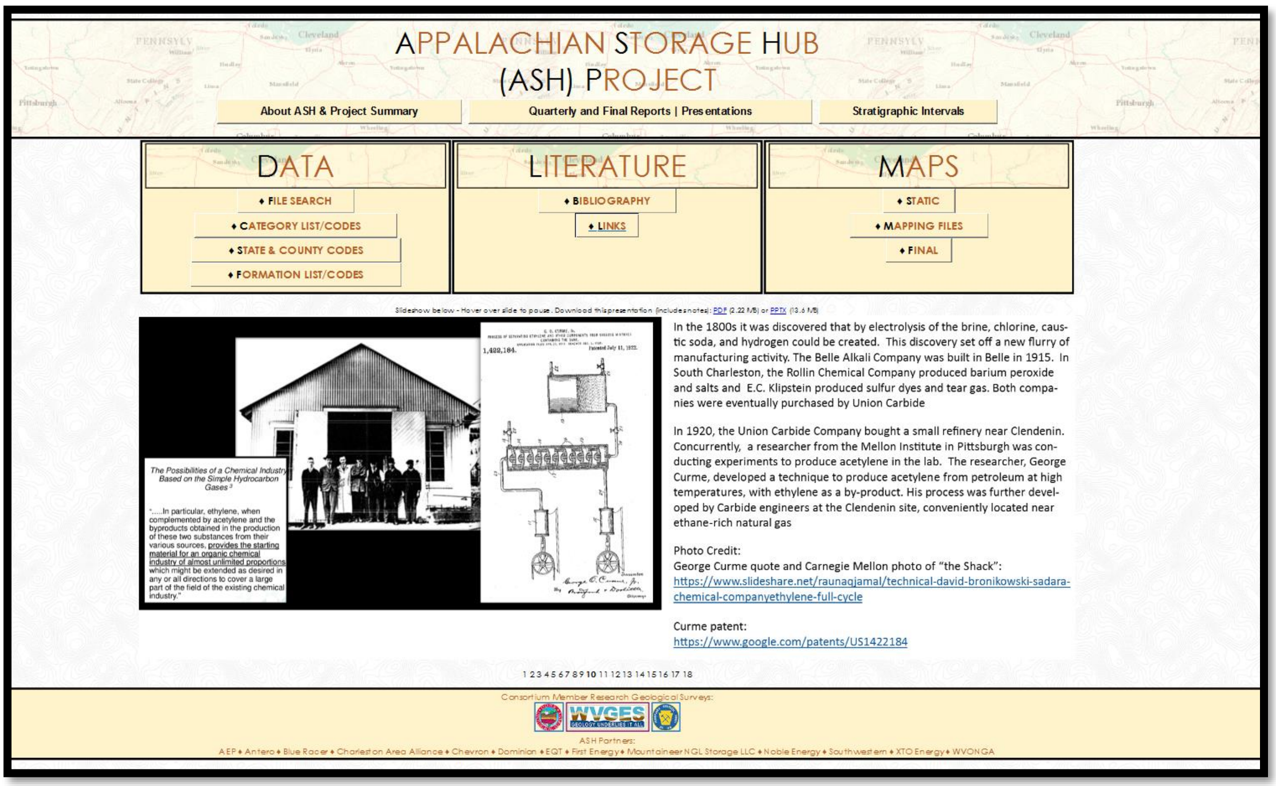



**Figure 2-2. The ASH project home page.**

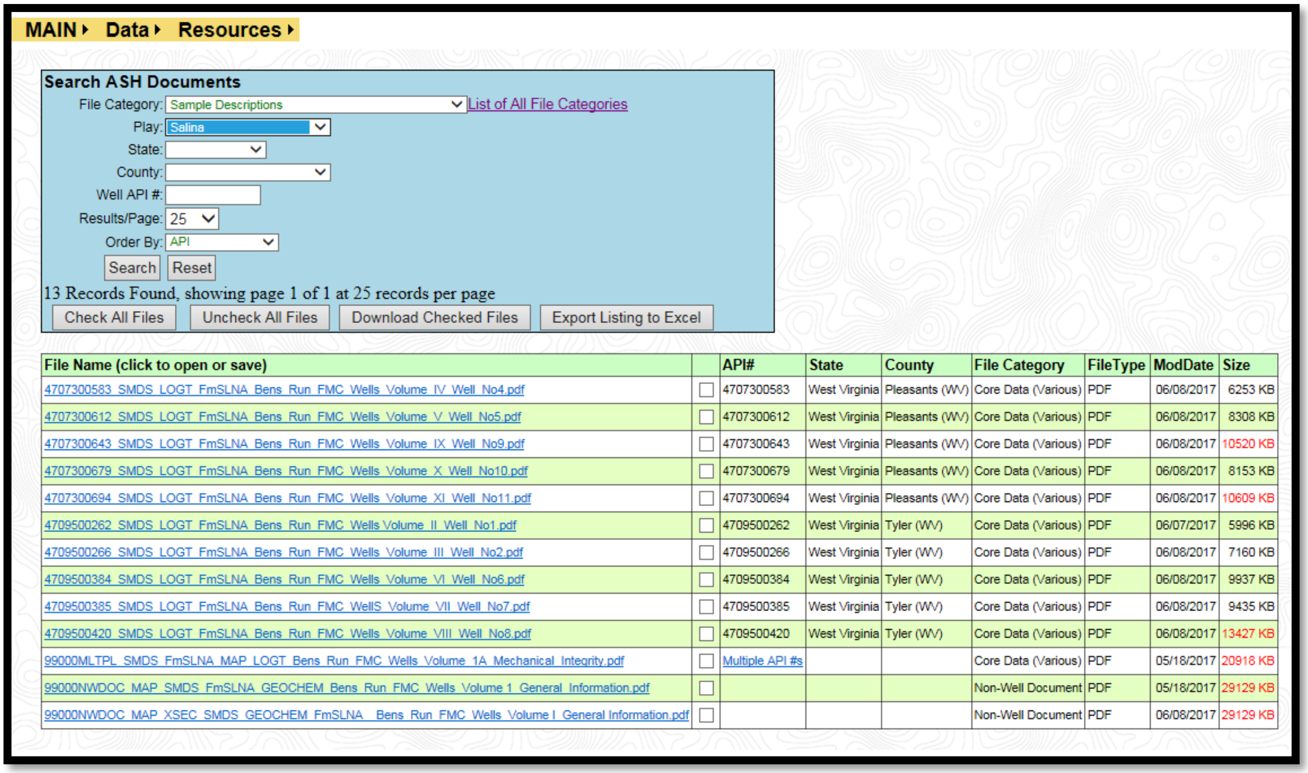
The main body of the website contains three subsections: Data, Literature and Maps. The contents of each are as follows:

The **DATA** subsection houses the ASH Project Document Search (Figure 2-3). This search function allows users to retrieve project documents based on a series of dropdown search menus:

- Category (see Figure 2-4 for list of file types)
- Play (Greenbrier/Depleted Gas/Existing Storage/Salina)

- State (OH/PA/WV)
- County (within ASH AOI)
- Well API Number

Users can check individual search results for download, and may also export the file listings to a Microsoft Excel file. If the user chooses the latter option, the hyperlink to the document remains active in the Excel file, allowing retrieval of the document at any time.


MAIN ▸ Data ▸ Resources ▸

**Search ASH Documents**

File Category: Sample Descriptions — List of All File Categories
Play: Salina
State:
County:
Well API #:
Results/Page: 25
Order By: API
Search | Reset

13 Records Found, showing page 1 of 1 at 25 records per page

Check All Files | Uncheck All Files | Download Checked Files | Export Listing to Excel

| File Name (click to open or save) | | API# | State | County | File Category | FileType | ModDate | Size |
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| 4707300583_SMDS_LOGT_FmSLNA_Bens_Run_FMC_Wells_Volume_IV_Well_No4.pdf | ☐ | 4707300583 | West Virginia | Pleasants (WV) | Core Data (Various) | PDF | 06/08/2017 | 6253 KB |
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| 4707300679_SMDS_LOGT_FmSLNA_Bens_Run_FMC_Wells_Volume_X_Well_No10.pdf | ☐ | 4707300679 | West Virginia | Pleasants (WV) | Core Data (Various) | PDF | 06/08/2017 | 8153 KB |
| 4707300694_SMDS_LOGT_FmSLNA_Bens_Run_FMC_Wells_Volume_XI_Well_No11.pdf | ☐ | 4707300694 | West Virginia | Pleasants (WV) | Core Data (Various) | PDF | 06/08/2017 | 10609 KB |
| 4709500262_SMDS_LOGT_FmSLNA_Bens_Run_FMC_Wells Volume_II_Well_No1.pdf | ☐ | 4709500262 | West Virginia | Tyler (WV) | Core Data (Various) | PDF | 06/07/2017 | 5996 KB |
| 4709500266_SMDS_LOGT_FmSLNA_Bens_Run_FMC_Wells_Volume_III_Well_No2.pdf | ☐ | 4709500266 | West Virginia | Tyler (WV) | Core Data (Various) | PDF | 06/08/2017 | 7160 KB |
| 4709500384_SMDS_LOGT_FmSLNA_Bens_Run_FMC_Wells_Volume_VI_Well_No6.pdf | ☐ | 4709500384 | West Virginia | Tyler (WV) | Core Data (Various) | PDF | 06/08/2017 | 9937 KB |
| 4709500385_SMDS_LOGT_FmSLNA_Bens_Run_FMC_WellS_Volume_VII_Well_No7.pdf | ☐ | 4709500385 | West Virginia | Tyler (WV) | Core Data (Various) | PDF | 06/08/2017 | 9435 KB |
| 4709500420_SMDS_LOGT_FmSLNA_Bens_Run_FMC_Wells_Volume_VIII_Well_No8.pdf | ☐ | 4709500420 | West Virginia | Tyler (WV) | Core Data (Various) | PDF | 06/08/2017 | 13427 KB |
| 99000MLTPL_SMDS_FmSLNA_MAP_LOGT_Bens_Run_FMC_Wells_Volume_1A_Mechanical_Integrity.pdf | ☐ | Multiple API #s | | | Core Data (Various) | PDF | 05/18/2017 | 20918 KB |
| 99000NWDOC_MAP_SMDS_FmSLNA_GEOCHEM_Bens_Run_FMC_Wells_Volume_1_General_Information.pdf | ☐ | | | | Non-Well Document | PDF | 05/18/2017 | 29129 KB |
| 99000NWDOC_MAP_XSEC_SMDS_GEOCHEM_FmSLNA__Bens_Run_FMC_Wells_Volume I_General Information.pdf | ☐ | | | | Non-Well Document | PDF | 06/08/2017 | 29129 KB |

**Figure 2-3. Example of a customized document search of the ASH project database.**

Excel

| File Category | Code |
|---|---|
| Biostratigraphy | BIOSTRAT |
| Bitumen Reflectance Report | BRR |
| CT Image | CTIMG |
| CT Scan Data | CTDAT |
| CT Zipped Images(CTIMGZ) | CTIMGZ |
| Core Analysis | CRAN |
| Core Analysis Crossplot | CRANXPLT |
| Core Description | CRDS |
| Core Photos | CRPH |
| Core Photos Zipped | CRPHZ |
| Cross Section | XSEC |
| Crushed Stone Properties (CSP) | CSP |
| Digitized Logs | DLOG |
| Federal Energy Regulatory Commison Documents | FERC |
| Fluid Inclusion Report | FIR |
| General Mineralogy (MNRLGY) | MNRLGY |
| Geo Chem | GEOCHEM |
| High Pressure Mercury Injection Porosity (MICP) | MICP |
| Isotopes | ISO |
| Log Tops | LOGT |
| Map | MAP |

| | |
|---|---|
| Microscopic Organic Analysis (MOA) | MOA |
| Non-Well Document | NWDOC |
| Other Well Documents | OTHR |
| Permeability | PERM |
| Porosity | PORO |
| Production Data | PROD |
| Project Presentation | PRST |
| Publication | PUB |
| Ro Histograms | ROHIST |
| Rock Mechanics | RKMECH |
| Routine Core Analysis (grain size) (RCA) | RCA |
| SEM Zipped Images (SEMZ) | SEMZ |
| Sample Descriptions | SMDS |
| Scanned Logs | ELOG |
| Scanning Electron Microscope (SEM) | SEM |
| Source Rock Analyses (SRA) | SRA |
| Thin Section Description | TSDESC |
| Thin Section Image | TSIMG |
| Thin Section Zipped Images | TSIMGZ |
| Tight Rock Analysis (TRA) | TRA |
| Total Organic Carbon (TOC) | TOC |
| X-Ray Defraction (XRD) | XRD |
| X-Ray Fluorescence (XRF) | XRF |

**Figure 2-4. File categories contained within the ASH project database.**

The **LITERATURE** subsection serves as the main repository for background information and previous studies. It contains two main parts:

- Bibliography (annotated with brief descriptions and keywords; also included herein as Appendix A)
- Links to previous projects (Figure 2-5). These links take users directly to the following project pages:
    - Appalachian Basin Tight Gas Reservoir Study
    - Trenton-Black River Reservoirs
    - A Geological Play Book for Utica Shale Appalachian Basin Exploration
    - Midwest Regional Carbon Sequestration Partnership
    - RPSEA Brine Disposal Framework Study

The Links tab also includes information on State and Federal Government Agencies; Natural Gas Data and Research Information; Geospatial Resources and Services; and News.


**Figure 2-5. Screen capture of the selected links page of the ASH project web page.**

The **MAPS** subsection serves as the main repository for final mapping products. These includes a set of static maps and cross sections as well as a subset of spatial data files generated for use in ESRI® ArcMap™.

The final portion of the ASH project website is an overview presentation given at the February 2017 Partners meeting. This presentation provides an historical background of oil and gas development as it applies to the Appalachian basin. The presentation is accompanied by notes and can be downloaded as either a Microsoft PowerPoint presentation or as an Adobe® PDF.

## 2.2 Data Management

The main method of communication between various User Groups was a series of email listservs established through the WVGES's email provider, WVNet. The Research Group listserv was distributed in October 2016 and served as the primary communication method between researchers. The Industry and Advisory Group listservs were populated with member information and distributed the following month. WVGES was responsible for maintenance and troubleshooting of the email groups.

In addition to communication via email, a file transfer protocol (FTP) site was established for file sharing (Figure 2-6). This feature enabled the Research Team to view, copy and transfer files through the duration of the project and will remain archived on the WVGES server following the conclusion of the Study.

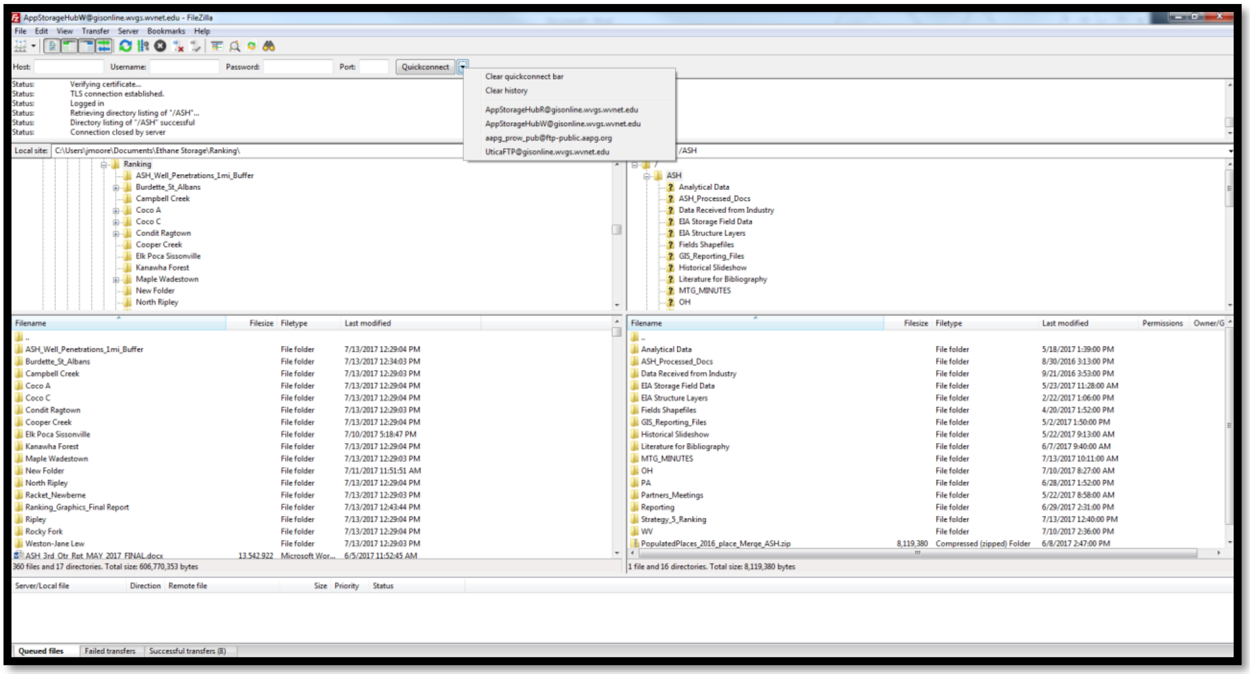



**Figure 2-6. Screen capture of the ASH project FTP site.**

## 3.0 SUBSURFACE GEOLOGY OF INTERVALS OF INTEREST

The tri-state area of Ohio, Pennsylvania and West Virginia is located in the central Appalachian basin. The Appalachian basin extends from Quebec, Canada, to the northern portion of Alabama, and has preserved sediments that were shed from episodic rifting and mountain-building events over geologic time. Appalachian basin history can be generally divided into four orogenic events: (1) the Latest Precambrian to Early Ordovician synrift and postrift, depositing passive margin clastic and carbonate sediments; (2) the Early Ordovician to Devonian Taconic Orogeny foreland basin, depositing marine carbonates, evaporates and clastic sediments; (3) the Devonian Acadian Orogeny foreland basin, depositing marine clastic sediments; and (4) the Mississippian to Early Permian Alleghanian Orogeny, depositing terrestrial and marginal marine clastic sediments. During each of these four major events, accommodation space was created, which helped to preserve the thick, relatively continuous stratigraphic succession of sediments here. For a complete summary of Appalachian basin history, refer to Ettensohn (2008).

Ten distinct intervals have been identified within the AOI as potential storage opportunities (Figure 3-1). These intervals are addressed in the following sections, first in terms of a lithostratigraphic framework, and then by way of regional structure and isopach maps for each of the geologic intervals, discussed in stratigraphically descending order.

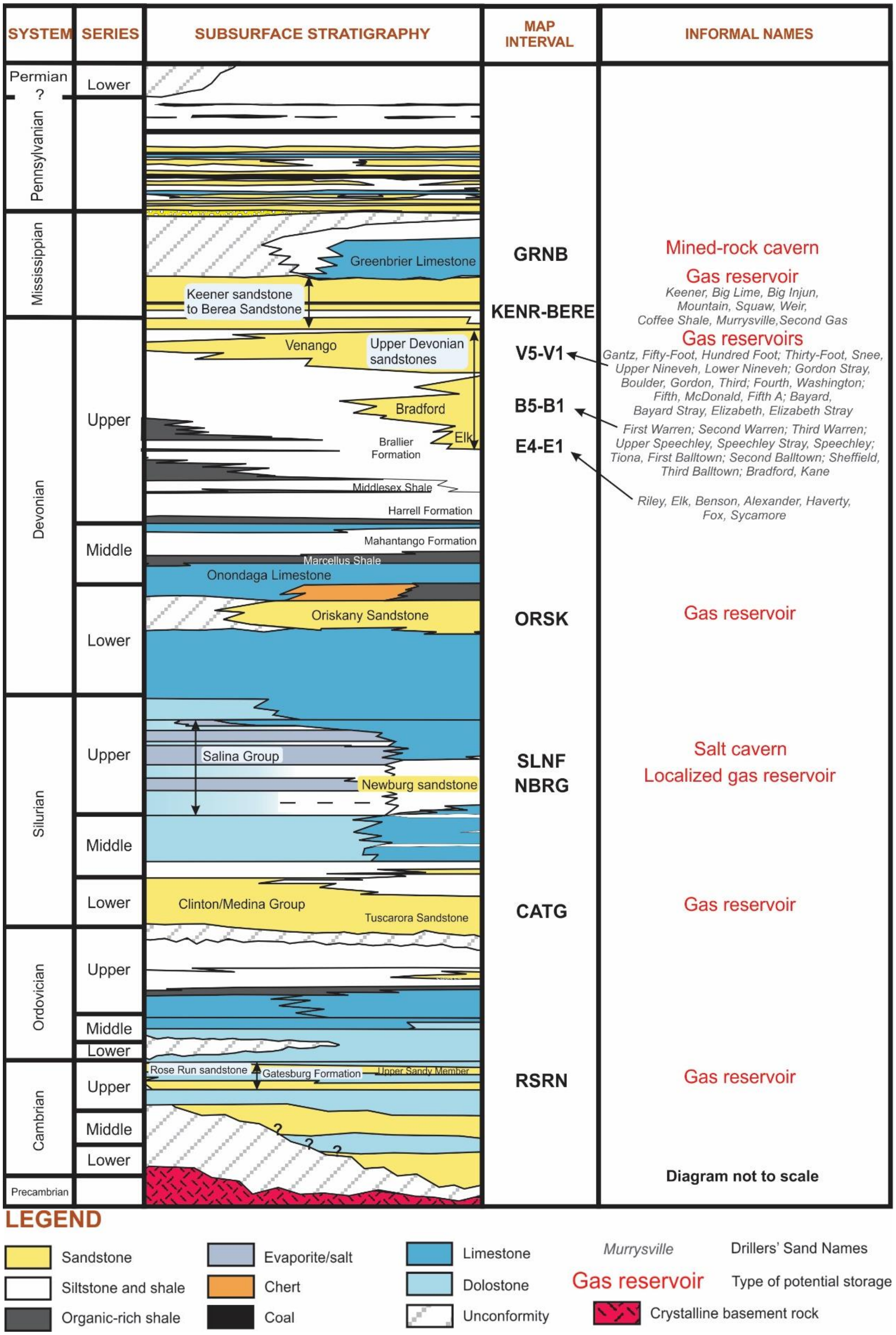



**Figure 3-1. Generalized subsurface stratigraphy for the AOI, indicating acronyms for intervals of interest and type of storage options.**

## 3.1 Regional Cross Sections

The Research Team prepared geologic cross sections throughout the AOI to provide a visual representation of the AOI's subsurface stratigraphy, illustrate lateral and vertical relationships among potential reservoirs for NGL storage, and most importantly, to correlate the subsurface lithostratigraphy for the region. To this end, a total of nine geologic cross sections were prepared using available subsurface data. These intervals were grouped by stratigraphic position and include (from youngest to oldest): Lower Mississippian to Upper Devonian, Lower Devonian to Silurian and Cambrian to Ordovician.

Two dip and one strike cross section were created for each of these three intervals. The locations of these cross sections are shown in Figures 3-2 through 3-4. Due to size, the cross sections are provided as multiple plates in Appendix B.

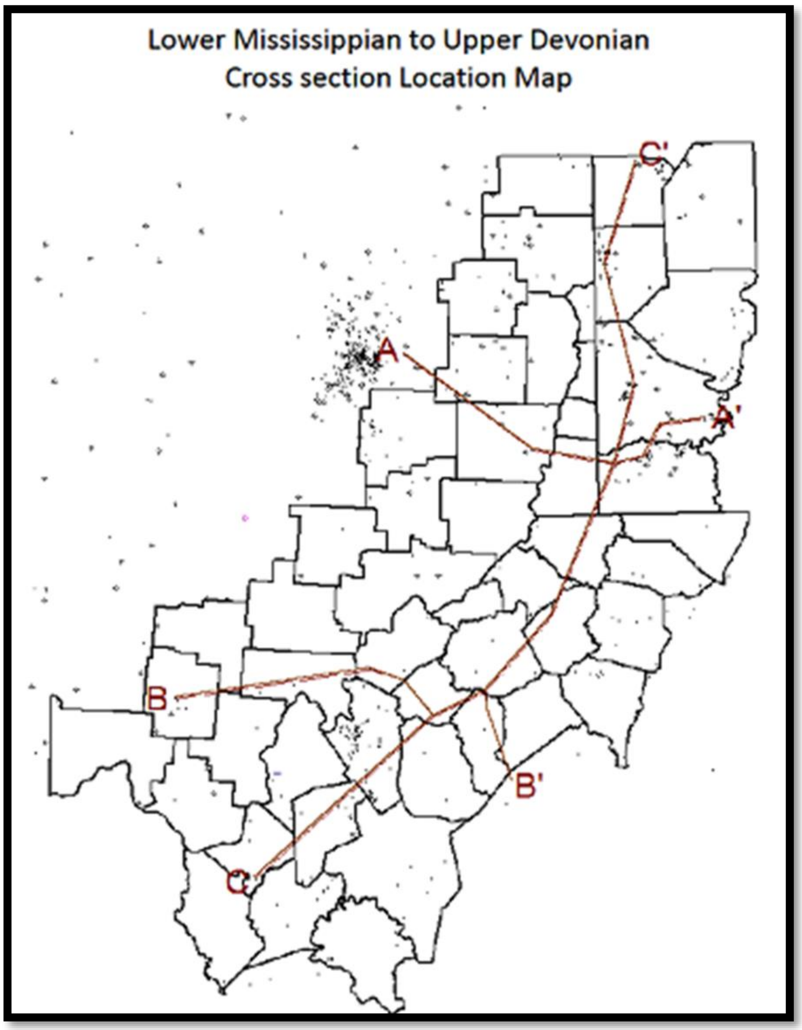



**Figure 3-2. Location map of Lower Mississippian to Upper Devonian cross section lines. These sections include the Greenbrier Limestone, Berea to Keener interval and Upper Devonian Venango, Bradford and Elk groups.**

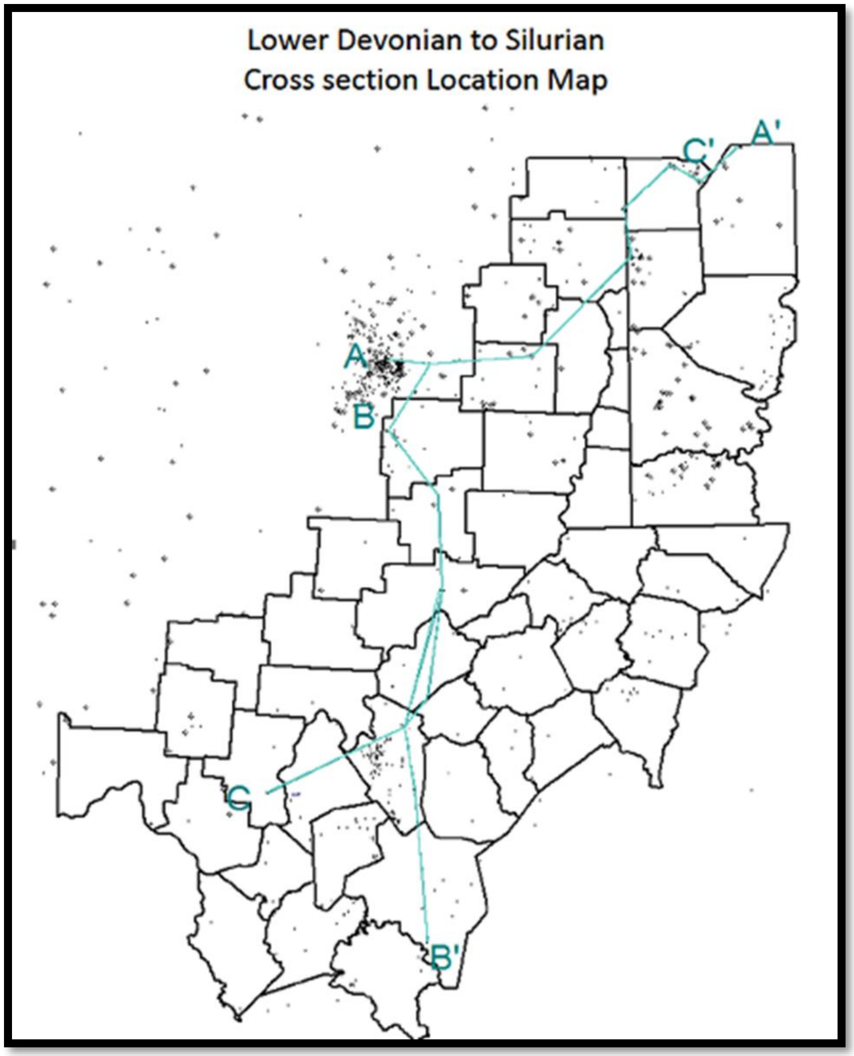



**Figure 3-3. Location map of Lower Devonian to Lower Silurian cross section lines. These sections include the Oriskany Sandstone, Salina Group, Newburg sandstone and Clinton/Medina Group.**

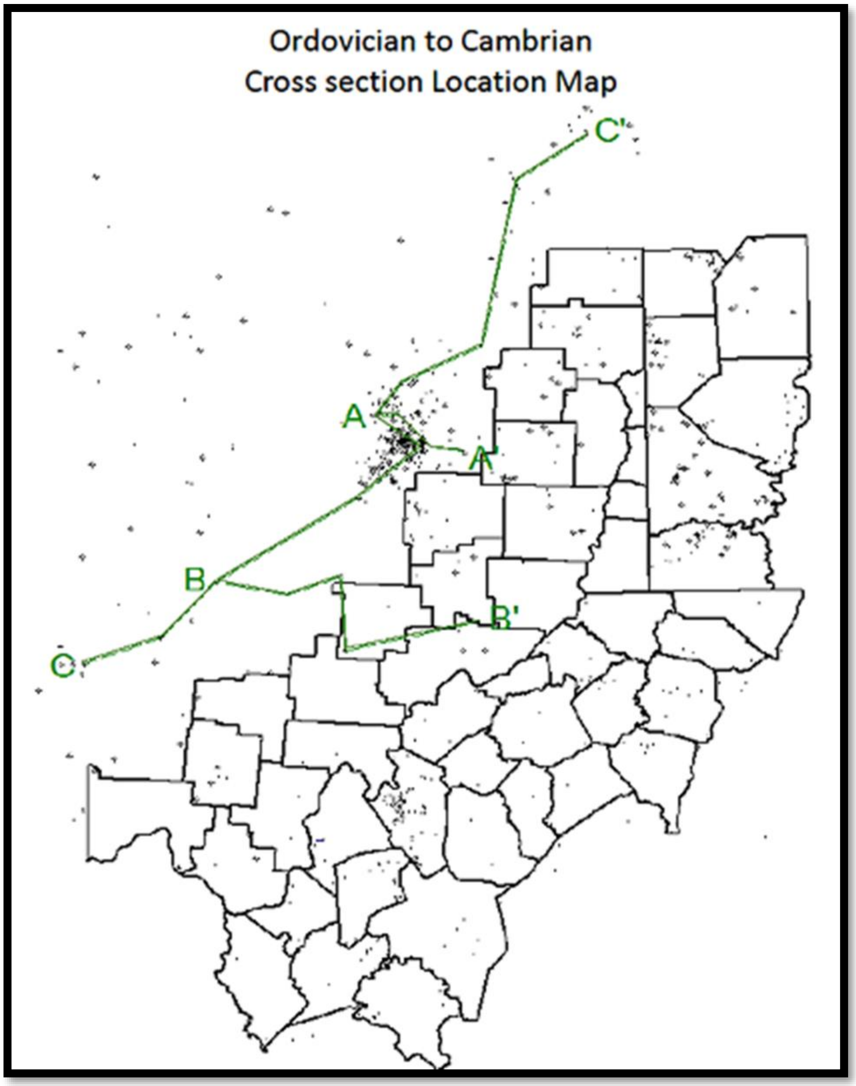



**Figure 3-4. Location map of the Ordovician to Cambrian cross section lines, which include the Rose Run and Gatesburg formations. Many of the Rose Run depleted gas fields are located beyond the AOI to the northwest.**

## 3.2 Map Preparation Methods

Regional well header, geophysical log and formation tops data were imported into a master IHS PETRA® project for data management and mapping purposes. Structure contour maps and gross isopach (thickness) maps were generated using ArcMap™ software for each of the following geologic intervals: Greenbrier Limestone (GRNB), Keener to Berea sandstones (KENR-BERE), Venango Group (V5-V1), Bradford Group (B5-B1), Elk Group (E4-E1), Oriskany Sandstone (ORSK), Newburg sandstone (NBRG), Salina F4 Salt (SLNF), Clinton/Medina Group (CATG) and Rose Run-Gatesburg formations (RSRN). Although not included in the Study's original scope of work, the Research Team opted to include the Newburg sandstone of southwestern West Virginia in its regional mapping efforts due to its favorable reservoir properties, as reported by Lewis (2013). The Silurian Newburg sandstone occupies roughly the same stratigraphic position as the Salina C interval, and is thickest in the Kanawha River Valley.

Maps for the following intervals were generated by combining previously prepared maps with the latest data available for these intervals in the AOI: Oriskany Sandstone (Wickstrom and others, 2005; Carter and others, 2010; Sminchak and Gupta, 2015); Clinton/Medina Group (Wickstrom and others, 2005; Carter and others, 2010; Sminchak and Gupta, 2015); and Rose Run-Gatesburg formations (Wickstrom and others, 2005; Sminchak and Gupta, 2015). New structure and gross isopach maps were created for the Keener to Berea, Venango, Bradford and Elk intervals. Maps of the Greenbrier Limestone were modified after Rice and Schwietering (1988) and used these workers' subcrop extents (i.e., areas removed by erosion) to delineate the presence/absence of this interval along the western and northern portions of the AOI. New maps were prepared for the Salina F structure and F4 Salt thickness, following Clifford's (1973) interpretation of the Salina salts.

Subsurface structure maps utilized a contour interval ranging from 100 to 250 feet (ft), while the isopach maps utilized contour intervals ranging from 5 to 100 ft, depending on individual interval characteristics. In addition, the Salina F4 Salt isopach map illustrates net salt thicknesses, as this mapped interval is interpreted to be entirely comprised of salt above a persistent dolomite or anhydrite zone, and does not include the thickness of that zone or any salt below the dolomite or anhydrite zone.

The geologic maps presented in the remainder of this chapter represent interpretations by experienced geologists based on publicly available data used by the Research Team at the time of the Study. These maps have been prepared using the best information available to the Research Team to illustrate and convey subsurface geologic information specific to the AOI. It is expected that end users will have occasion to modify these maps using new and/or proprietary data and information pertinent to their needs.

## 3.3 Greenbrier Limestone (GRNB)

The Mississippian Greenbrier Limestone is present across much of West Virginia, Kentucky and southwestern Pennsylvania, and is typically mined for aggregate in West Virginia. In Pennsylvania, the Greenbrier Limestone is comprised of the Wymps Gap and Loyalhanna members. Although not present in Ohio, the Greenbrier is stratigraphically equivalent to the Maxville Limestone.

The Greenbrier Limestone varies gray to brown to black in color. It is micro- to coarsely-crystalline, mostly thick bedded, with occasional cross-bedding and thin beds towards the upper contact. It is fossiliferous, argillaceous and locally cherty (Huggins, 1983; Wilpolt and Marden, 1959). The Greenbrier was deposited in a tropical, shallow carbonate ramp setting during a time of tectonic quiescence (Scotese and others, 2001; Wilpolt and Marden, 1959). It is often called the "Big Lime" in West Virginia, not to be confused with Ohio's "Big Lime" interval, which consists of the Devonian Onondaga Limestone through Silurian Lockport Dolomite.

The elevation of the Greenbrier Limestone in the AOI ranges from 1,400 ft above Mean Sea Level (MSL) in an anticline in Monongalia County, West Virginia, to -1,400 ft MSL in northern West Virginia near the Ohio River (Figure 3-5). Elevation of the unfolded Greenbrier in Jackson County, Ohio, is about 450 ft MSL. The Greenbrier Limestone varies in thickness from 300 ft in Boone County, West Virginia to 0 ft in Ohio and counties north of Pittsburgh, Pennsylvania, where the unit is removed by erosion (Figure 3-6).

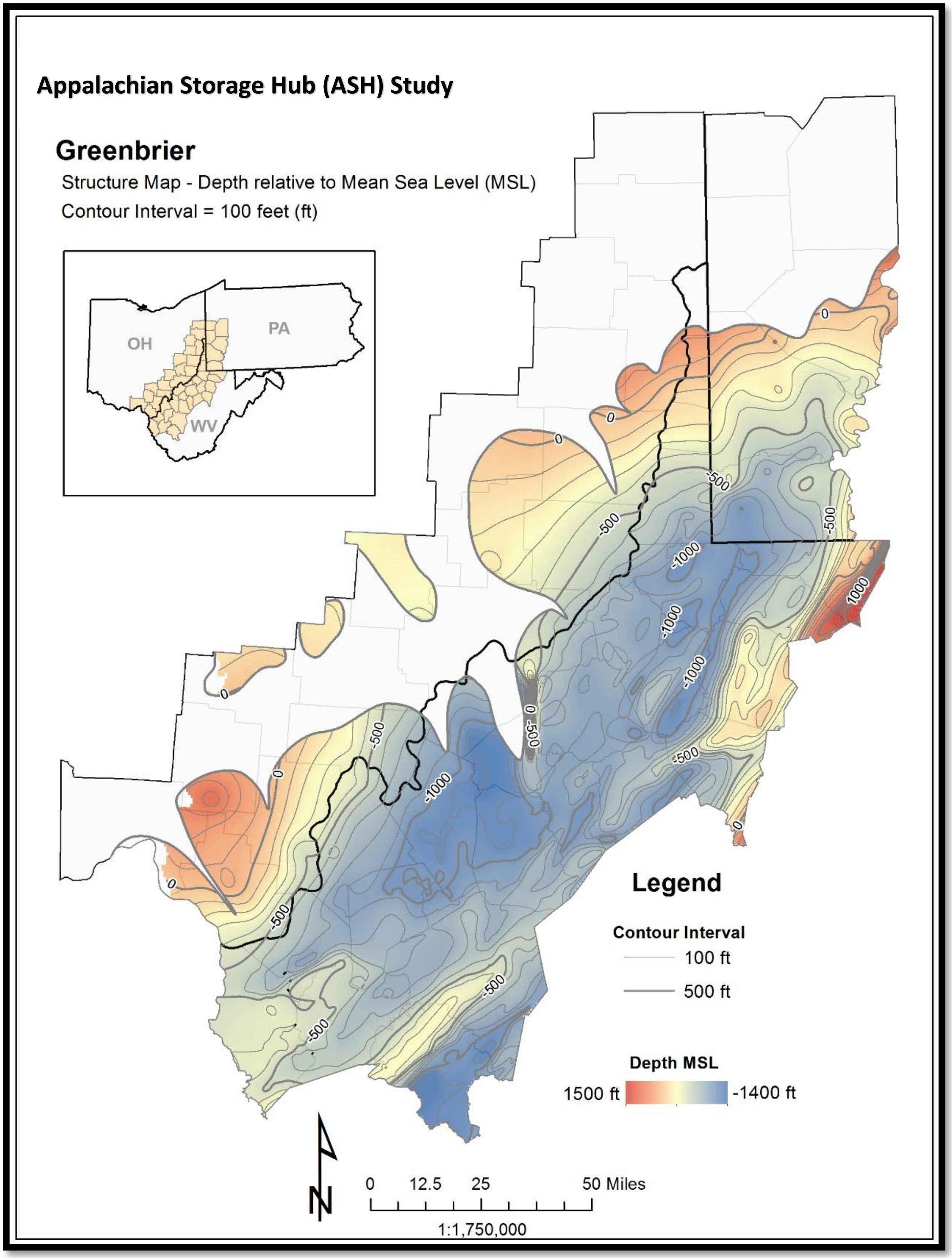



**Figure 3-5. Structure contour map on top of the Greenbrier Limestone (GRNB) interval. Subcrop from Rice and Schwietering (1988).**

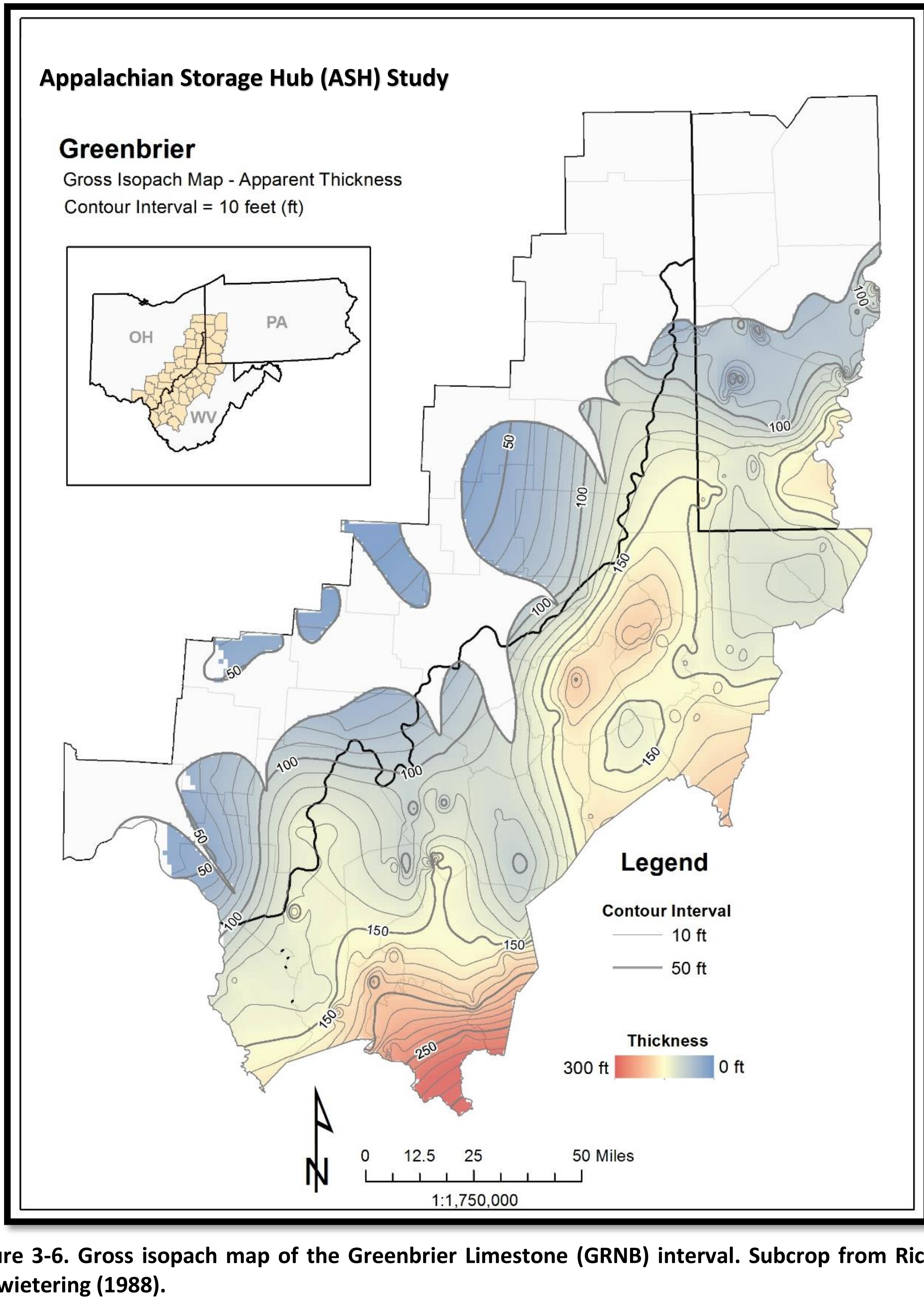



**Figure 3-6. Gross isopach map of the Greenbrier Limestone (GRNB) interval. Subcrop from Rice and Schwietering (1988).**

## 3.4 Keener to Berea Interval (KENR-BERE)

The Keener to Berea interval consists of several Upper Devonian through Middle Mississippian depleted sandstone reservoirs interbedded with finer-grained units. These include the Keener sandstone, Big Injun sandstone, Weir sandstone and Berea Sandstone and stratigraphic equivalents. These sandstones are present as discontinuous lenses throughout the AOI, deposited in shallow marine through fluvial-deltaic environments.

The Mississippian Keener sandstone is a fine-grained, well sorted sandstone primarily cemented with carbonates, and interbedded with carbonates (Smosna, 1996). It has been described to have small amounts of pyrite and clay minerals (McCord and Eckard, 1963).

The Big Injun sandstone is a light-gray, very fine to medium-grained, carbonate-rich sandstone with occasional pyrite and clay minerals, interbedded with carbonates (Vargo and Matchen, 1996; McCord and Eckard, 1963). It occurs below the Keener sandstone, with limestone interbeds, and is stratigraphically equivalent to Pennsylvania's Lower Mississippian Burgoon Formation, Shenango Formation and Cuyahoga Group, and Ohio's Lower Mississippian Black Hand Member of the Cuyahoga Formation (Vargo and Matchen, 1996).

Below the Big Injun are the Lower Mississippian Weir sandstones, which occur within the Price Formation in West Virginia (Hohn and others, 1993; Matchen and Vargo, 1996). It can be a single bed of sandstone, or multiple beds within a location, and has been informally divided into the Upper, Middle and Lower Weir. The Weir sandstones are fine- to medium-grained sandstones, with abundant deltaic and tidal sedimentary structures, and occasional secondary uranium-salt deposits (Matchen and Vargo, 1996).

The basal sandstone in this interval is the Lower Mississippian-Upper Devonian Berea Sandstone and its Murrysville sandstone equivalent in southwestern Pennsylvania. The Berea Sandstone is a medium to fine-grained, clay-bonded quartz sandstone, occupying deltaic channels throughout the region.

The top of this interval is as shallow as 1,400 ft MSL and deepens to approximately -1,500 ft MSL in the AOI (Figure 3-7). The gross thickness of the Keener to Berea Interval ranges from 325 ft to more than 800 ft (Figure 3-8) in the Study area.

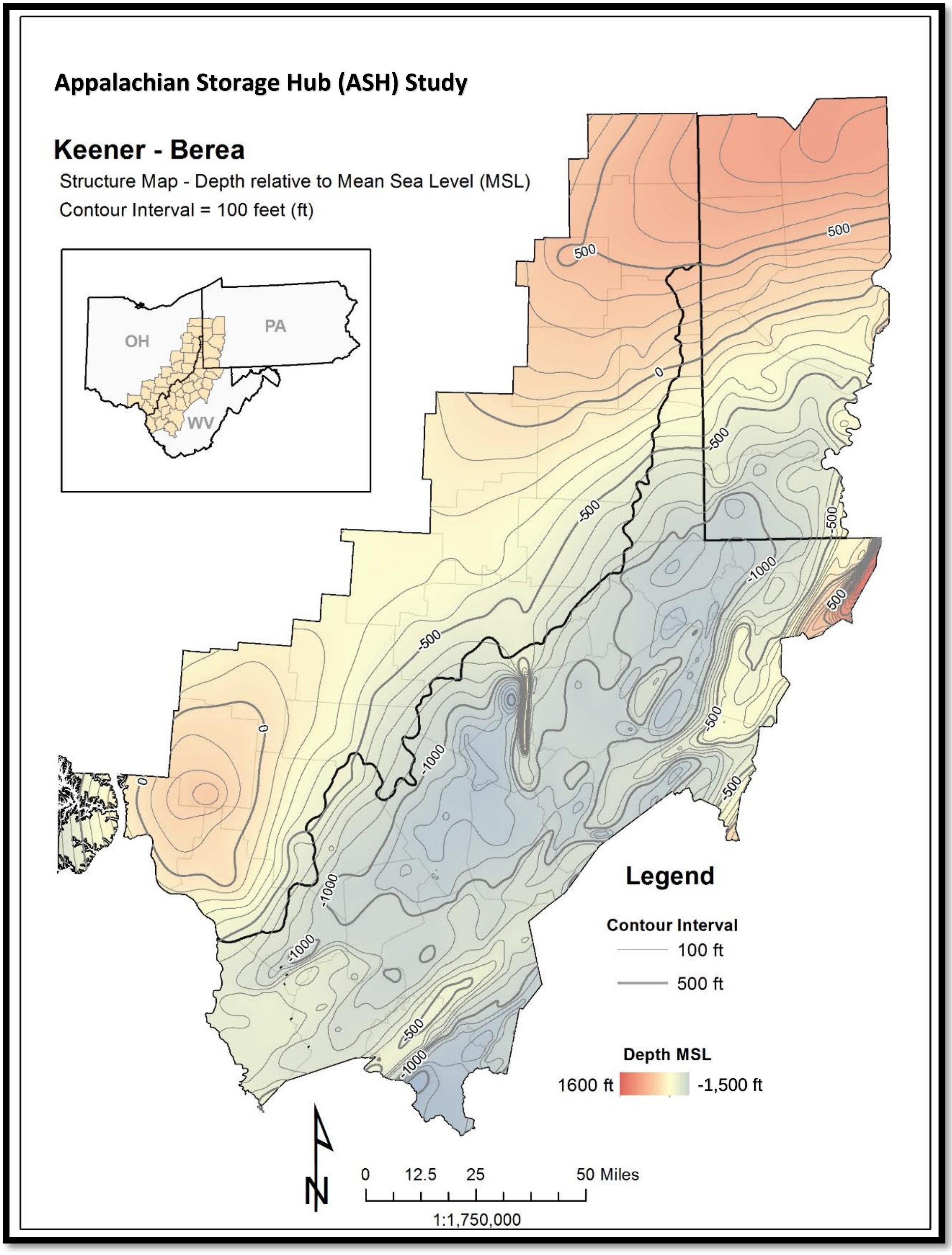



**Figure 3-7. Structure contour map on top of the Keener to Berea (KENR-BERE) interval.**

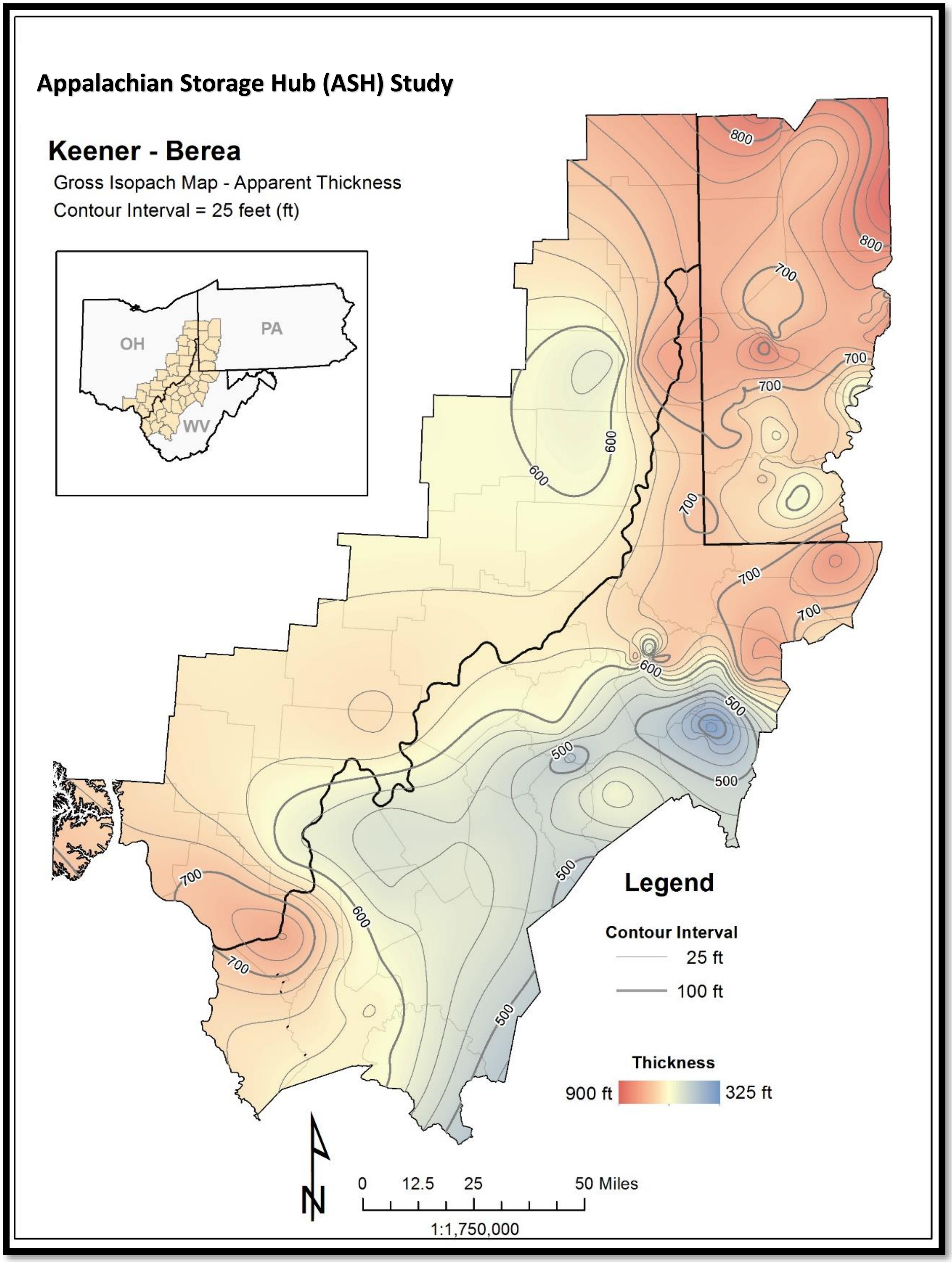



**Figure 3-8. Gross isopach map of the Keener to Berea (KENR-BERE) interval.**

## 3.5 Upper Devonian Sandstones

The Upper Devonian Venango, Bradford and Elk Groups comprise thousands of feet of sedimentary rock, and the sandstone units within these intervals account for hundreds of depleted gas reservoirs throughout the AOI. Each group consists of shale interbedded with discontinuous sandstone and siltstone layers. Correlation of the sandstones in these intervals generally followed the approach of Boswell and others (1996a), hence the reference to these packages as “V5-V1,” “B5-B1” and “E4-E1.” Regional mapping was performed separately for each package, as presented below.

### 3.5.1 Venango Group (V5-V1)

The Upper Devonian Venango Group is the shallowest and most sandstone-rich of the three clastic progradational episodes of the Catskill delta complex (Boswell and others, 1996a). The Research Team divided the Venango Group into five sandstone intervals for correlation purposes, where the top-most unit was identified as V5 and bottom-most unit as V1.

The top of the Venango Group is shallowest in the northern and eastern portions of the AOI at about 800 ft MSL and deepens toward the southeast to -2,100 ft MSL in West Virginia (Figure 3-9). The gross thickness of this interval is greatest in the southeastern portion of the AOI, where it measures up to 1,675 ft, and thins to the northwest to about 25 ft (Figure 3-10). The average gross thickness of the Venango Group along the Ohio River in northern West Virginia is approximately 700 ft.

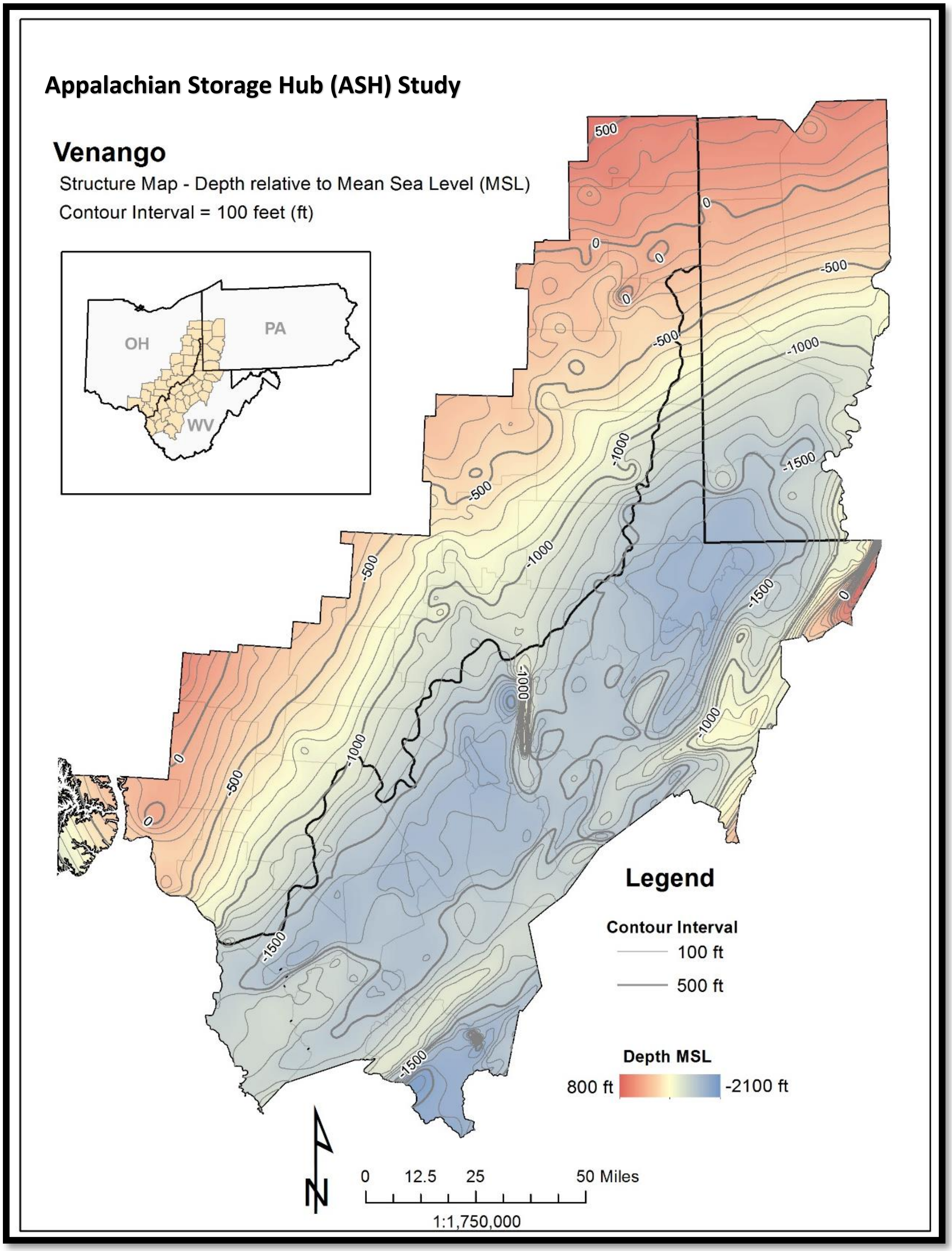



**Figure 3-9. Structure contour map on top of the Venango Group (V5-V1 interval).**

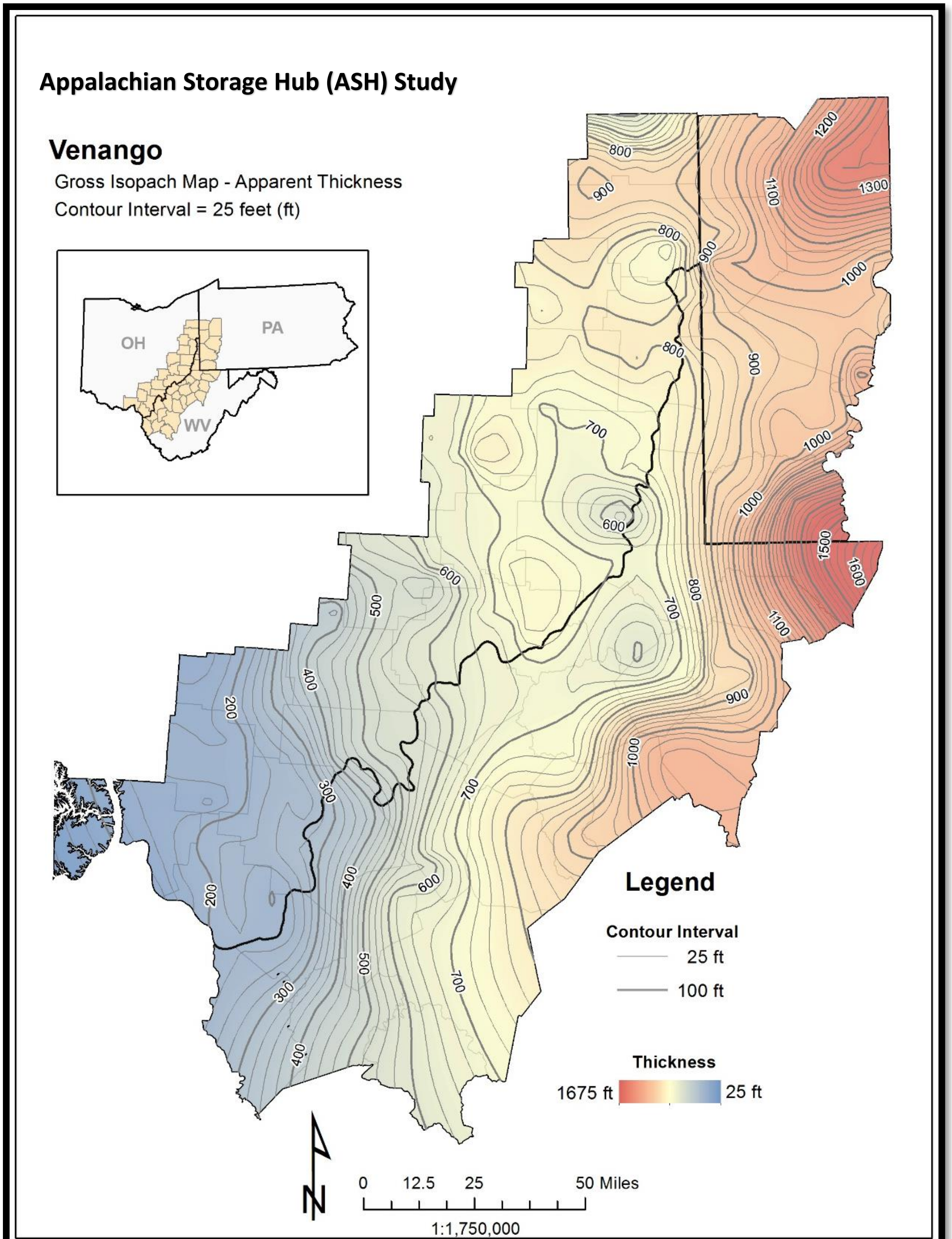



**Figure 3-10. Gross isopach map of the Venango Group (V5-V1 interval).**

### 3.5.2 Bradford Group (B5-B1)

The Upper Devonian Bradford Group represents the middle clastic progradational episode of the Catskill delta and primarily consists of shale and interbedded sandstones. Bradford sandstone reservoirs in northern West Virginia are typically siltstones and thin-bedded, fine-grained sandstones. The Research Team correlated this interval as a series of five sandstone units, where the top-most was identified as B5 and bottom-most unit as B1, as per Boswell and others (1996b).

The top of the Bradford Group is shallowest in the western portion of the AOI in Ohio at about 250 ft MSL and deepens towards the \east to -2,800 ft MSL in West Virginia, namely in Wood County (near the Ohio River) and in Monongalia County (Figure 3-11).

The gross thickness of the Bradford Group is defined as the interval between the B5 and E4 (i.e., top of the Elk Group, see Section 3.5.3). The Bradford Group is thickest (1,800 ft) in the eastern portion of the AOI and thins toward the west (100 ft) (Figure 3-12). The average gross thickness of the Bradford Group along the Ohio River in northern West Virginia is about 1,500 ft.

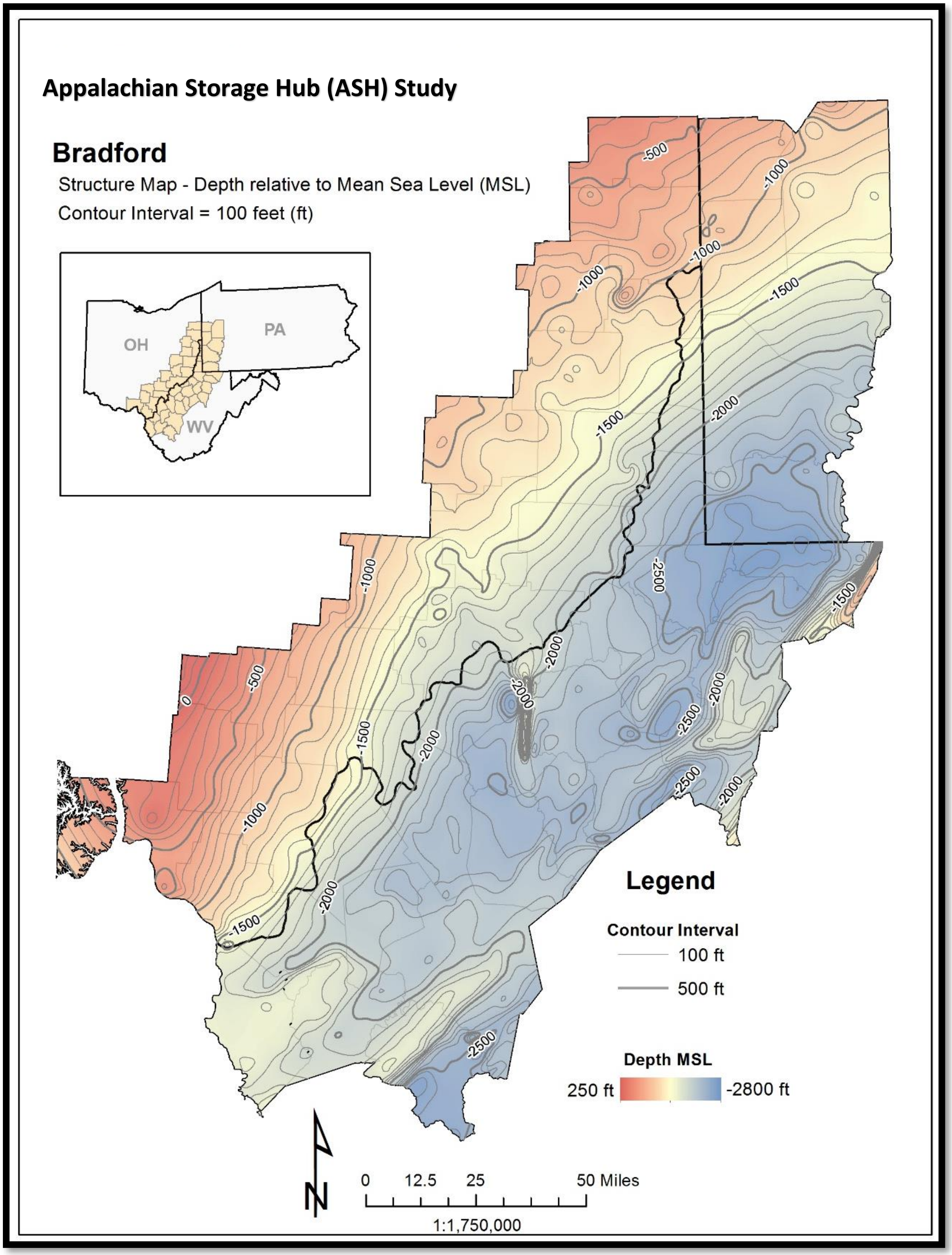



**Figure 3-11. Structure contour map on top of the Bradford Group (B5-B1 interval).**

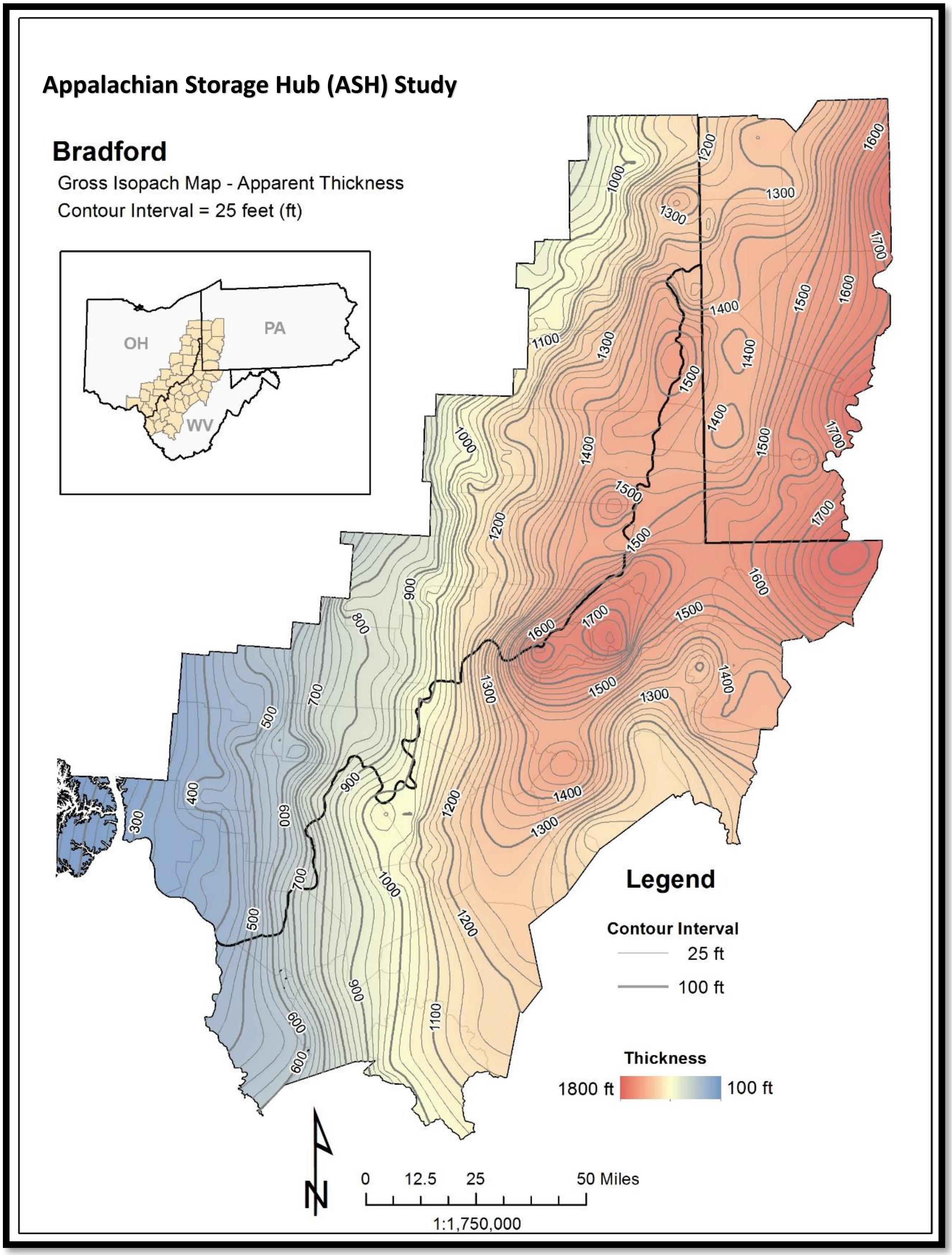



**Figure 3-12. Gross isopach map of the Bradford Group (B5-B1 interval).**

### 3.5.3 Elk Group (E4-E1)

The Upper Devonian Elk Group and underlying Brallier Formation sandstones and siltstones represent the lowermost portion of the Acadian clastic wedge of the Catskill delta. Collectively, the various producing units in this interval, ranging from the Benson siltstone at the top to the Sycamore sandstone at the base, have been defined as the Elk Play (Donaldson and others, 1996). The Elk Play consists of four sandstone and siltstone units, correlated by the Research Team as E4 (top-most unit defined by the Benson) through E1 (bottom-most unit above the Harrell Shale, which in West Virginia correlates with the base of the Middlesex Shale).

The top of the Elk Group is shallowest in the western portion of the AOI in Ohio at -100 ft MSL and deepens toward the east to -4,500 ft MSL in West Virginia (Figure 3-13).

Two isopach maps were prepared for the Elk interval. The gross thickness mapped in Figure 3-14 includes the interval between the E4 (and equivalent units) and the top of Onondaga Limestone (see Figure 3-1), which includes the Elk, Brallier, Harrell, Mahantango and Marcellus formations. This interval is thickest in Lewis County, West Virginia (2,625 ft) and thins toward the west (25 ft) (Figure 3-14). Figure 3-15 provides a focused representation of the Elk Group (E4-E1) in northern West Virginia, where the gross thickness was determined based strictly on Benson and Middlesex formation data (consistent with Donaldson and others, 1996). In this area of the AOI, gas production from units within the E4-E1 interval has been notable, and the gross thickness of the package ranges from 1,000 to 2,100 ft.

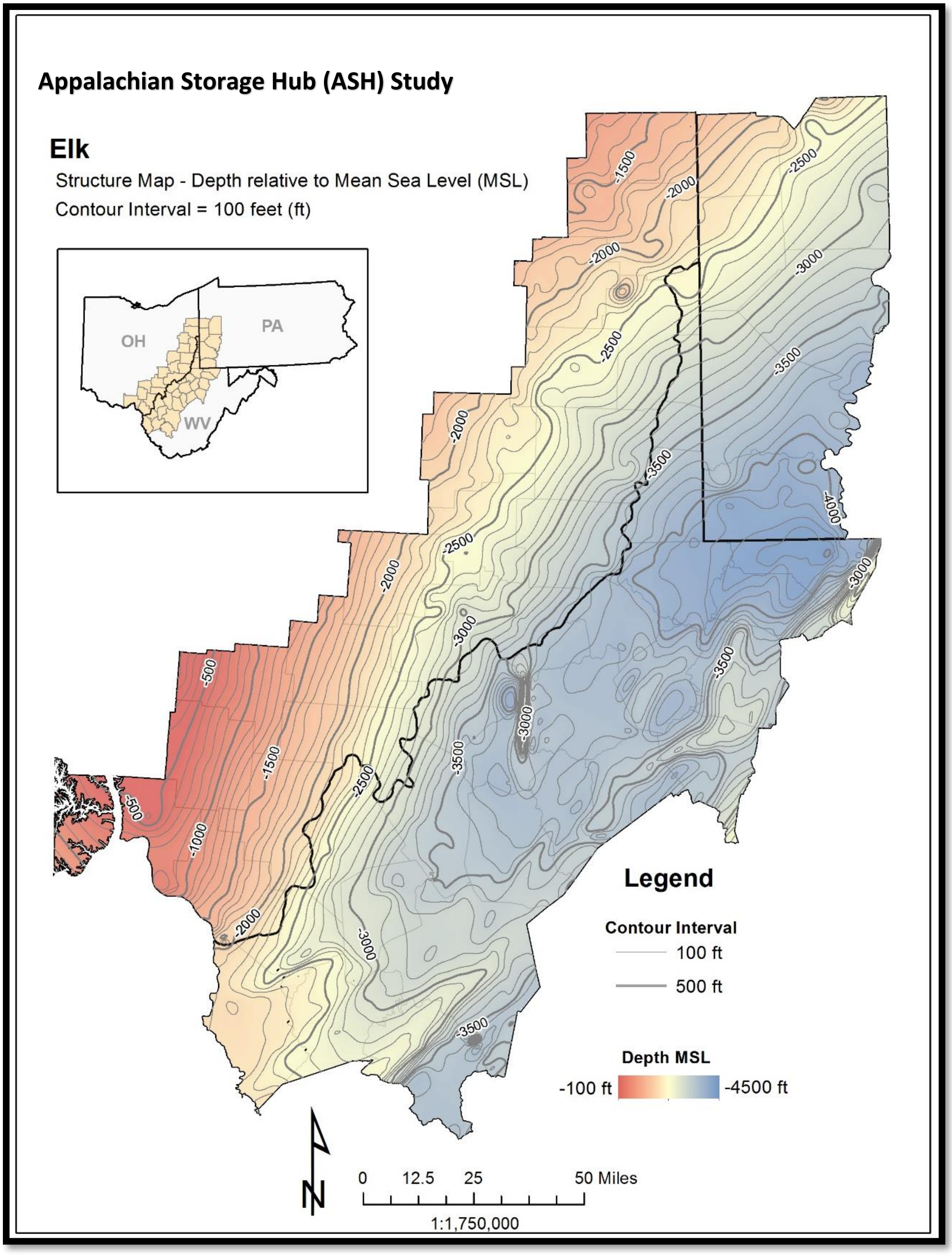



**Figure 3-13. Structure contour map on top of the Elk Group (E4-E1 interval).**

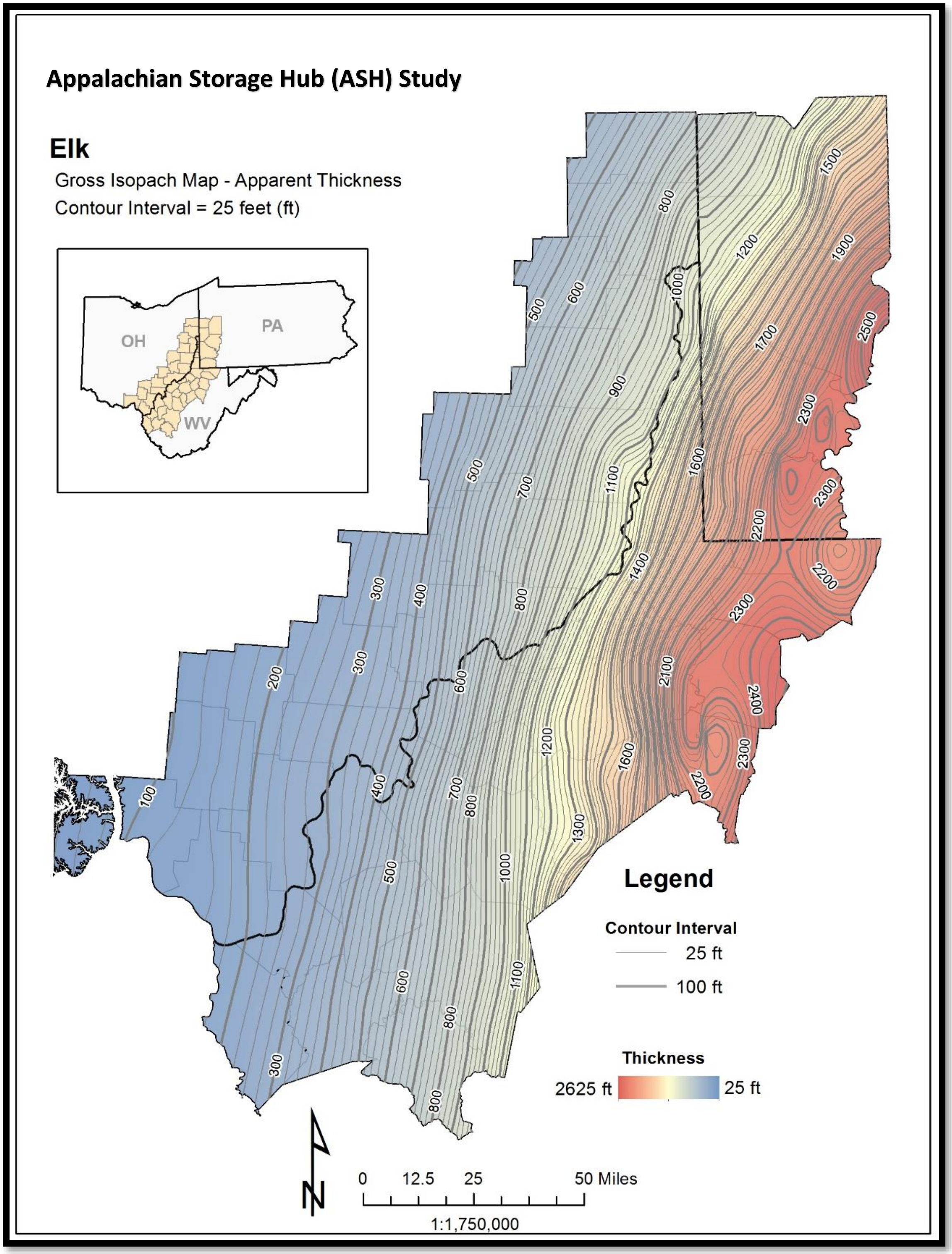



**Figure 3-14. Gross isopach map of the Elk Group (E4-E1 interval) and underlying Upper Devonian clastics.**

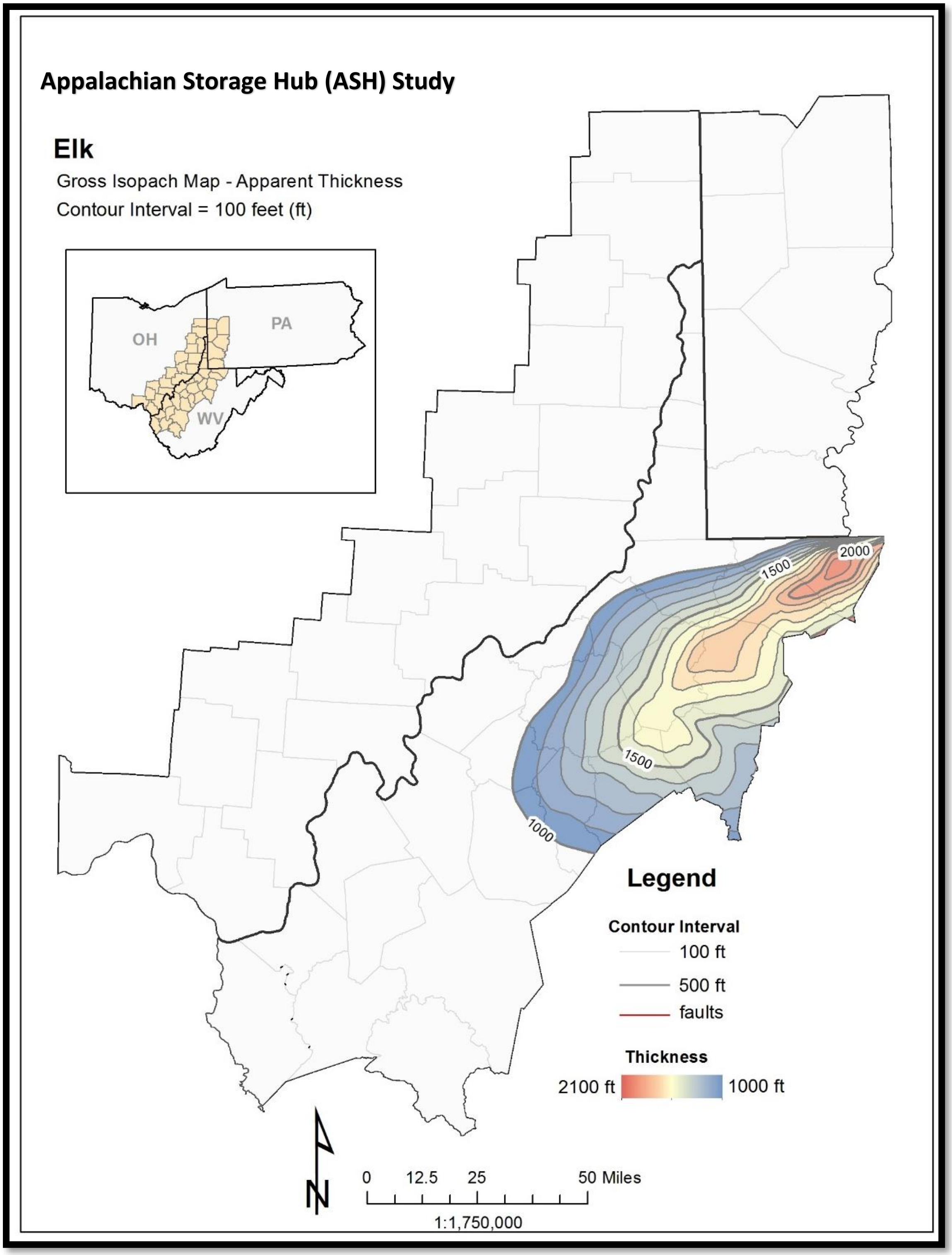



**Figure 3-15. Gross isopach map of the Elk Group (E4-E1 interval) in northern West Virginia.**

## 3.6 Oriskany Sandstone (ORSK)

The Devonian Oriskany Sandstone is a regionally persistent, monocrystalline quartz sandstone that is medium- to coarse-grained, contains well-sorted, well-rounded and tightly cemented grains, and is conglomeratic in places (Diecchio, 1985; Harper and Patchen, 1996). Quartz and calcite are the most common cementing materials. In some parts of the AOI, the sandstone 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 amounts of pyrite, dolomite, rutile, zircon and other minerals have also been observed (Harper and Patchen, 1996). Minerals that formed in place after the Oriskany was deposited include several clay minerals, sphalerite and pyrite (Martens, 1939; Basan and others, 1980). Minor cements include pyrite, dolomite, ankerite, glauconite and chalcedony (Basan and others, 1980).

The top of the Oriskany Sandstone ranges from -600 ft MSL in Scioto County, Ohio, to -7,000 ft MSL in Greene County, Pennsylvania (Figure 3-16). This unit is thickest in northern West Virginia (175 ft), and thins toward the west and northwest, pinching out in western West Virginia and parts of central and northeastern Ohio (Figure 3-17). These pinchout areas define the Oriskany subcrop – places where the Oriskany is bounded by erosional surfaces below and above it – in southeastern Ohio. Here, the sandstone forms a thin wedge between relatively impermeable Lower and Middle Devonian carbonates and shales.

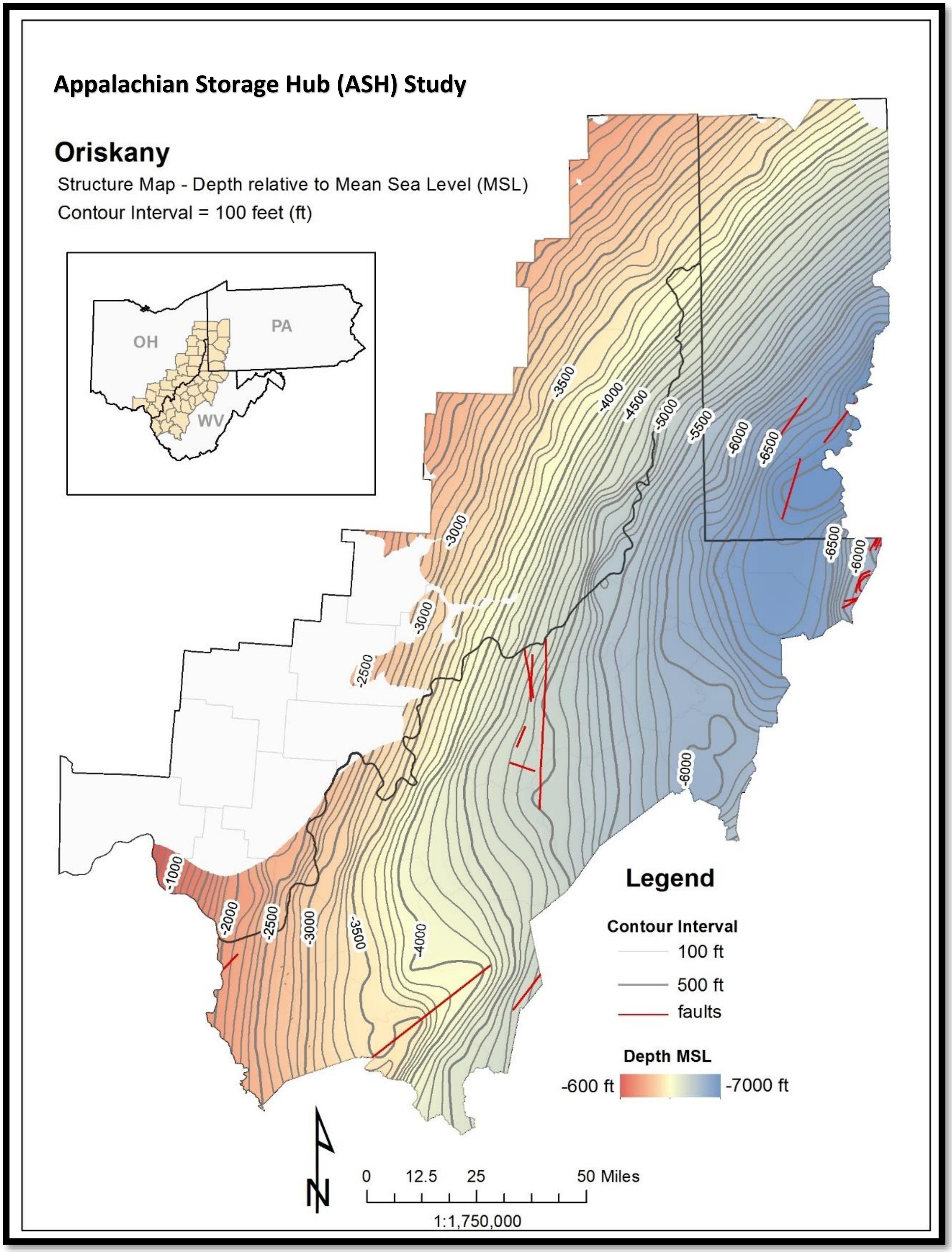



**Figure 3-16. Structure contour map on top of the Oriskany Sandstone (ORSK).**

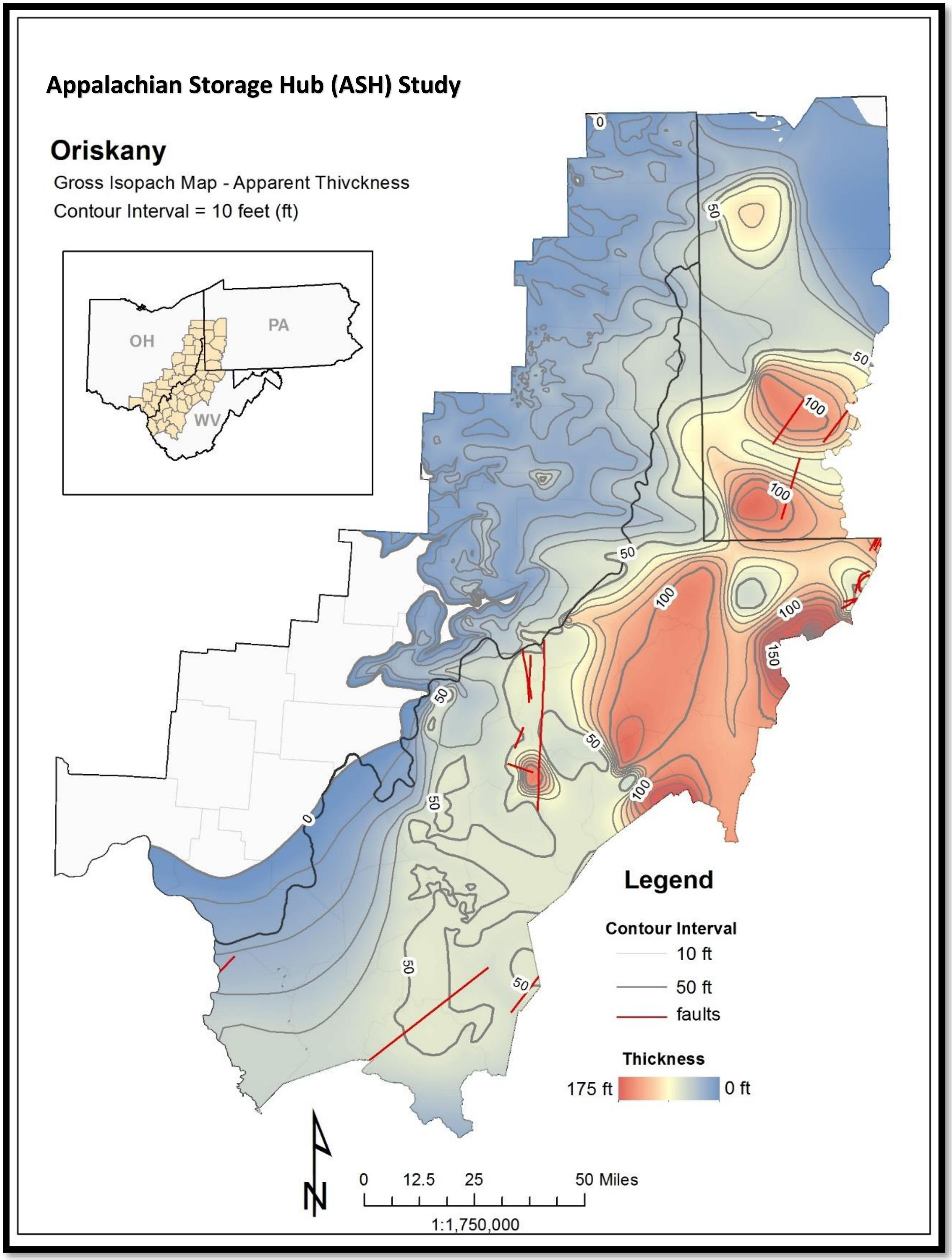



**Figure 3-17. Gross isopach map of the Oriskany Sandstone (ORSK).**

## 3.7 Salina F4 Salt (SLNF)

The Silurian Salina Group is a lithologically mixed interval that exists throughout the Appalachian basin, thickening and deepening towards the basin center (Clifford, 1973). The Salina Group was deposited in a subtropical, shallow marine environment that experienced occasional lowering of sea level, which allowed for the deposition of extensive and thick evaporites interbedded with carbonates and shales across the Appalachian basin. These beds are consistent and widespread throughout the AOI, gently dipping, gradually thinning and ultimately outcropping towards western Ohio beyond the boundary of the AOI (Clifford, 1973; Wickstrom and others, 2005; Ulteig, 1964).

The Salina Group's dolomites, anhydrites, shales and salt grade into sandstones, shales and limestones toward the southeast in Pennsylvania, Maryland and West Virginia (Wickstrom and others, 2005). The evaporite (salt) layers are typically marker beds for dividing the Salina Group into the seven units (A-G) recognized within the Appalachian basin (Clifford, 1973). Salt is found with the B, D, E and F units, while anhydrites are found within the A, C and G units.

This Study focused on the Salina F4 Salt because it is currently being solution-mined within the AOI along the Ohio River in West Virginia, and is reported to be the thickest salt within the Salina Group (Clifford, 1973; Wickstrom and others, 2005). When the Salina F4 Salt is present, it is situated at the top of the Salina F unit. A thin, persistent dolomite/anhydrite zone is present below the upper F4 Salt, with a second, but thinner, salt at the base (see Chapter 4). The Salina F4 Salt occurs at depths of approximately -300 ft MSL in Athens County, Ohio, to more than -7,400 ft MSL in Lewis County, West Virginia (Figure 3-18). The Salina F4 Salt is restricted to the northcentral portion of the AOI, and is absent just north/northwest of the AOI (Tuscarawas County, Ohio and beyond). It reaches maximum thicknesses of 100 ft or more along the Ohio River (Figure 3-19).

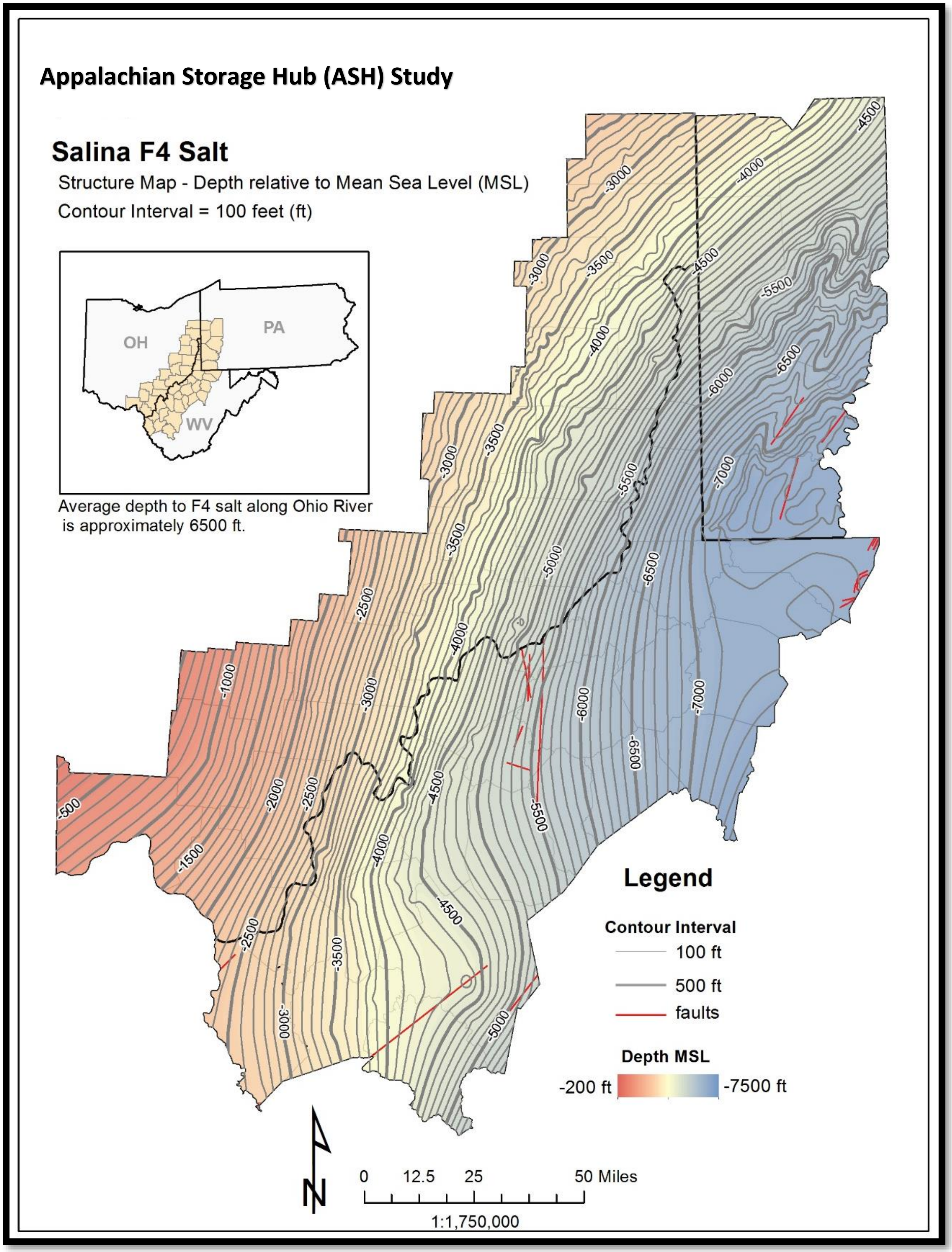



**Figure 3-18. Structure contour map on top of the Salina F4 Salt (SLNF) interval. The F4 Salt is at the top of the Salina F unit.**

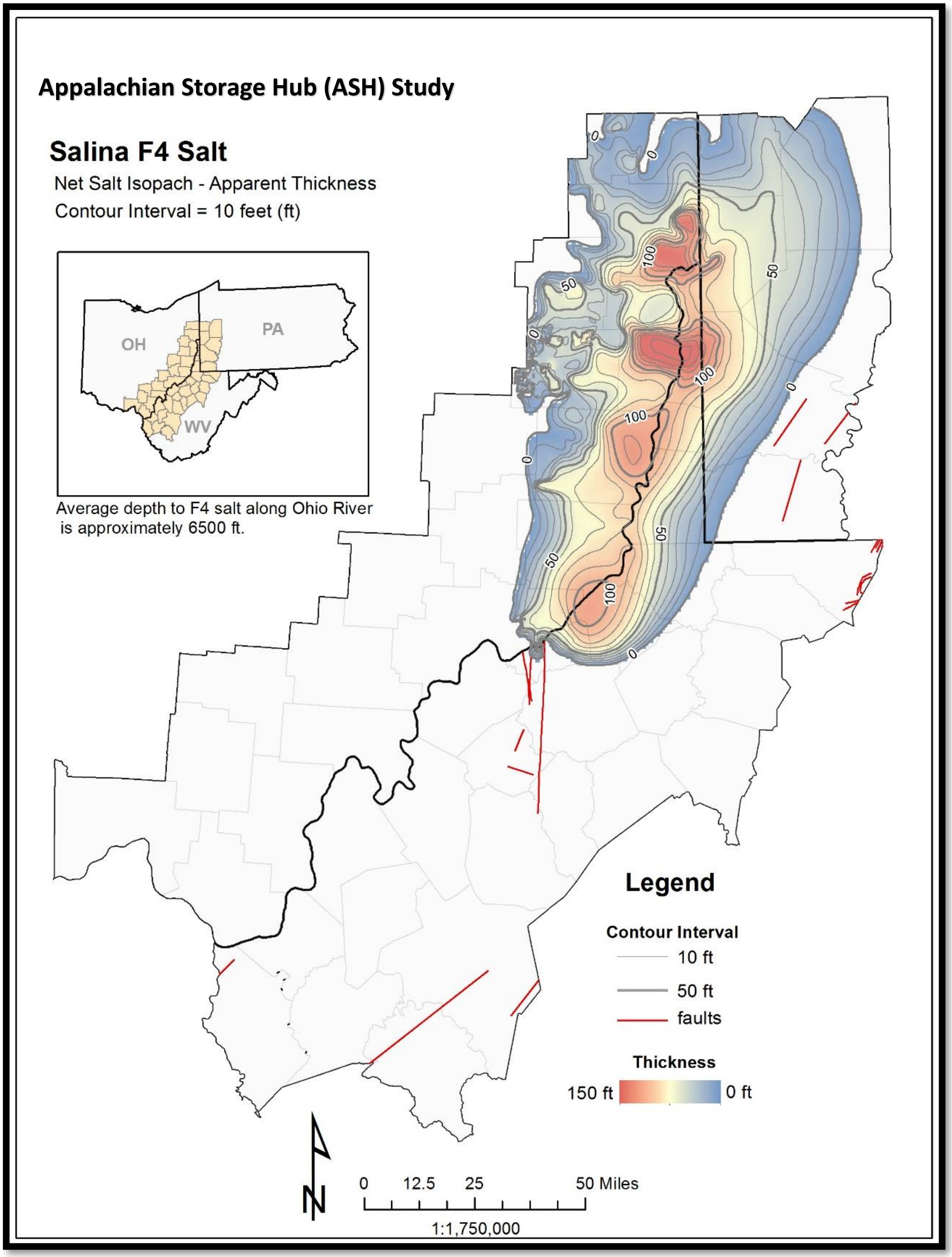



**Figure 3-19. Net isopach map of the Salina F4 Salt (SLNF) interval. Thicknesses do not include a persistent dolomite/anhydrite zone below the salt, or salt below the dolomite/anhydrite zone.**

## 3.8 Newburg Sandstone (NBRG)

The Newburg sandstone is a white to gray, very fine- to fine-grained, clean, well sorted sandstone, consisting of mostly rounded quartz grains. The Newburg sandstone is stratigraphically higher in the section than the Ohio "Newburg" zone, and correlates to a sandy bed that occurs within the C interval of the Salina Group in central West Virginia (Patchen, 1996). This sandstone was deposited in a high-energy, shallow-water environment, such as on a proximal shallow sandstone shelf (Patchen, 1996).

Newburg sandstone formation tops were correlated following the stratigraphy of Patchen (1996). Structure and gross isopach maps were hand contoured following a high-energy shoreline model, interpreted variously as either barrier island (Patchen, 1996) or carbonate ramp with estuarine influence (Lewis, 2013).

The top of the Newburg sandstone ranges from about -3,500 ft MSL near the Ohio River to about -5,500 ft MSL in the eastern portion of the AOI (Figure 3-20). The gross thickness of the Newburg sandstone ranges from about 5 to 30 ft (Figure 3-21).

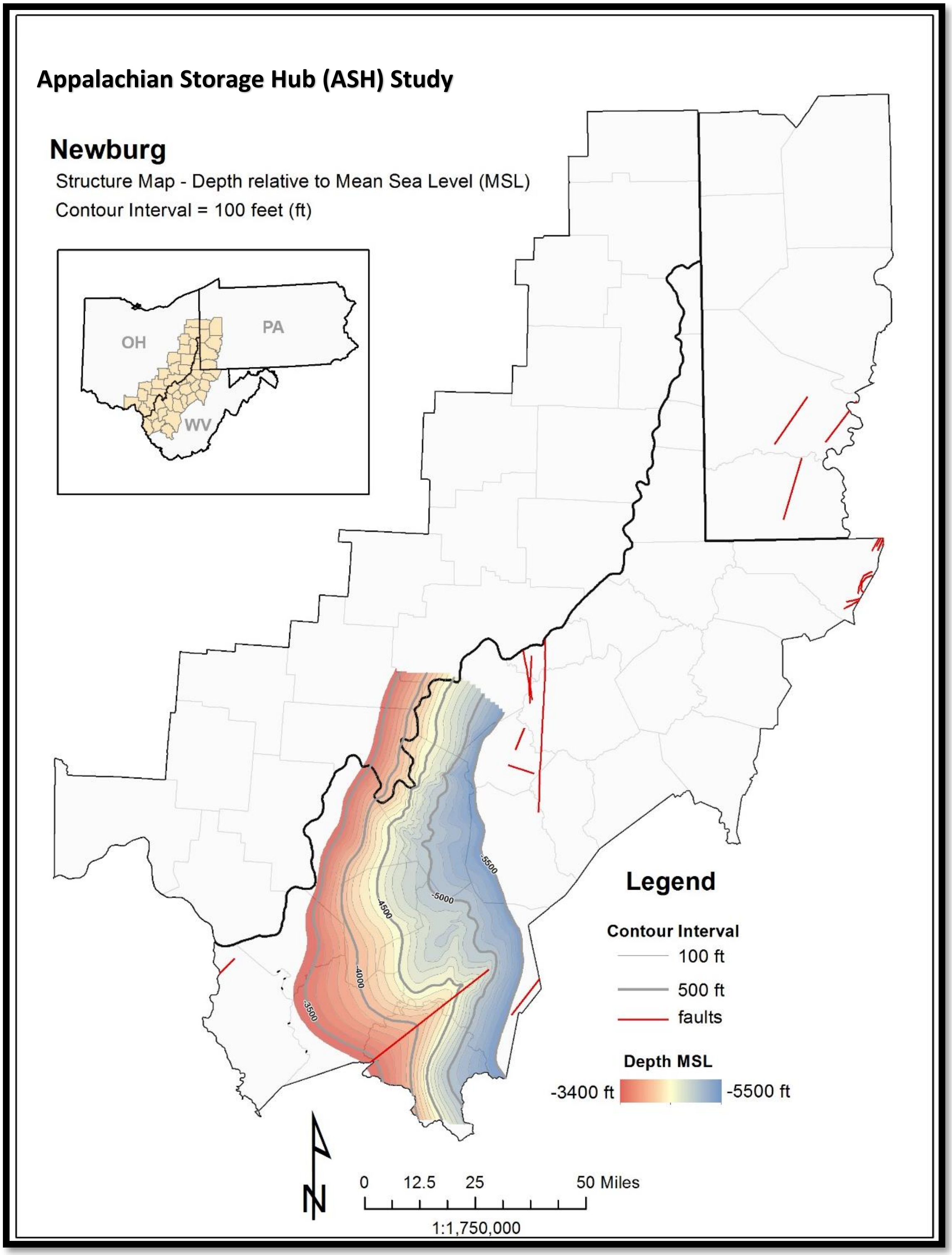



**Figure 3-20. Structure contour map on top of the Newburg sandstone (NBRG).**

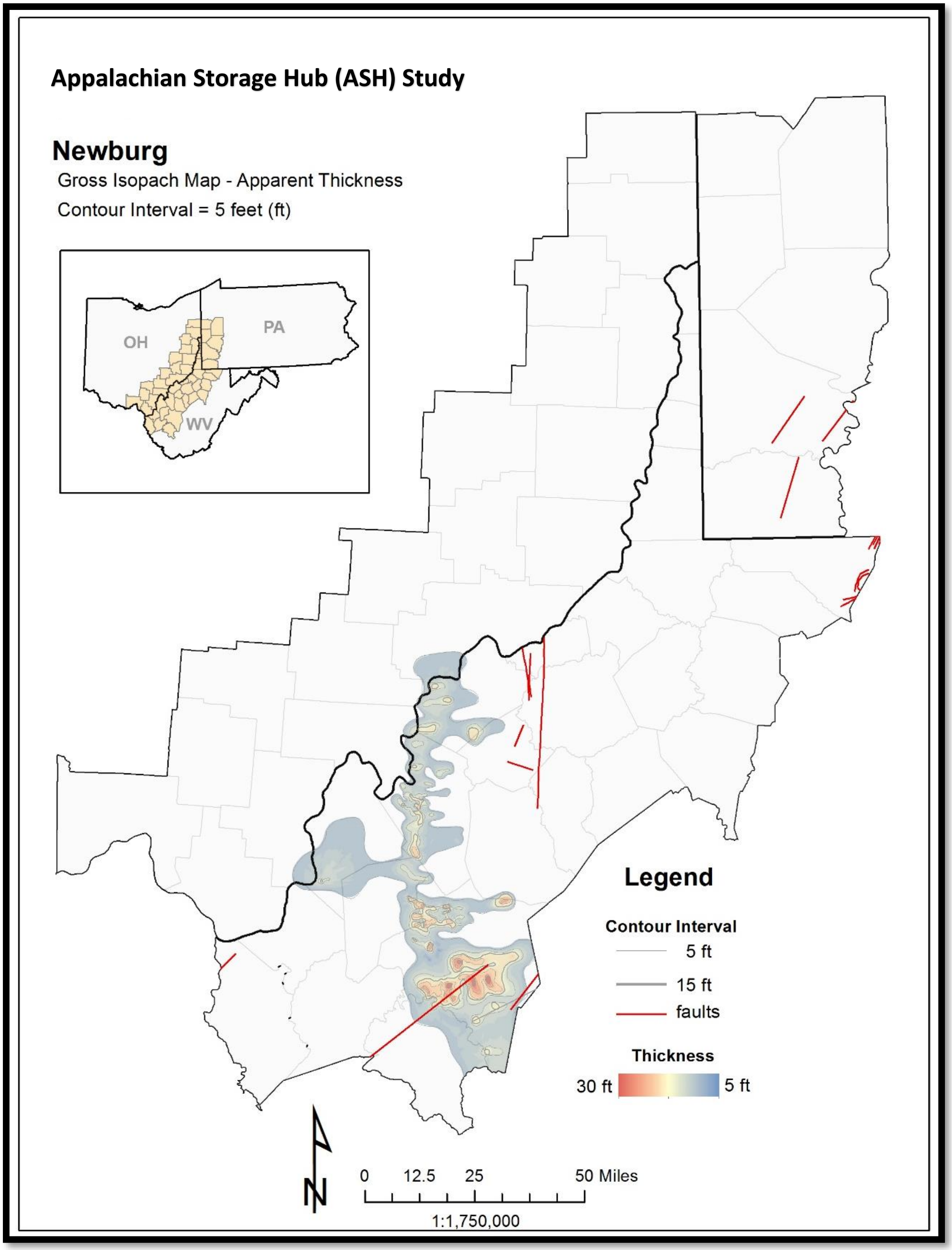



**Figure 3-21. Gross isopach map of the Newburg sandstone (NBRG).**

## 3.9 Clinton/Medina Group (CATG)

The Medina (or Cataract) Group is composed of interbedded sandstones, siltstones and shales, with some carbonates (Laughrey, 1984; Laughrey and Harper, 1986; McCormac and others, 1996). The stratigraphic nomenclature of this interval is somewhat complex, due to the influence of both facies changes and drillers' terminology across the Appalachian basin. This sequence is known as the Medina Group in northwestern Pennsylvania and western New York; the Cataract Group in eastern Ohio and southern Ontario; and erroneously as the "Clinton" sandstone by drillers, particularly in eastern Ohio and northern Kentucky. The lateral equivalent of the Medina Group in Pennsylvania and West Virginia is the Tuscarora Sandstone, a fine-grained to conglomeratic, massively bedded, quartz sandstone with quartz cement. For the purposes of this Study, this interval is referred to as the Clinton/Medina Group.

The Clinton/Medina Group is comprised of three major stratigraphic units – the Grimsby Formation ("Clinton" sandstone), the Cabot Head ("Power Glen") Shale and the Whirlpool Sandstone ("Medina" sandstone). The sandstones of the Grimsby Formation are very fine- to medium-grained, monocrystalline, quartzose rocks, with subangular to subrounded grains, variable sorting and thin, discontinuous, silty shale interbeds. Cementing materials include secondary silica, evaporites, hematite and carbonates (Piotrowski, 1981; McCormac and others, 1996). The Cabot Head Shale is a dark green to black, marine shale with thin, quartzose, siltstone and sandstone laminations that increase in number toward the top of the unit (Piotrowski, 1981; Laughrey, 1984). The Whirlpool Sandstone is composed of a white to light gray to red, fine- to very fine-grained quartzose sandstone that is moderately well sorted and has subangular to subrounded grains (Piotrowski, 1981; Brett and others 1995; McCormac and others, 1996).

The top of the Clinton/Medina Group is shallowest along the western edge of the AOI (0 ft MSL) and rapidly deepens eastward to Greene County, Pennsylvania and northern West Virginia (-9,300 ft MSL) (Figure 3-22). The gross thickness of this interval reaches up to 250 ft along the eastern edge of the AOI and generally thins westward (60 ft) (Figure 3-23). The Clinton/Medina Group depositional system was that of a shelf/longshore-bar/tidal-flat/delta/fluvial complex. This complex, near-shore depositional system created discontinuous sand lenses throughout this interval, which accounts for some of the variability in thickness seen within the footprint of the AOI.

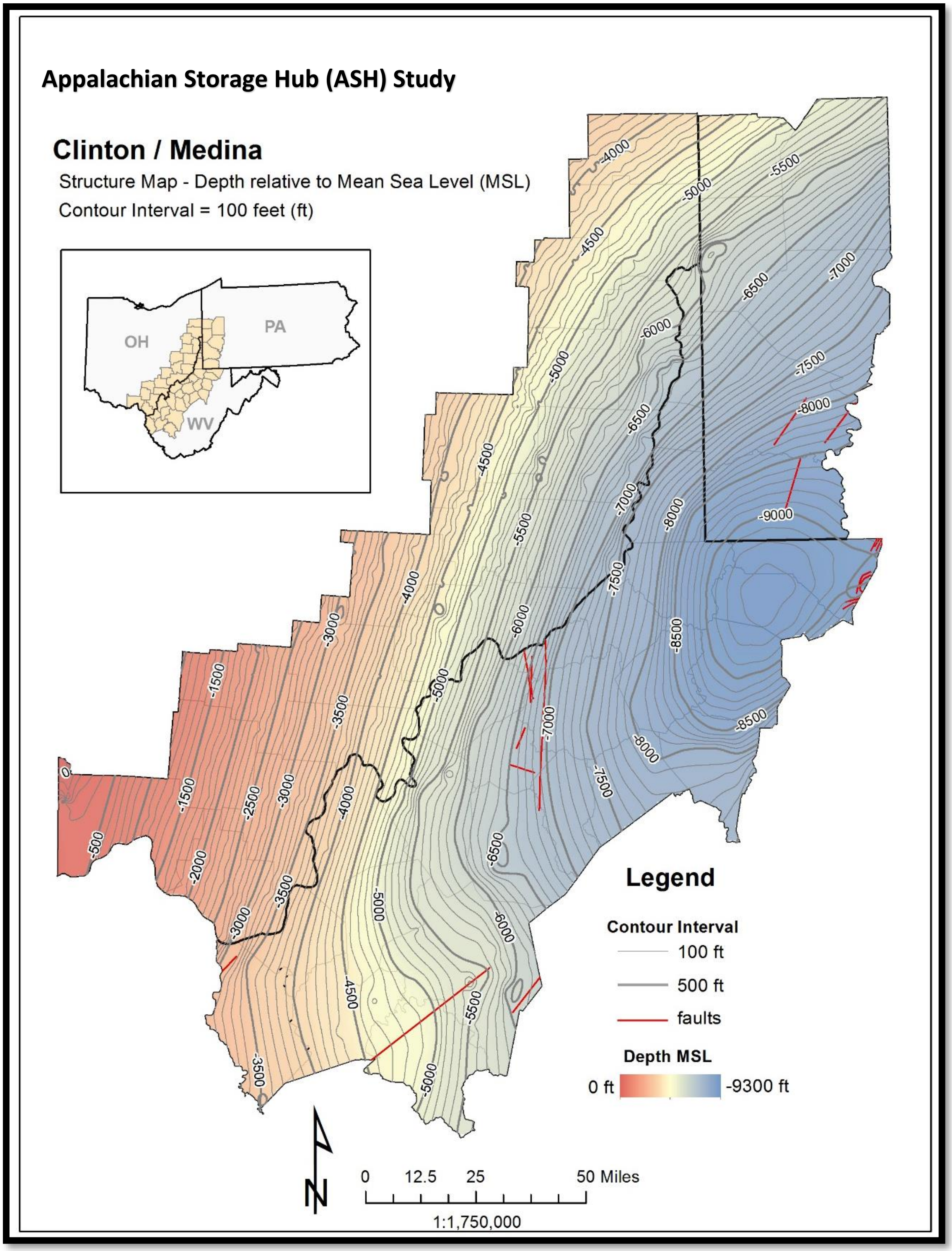



**Figure 3-22. Structure contour map on top of the Clinton/Medina Group (CATG).**

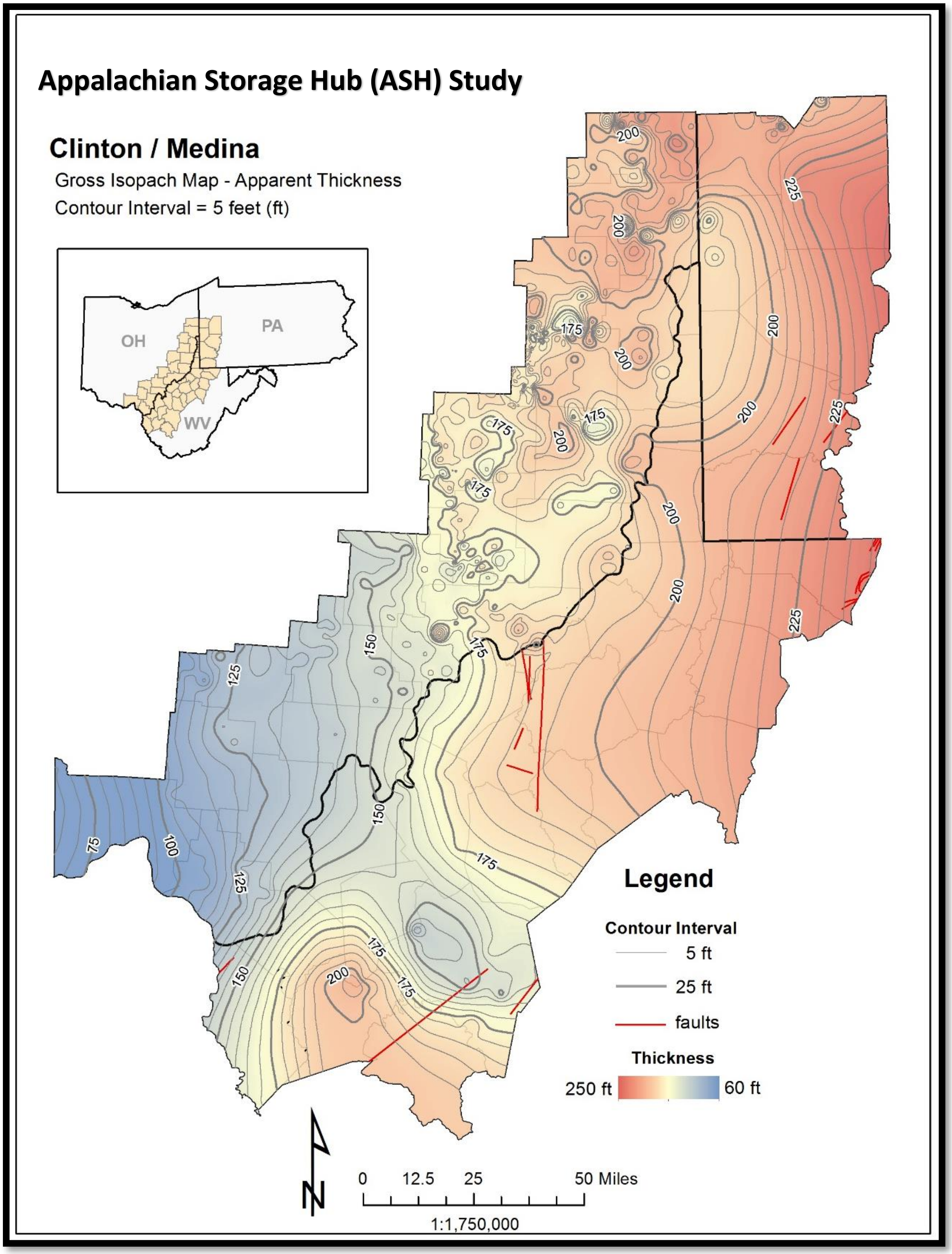



**Figure 3-23. Gross isopach map of the Clinton/Medina Group (CATG).**

## 3.10 Rose Run-Gatesburg Sandstones (RSRN)

The Rose Run-Gatesburg sandstones are laterally persistent sandstones that can be correlated in the subsurface from eastern Ohio, where the Rose Run subcrops beneath the Knox unconformity, to eastern Kentucky and into western West Virginia (where it is known as the upper sandstone member of the Knox), to Pennsylvania (the Upper Sandy member of the Gatesburg Formation), and beyond the AOI into New York.

The Rose Run Sandstone of Ohio consists of white to light-gray, fine- to medium-grained, sub- to well-rounded, moderately sorted quartz arenites to subarkoses, interbedded with thin lenses of nonporous dolostone (Riley and others, 1993; Baranoski and others, 1996). Glauconite and green shale laminae occur locally. The Rose Run equivalent in Pennsylvania, the Upper Sandy member of the Gatesburg Formation, contains three facies – sandstone, mixed sandstone and dolostone and dolostone (Riley and others, 1993). The sandstone facies consist of light-gray, fine-grained, well-sorted quartz arenites, primarily cemented with silica. The mixed sandstone and dolostone facies is dominated by fine- to medium-grained, moderately well-sorted quartz arenite sandstones, primarily cemented by dolomite. The dolostone facies are light gray to olive gray and display nodular bedding and bioturbation.

The top of the Rose Run-Gatesburg interval is shallowest in the western portion of the AOI (-1,500 ft MSL) and deepens toward the east to -17,500 ft MSL in Monongalia County, West Virginia, and Greene County, Pennsylvania (Figure 3-24). This interval is thickest along the eastern limits of the AOI (400 ft) and thins toward the west and northwest (50 ft) (Figure 3-25). The interval subcrops just northwest of the AOI, and is bound towards the southeast by the eastern margin fault. Within West Virginia, the irregular thickness is due to faults within the Rome Trough, while along the north and northwestern margin of the AOI, the irregular thickness is due to erosion on the Knox unconformity.

The major tectonic features affecting Rose Run-Gatesburg structure occur in northeastern Ohio, western Pennsylvania, eastern Kentucky and western West Virginia. In western Pennsylvania, these include the Tyrone-Mt. Union and Pittsburgh-Washington lineaments, which have been interpreted as northwest–southeast-trending wrench faults (Riley and others, 1993). In addition, numerous growth faults above basement rifts have been proposed that have been offset by movement along these major wrench faults (Laughrey and Harper, 1986; Harper, 1989; Riley and others, 1993). In eastern Kentucky and western West Virginia, structure is truncated by the east–northeast-trending Rome Trough. Locally, small-scale features are present that are not evident on regional-scale maps.

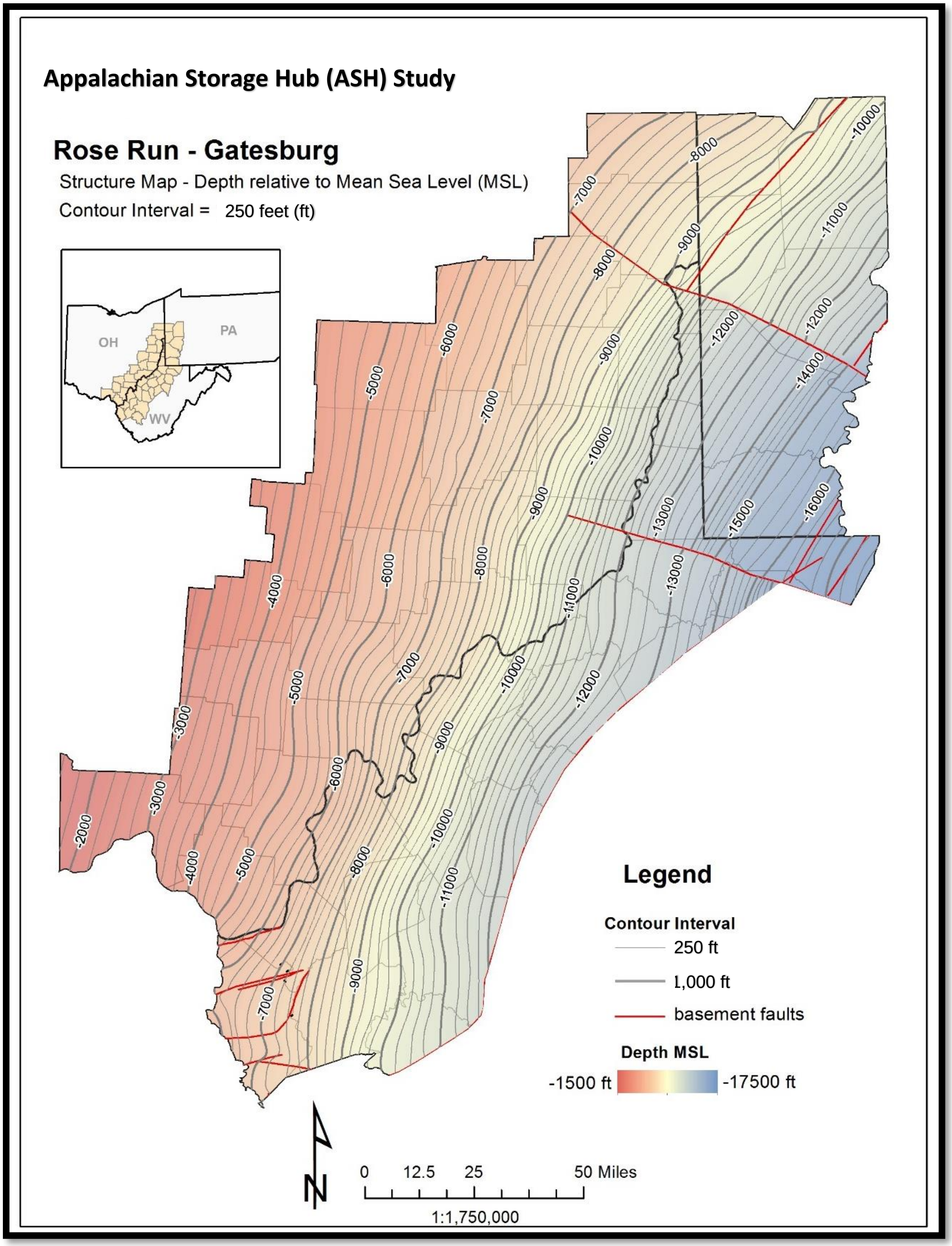



**Figure 3-24. Structure contour map on top of the Rose Run-Gatesburg (RSRN) interval.**

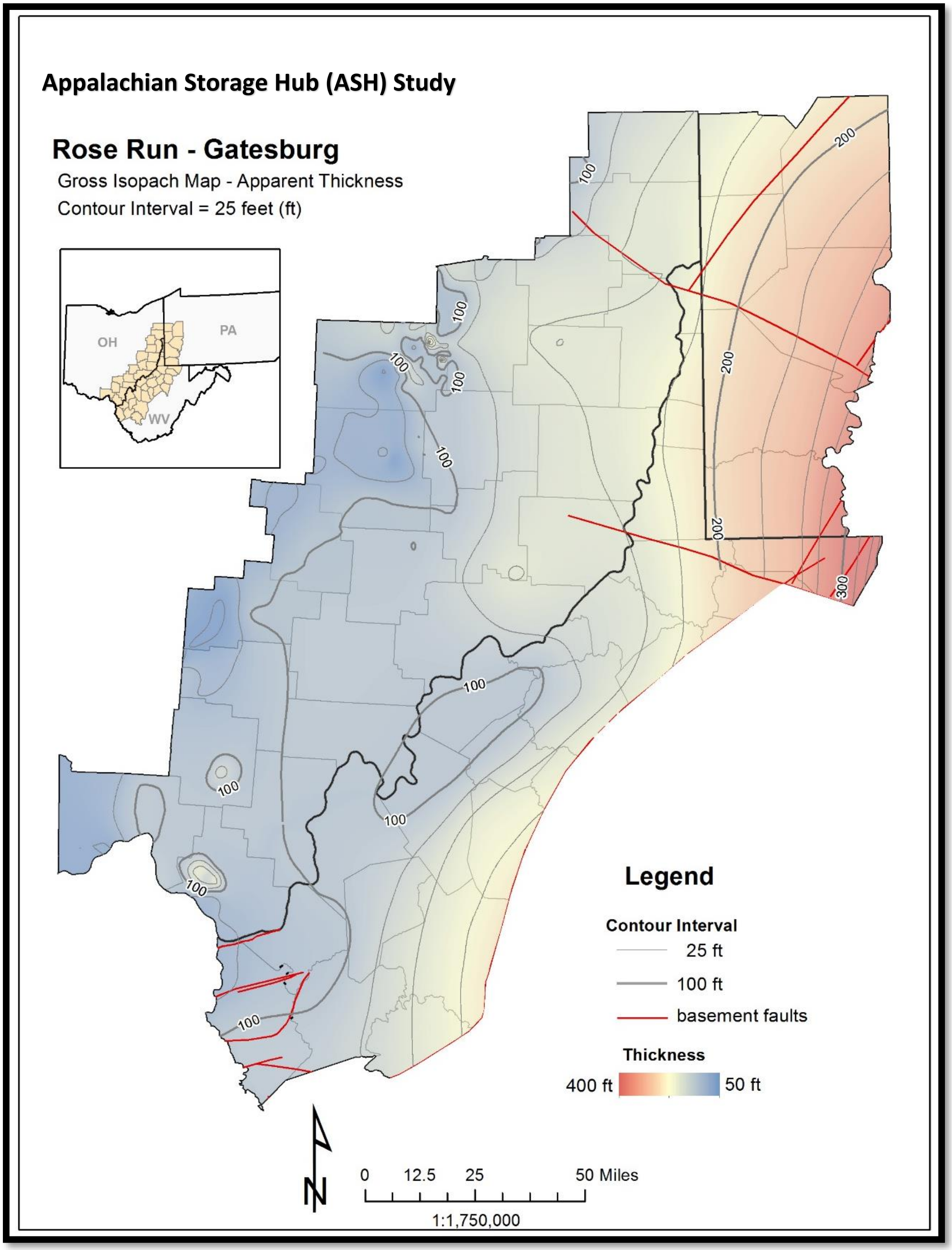



**Figure 3-25. Gross isopach map of the Rose Run-Gatesburg (RSRN) interval.**

# 4.0 RESERVOIR CHARACTERIZATION

The intent of the Study was to identify the stratigraphic units or reservoirs with the best geologic and geomechanical properties to ensure long-term, secure storage of ethane and other NGLs. Due to the varied nature of geologic intervals being evaluated as storage prospects, characterization efforts for each type of storage container (i.e., mined-rock cavern, salt cavern and depleted gas reservoir) were necessarily unique. While regional depth (structure) and thickness (isopach) mapping efforts went a long way toward identifying those geographic areas with the best mined-rock and salt cavern opportunities, the Research Team found that performing a preliminary assessment of the more than 2,700 depleted gas fields was necessary to focus characterization work for the multitude of siliciclastic reservoirs within the AOI. The remainder of this chapter describes the methods used by the Research Team to characterize the storage opportunities in the AOI and the findings of this work.

## 4.1 Greenbrier Limestone (Mined-Rock Caverns)

### 4.1.1 Methods

Reservoir characterization efforts conducted on the Greenbrier Limestone for the Study focused on improved characterization of discrete lithology type (facies) distribution. Potential mined-rock cavern locations must meet several criteria for consideration. The host unit must be relatively homogeneous and at least 40 ft thick to accommodate the storage gallery. Adequate distribution of in situ stresses requires a lithologic target that exhibits mechanical integrity and the compressive strength necessary to support a mined-cavern opening. Limestone, dolomite and sandstone generally possess adequate compressive strength; shale typically does not. An additional recommendation to avoid units with high clay mineral content, due to potential gas adsorption onto the clay particles, was received from a member of the ASH Industry Group. Figure 4-1 lists the major geologic criteria necessary to construct a mined-rock cavern (Nelson and others, 2011).

- At least 40 ft. of homogeneous section
- Moderately high compressive-strength lithology to maintain stable opening during construction. Generally, sandstone or limestone are best
- Overlying rock must be able to support overburden load while shedding load to the pillars
- Rock surrounding the storage galleries must remain water saturated at all times to ensure product containment
- Low porosity is desirable, but not essential
- Host rock must have a very low permeability to groundwater flow
- Most U.S. mined-rock caverns are constructed in extremely low-permeability shale formations; others are constructed in dolomite, limestone, or granite

* ASH Industry team recommendation: avoid clay minerals (i.e., those with a terrigenous source) due to potential for gas adsorption onto clay particles.

**Figure 4-1. Major geologic criteria for construction of a mined-rock storage cavern (modified from Nelson and others, 2011).**

The primary dataset used for determination of areas with subsurface geology favorable for creation of mined-rock caverns consisted of the regional isopach and structure contour maps of the Greenbrier Limestone (see Section 3.3). The regional maps were created using all available digital logs; to increase data density in areas with required depth and thickness for a mined-rock cavern, additional geophysical logs in raster format and drillers' descriptions were added to the dataset to enable characterization of facies assemblages within the Greenbrier interval.

### 4.1.2 Depth

While the Greenbrier and its equivalents are present throughout much of the AOI, a subsurface target depth of 1,800 – 2,000 ft below ground surface is recommended as a cutoff value for further screening (Nelson and others, 2011). The 1,800-ft minimum cutoff takes into account the weight of overburden, which approaches 2,000 pounds per square inch (psi) presuming a lithostatic pressure of 1 psi per ft of depth. Creation of a mined-rock void increases this stress by a factor of 2.5 to 3.0, which is then further amplified by the anisotropic in-situ stress regime of the Appalachian basin. The maximum depth to target (2,000 ft) was suggested by PB Energy, a company actively involved in mined-rock cavern storage, as the approximate technological limit of current mining techniques. The trend of the Greenbrier Limestone with a top depth of 1,800 – 2,000 ft is shown in Figure 4-2.

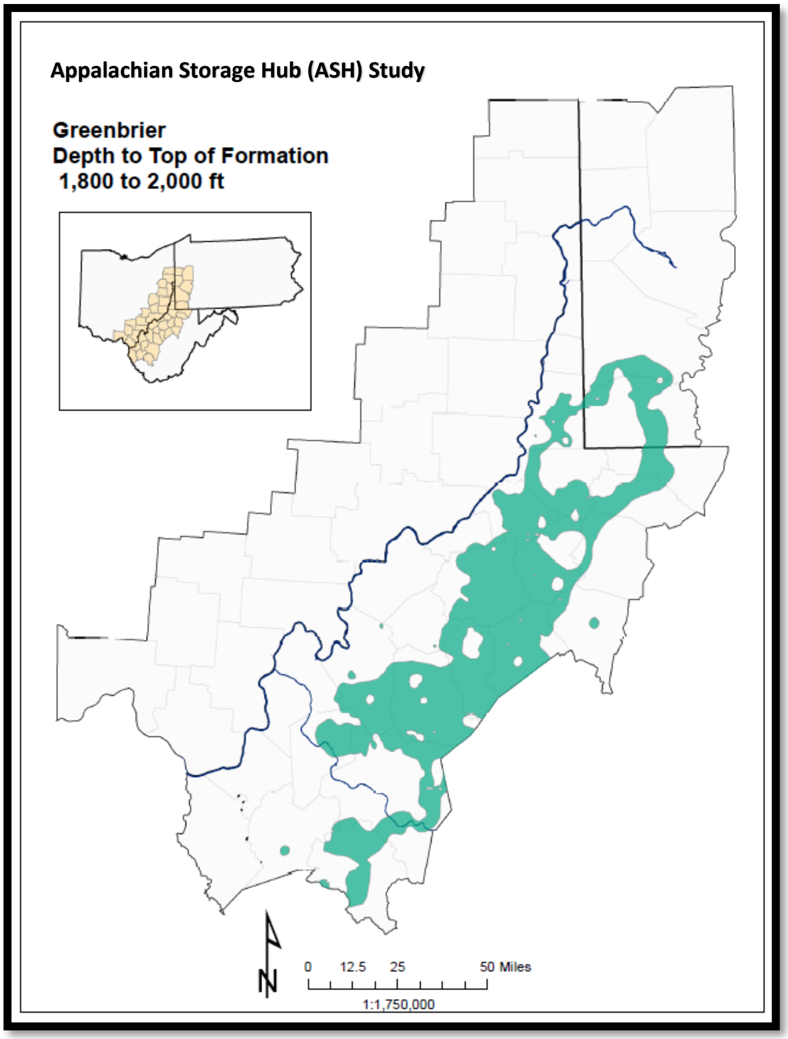



**Figure 4-2. Areas within the AOI where the top of the Greenbrier Limestone is encountered between 1,800 and 2,000 ft below ground surface, also referred to as the Greenbrier play fairway.**

### 4.1.3 Thickness

Following establishment of this Greenbrier play fairway, geophysical logs were analyzed to determine gross unit thickness. A mined-rock cavern requires at least 40 ft of relatively homogeneous strata (Nelson and others, 2011). Much of the Greenbrier interval attains this thickness, but post-depositional erosion features are common throughout much of the AOI, such that in some areas, the Greenbrier has been completely eroded, while in others the unit retains much of its original thickness. Gross interval thickness in these areas can exceed 200 ft. Figure 4-3 illustrates the gross interval thickness of the Greenbrier Limestone within the AOI.

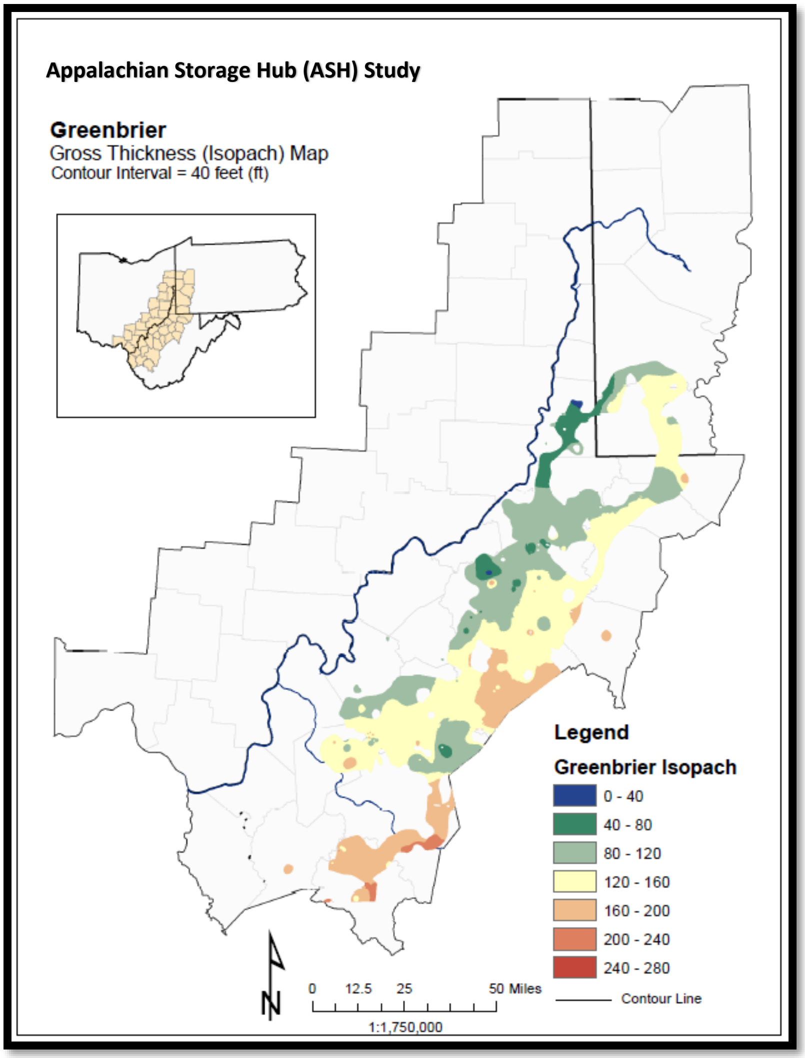



**Figure 4-3. Gross interval thickness of the Greenbrier Limestone in areas with a top depth between 1,800 and 2,000 ft below ground surface.**

### 4.1.4 Facies Distribution

The Greenbrier Limestone was deposited in a carbonate ramp environment (Wynn, 2003). Carbonate depositional environments are highly variable, both temporally and spatially. Relative thicknesses of individual carbonate facies types are closely tied to productivity of local biota (e.g., coral reefs, algal grasses, benthic and planktonic organisms). These communities are often sensitive to climatic changes, including changes in the position of relative sea-level, and therefore occupy a selective, and predictable, geometry on the sea-floor (Figure 4-4).

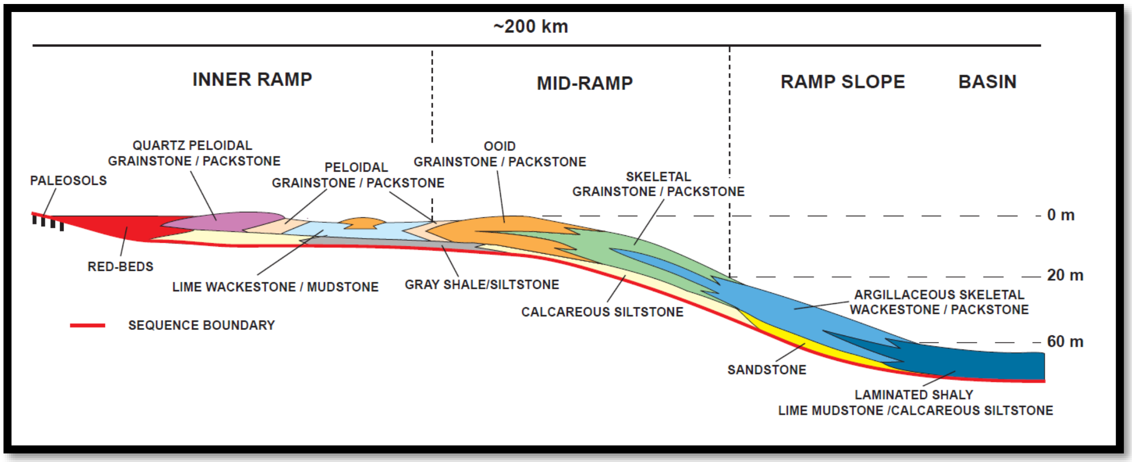



**Figure 4-4. Schematic illustration of Mississippian facies distribution of the Appalachian basin (Wynn, 2003). The main facies types within the AOI were deposited in inner- to mid-ramp settings.**

Work performed by the Research Team involved an examination of local- to regional-scale distribution of carbonate facies and their individual stacking patterns. This was performed using sources from the literature; a statewide sequence stratigraphic framework for the Greenbrier Limestone (Wynn, 2003) forms the backbone of the research.

Wynn identifies approximately one dozen major facies types in the “Big Lime” lithologic succession in West Virginia, but only a few of the facies types are observed in the AOI. Interbedded peloid and ooid grainstones with thin lime mud interbeds characterize the base of the section in most areas. Total thickness of the stacked grainstones is variable, and the succession is commonly overlain by 10 to 50 ft of lime mudstone. These facies types occur repeatedly throughout the Greenbrier interval, but their predictable stratigraphic position during cycles of sea level rise and fall enables geologic prognoses of rock types most likely to occur at the top of the Greenbrier succession. Figure 4-5 illustrates the facies types deposited in the uppermost stratigraphic sequences of the Greenbrier interval. In West Virginia, these intervals correspond to the Alderson and Union limestones.

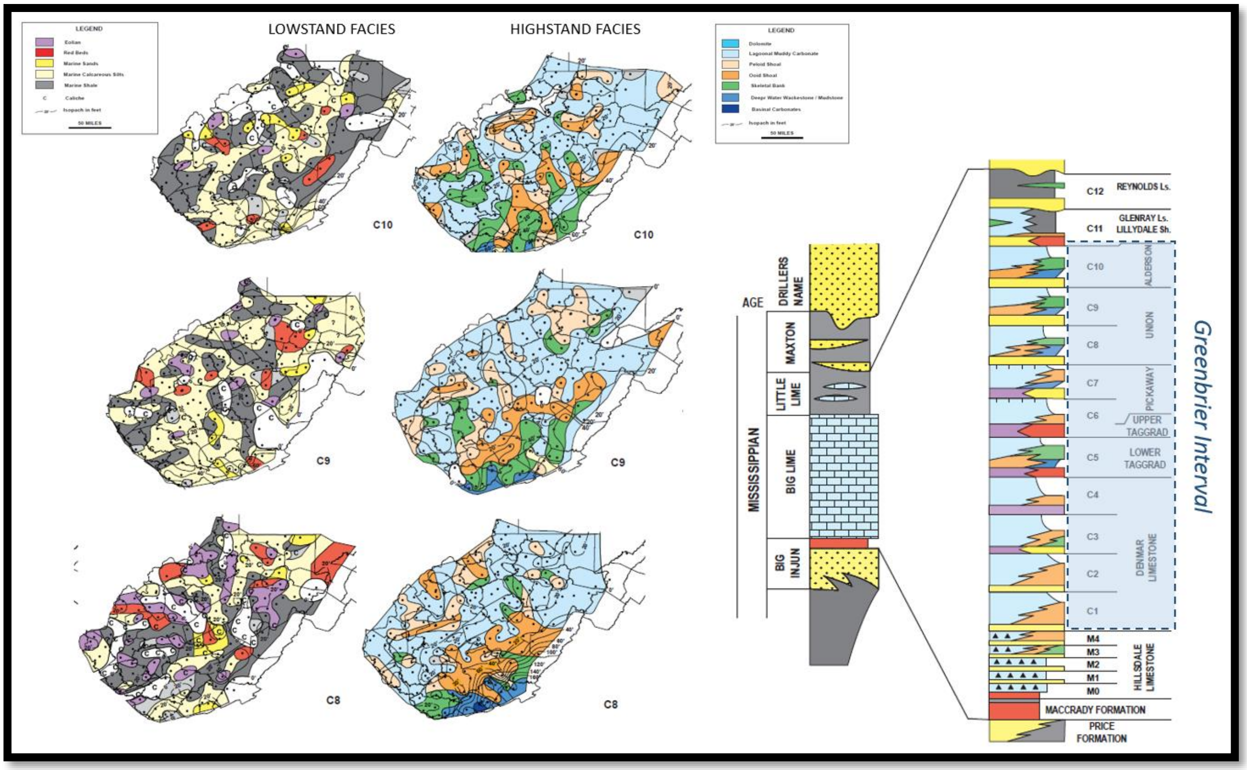



**Figure 4-5. Lowstand and highstand facies types deposited in the uppermost stratigraphic sequences of the Greenbrier interval. In West Virginia, these intervals correspond to the Alderson and Union limestones (Wynn, 2003).**

The relationship between facies stacking patterns and their suitability for mined-rock caverns was examined in more detail by analyzing geophysical logs collected from selected wells in western West Virginia and Pennsylvania. To assist with the log analysis task, a subset of approximately 180 geophysical logs and 85 drillers' logs of lithologic descriptions were compiled to determine the individual facies types and stacking patterns. The logs determined to be most useful for this task are the bulk density (RHOB)/density porosity (DPHI) logs and the photoelectric factor (Pe). When evaluated together, these data give an indication of lithology type (i.e., sandstone vs. limestone or dolomite). In addition to the RHOB and Pe measurements, logs must be accompanied by a caliper trace. This is due to the position of the density logger as a pad tool, which can lead to unreliable measurements in areas of borehole washout (Schlumberger, 2009). Figures 4-6 and 4-7 illustrate some of the lithologic and porosity matrix factors that may influence a geophysical log signature in carbonate lithologies.

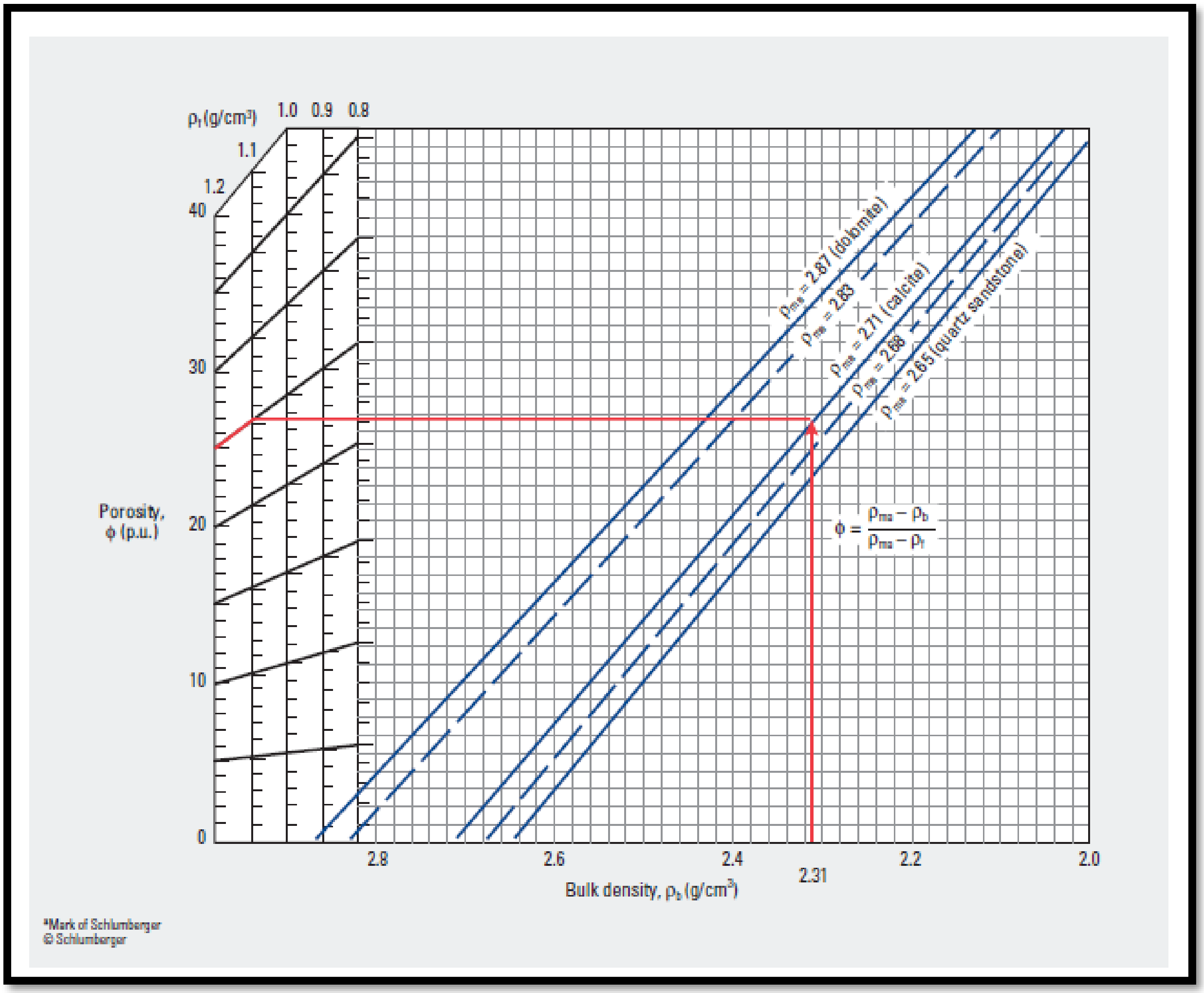
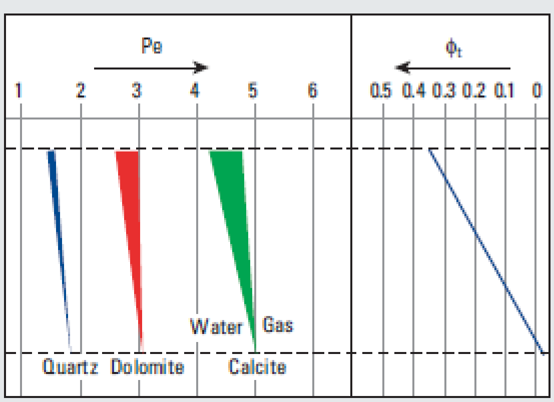



Figure 4-6. Chart used to convert RHOB (grams per cubic centimeter, or g/cm³) to DPHI (Schlumberger, 2009).




| Porosity Effect on Pe | | | |
|---|---|---|---|
| Matrix | $\phi_t$ | 100% $H_2O$ | 100% $CH_4$ |
| Quartz | 0.00 | 1.81 | 1.81 |
| | 0.35 | 1.54 | 1.76 |
| Calcite | 0.00 | 5.08 | 5.08 |
| | 0.35 | 4.23 | 4.96 |
| Dolomite | 0.00 | 3.14 | 3.14 |
| | 0.35 | 2.66 | 3.07 |
| Specific gravity | — | 1.00 | 0.10 |

Figure 4-7. Graph showing the effect of porosity, matrix type, formation water and presence of methane on the Pe cross section (Schlumberger, 2009).

Two type logs have been identified in the AOI that illustrate the application of log analysis of RHOB and Pe curves to determine facies relationships (Figure 4-8). The first example, from Roane County, West Virginia, shows a thick section of lime mud (micrite) at the top of the Greenbrier interval. The signal is attenuated, however, by washout zones both immediately above the top of the Greenbrier and at a depth of approximately 20 ft from the top of the unit. The second example, from Pleasants County, West Virginia, includes a lithology log calculated from RHOB, Pe, resistivity and gamma-ray (GR) log curves. This log clearly illustrates the presence of stacked grainstones at the base of the Greenbrier. The grainstone beds are overlain by a thick, relatively homogeneous, lime mudstone at the top of the unit. The lithology log also illustrates the presence of bound water and water-filled porosity immediately above and below the Greenbrier interval, the presence of which is one of the key criteria mentioned in PB Energy's pre-feasibility report (Nelson and others, 2011).

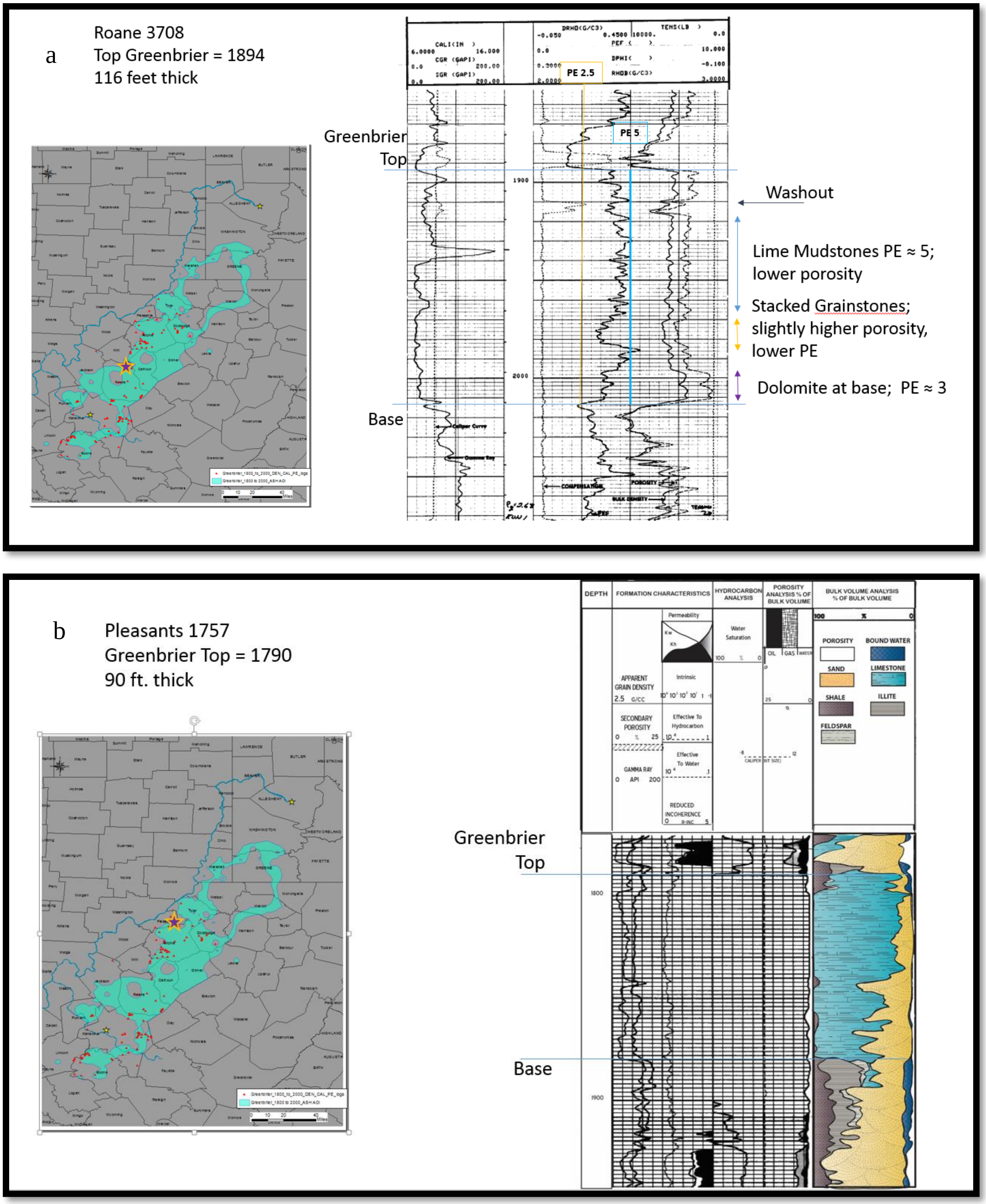



**Figure 4-8. Type logs of the Greenbrier Limestone illustrating the relationship of RHOB and Pe logs to individual facies.**

Using the parameters for facies identification established by analysis of the type logs, facies tops were mapped by examining the Pe and RHOB curves on the raster logs. For the mudstone facies, Pe generally measured between 5.1 (calcite) and 3.1 (dolomite) with formation density greater than 2.71 g/cc. The grainstone facies exhibited Pe values less than 4 and density values less than 2.71 g/cc. The mudstone facies was carefully correlated to identify the most internally homogeneous portions of this interval as possible. Three main facies packages were established: an upper grainstone package (not present in all areas); a lime mudstone package; and a lower grainstone package. Thicknesses for the upper grainstone, lime mudstone and lower grainstone facies packages along with the gross interval Greenbrier Limestone thickness were compiled for wells with tops and bases for each of these units. Any well that only contained a base for a particular facies received a null value for its thickness (generally due to well casing placement just above the Greenbrier interval, therefore attenuating log signatures in the uppermost portion of the unit). In any well where a facies was not present, a zero thickness was entered.

These data were then exported from the master IHS PETRA® project and loaded into ESRI® ArcMap™. Net thickness maps were generated in ArcMap using the inverse distance-weighted interpolation spatial analyst tool. A 500-ft cell size was used to create the net isopach rasters. The net thickness maps were then clipped to the 1,800 – 2,000 ft polygon and contoured to either 10- or 20-ft intervals. Figures 4-9 through 4-11 present the final net thickness maps for each of the three main facies packages.

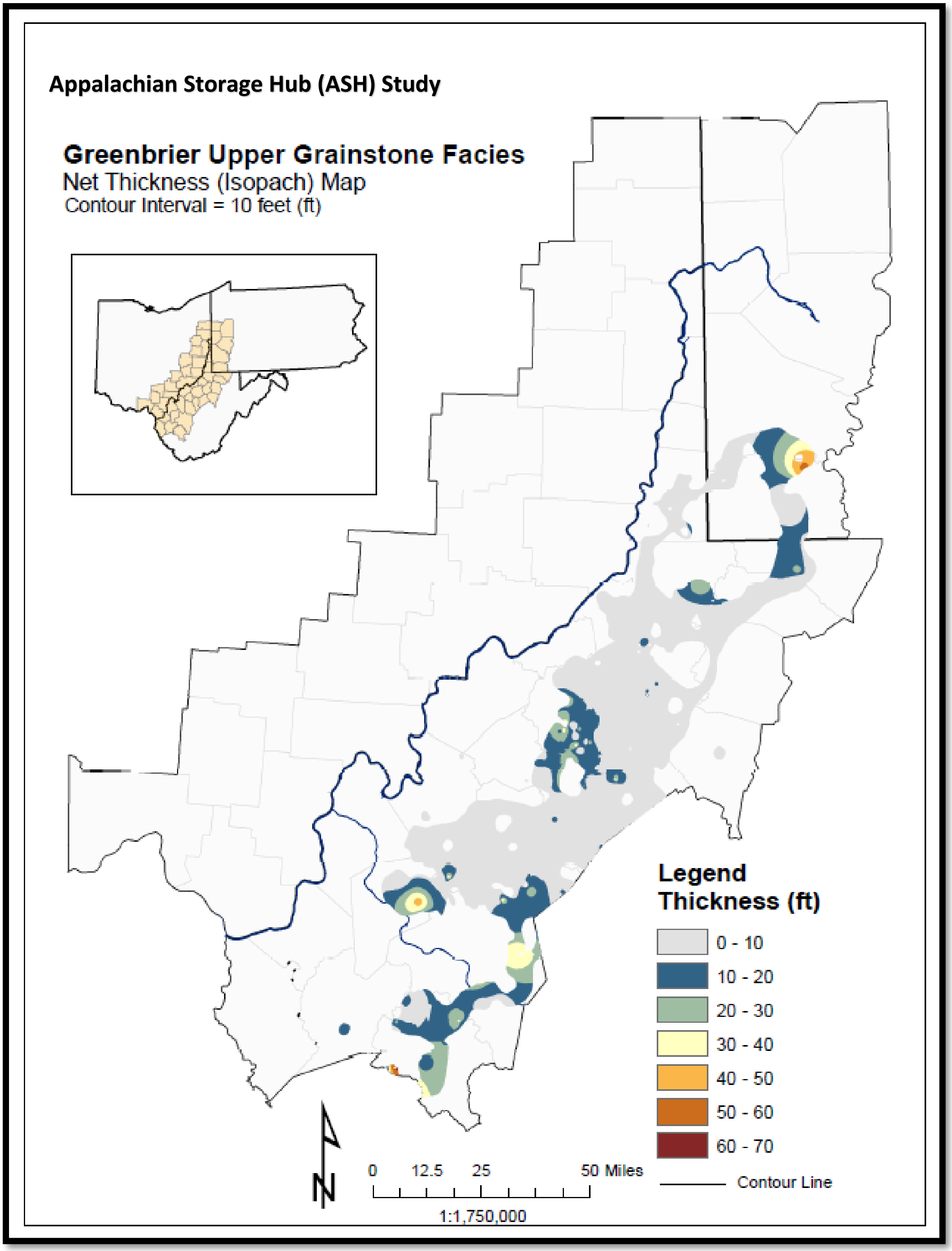



Figure 4-9. Net thickness map of the Greenbrier upper grainstone facies package.

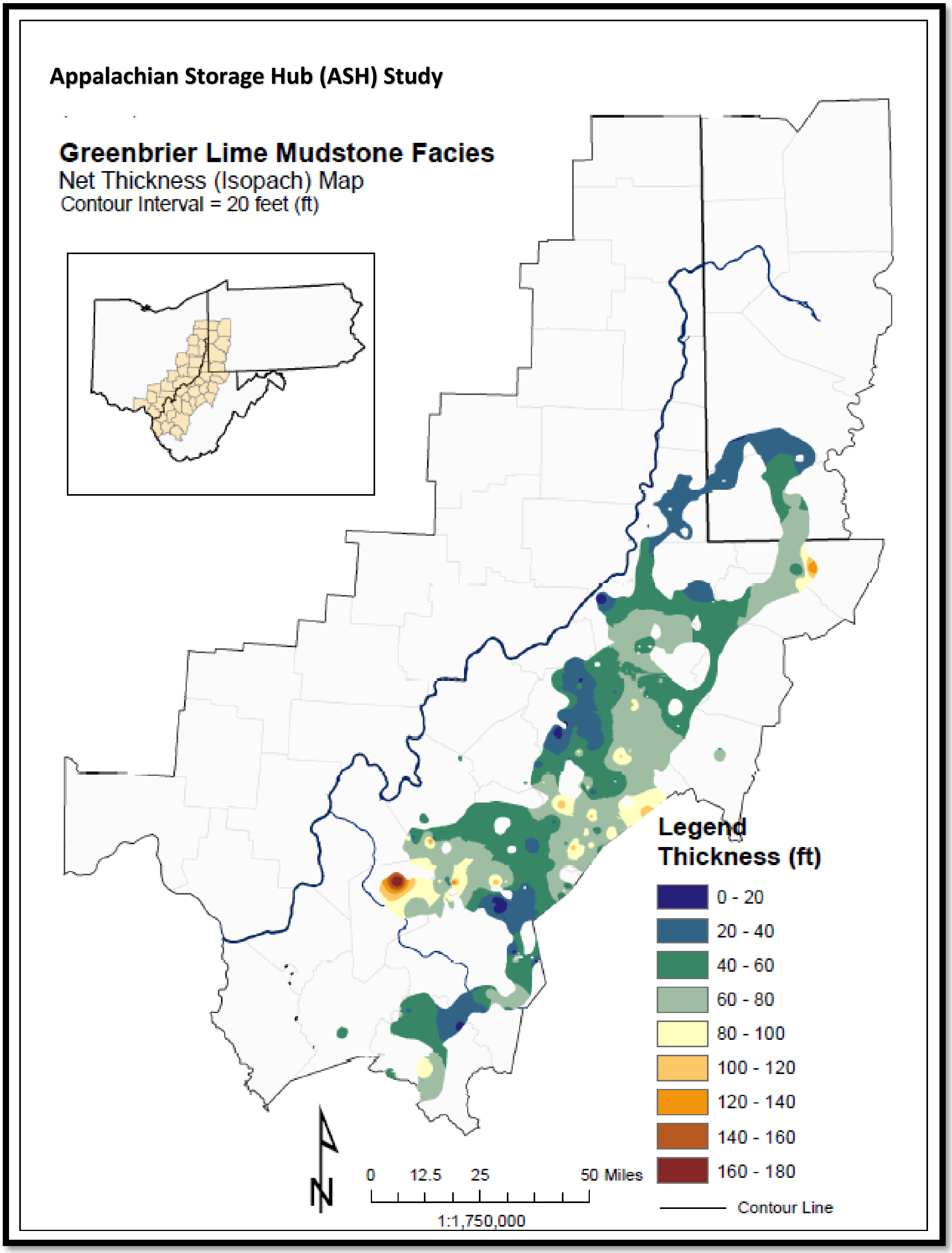



**Figure 4-10. Net thickness map of the Greenbrier lime mudstone facies package.**

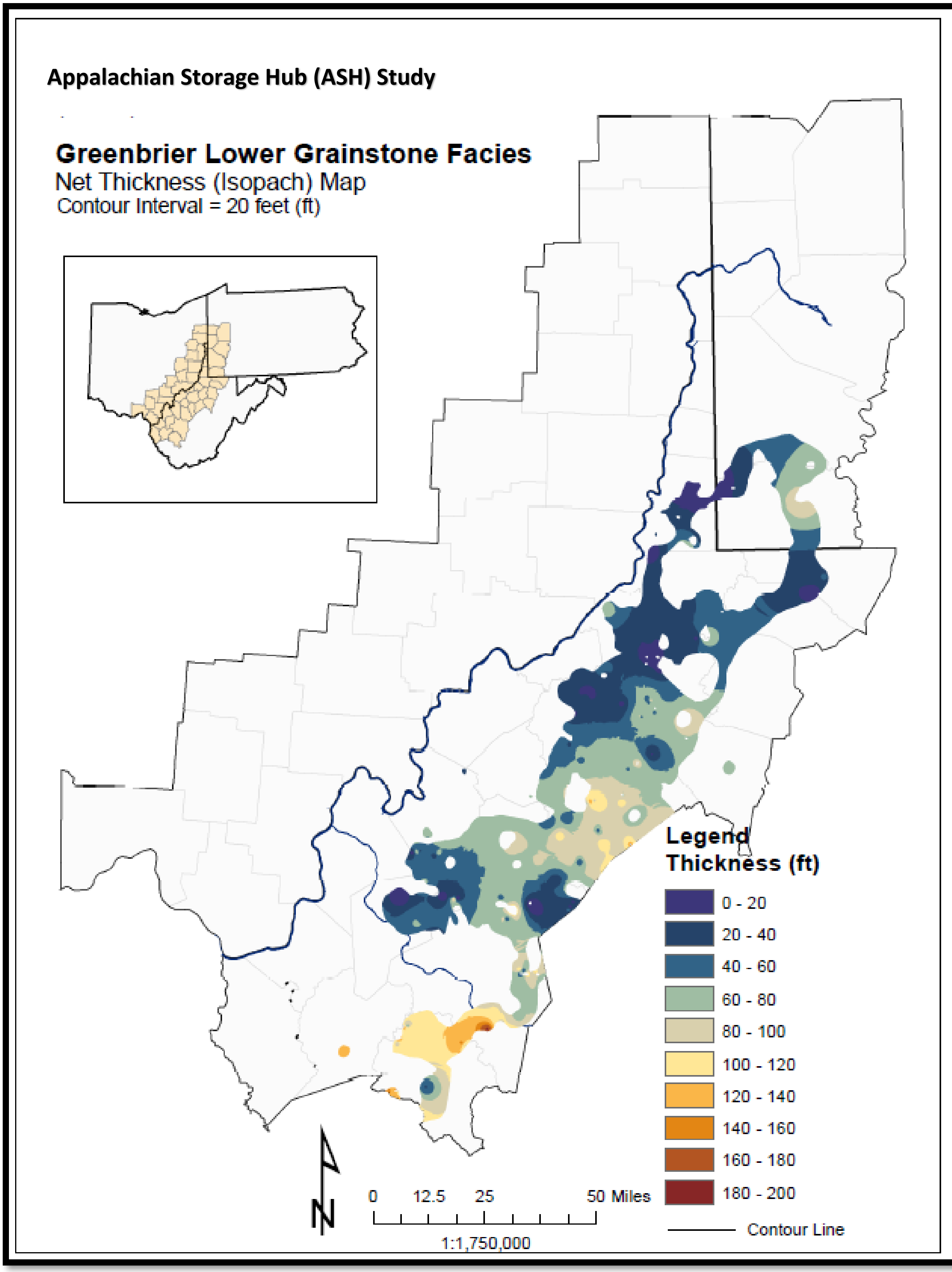



**Figure 4-11. Net thickness map of the Greenbrier lower grainstone facies package.**

The net thickness maps of the three discrete facies packages illustrate their variability of distribution throughout the AOI. Table 4-1 lists the main facies types identified in the AOI and gives criteria for qualitative/gross ranking based upon lithology. Comparison of the two datasets suggests that areas where the lime mudstone is thickest represents optimal conditions for a mined-rock cavern.

***Table 4-1. Criteria used to rank different carbonate lithology types for mined-rock cavern construction.***

| **Mined-Rock Suitability Comparison** | | |
|---|---|---|
| **Poor to Fair** | **Good** | **Optimal** |
| • Red Beds<br>• Peloid/Ooid Grainstone<br>• Skeletal Grainstone/Packstone<br>• Argillaceous and/or Skeletal Wackestone | • Quartz Sandstone<br>• Quartz Peloidal Grainstone<br>• Marine Calcareous Siltstone | • Fine-Grained Lime Wackestone/Mudstone<br>• Laminated Shaly Lime Mudstone |
| *Rationale: these lithologies may have higher permeability and/or clay mineral content* | *Rationale: these lithologies are most likely to have moderate porosity and permeability, low clay mineral content and sufficient unconfined compressive strength* | *Rationale: these lithologies will exhibit very low permeability, low clay mineral content and sufficient unconfined compressive strength* |

## 4.2 Salina F4 Salt (Salt Caverns)

Developing salt caverns for NGL storage requires the identification of salt formations that are relatively clean and have adequate thicknesses to support both product storage and allow for residual insoluble materials that may accumulate at the base of the caverns over time. Based on these criteria and with a view to minimize construction and operation costs, Nelson and others (2011) recommended a minimum thickness of 100 ft and subsurface depths ranging from 1,500 to 3,000 ft for solution-mined salt caverns, although it considered cavern depths of as much as 6,700 ft as a viable storage option. As of 2015, nine percent of the gas storage facilities in the United States are in mined salt caverns; this number does not include mined hard-rock caverns that store Liquid Petroleum Natural Gases (LPGs), five of which are in Ohio (GWPC and IOGCC, 2017).

In salt caverns, the salt itself is the sealing mechanism (Table 4-2), so high-quality salt is preferred to maintain cavern integrity and eliminate weak zones and lateral migration pathways. Therefore, understanding lateral and vertical variability within the salt interval is important, and sufficient log control is needed to identify and correlate interbedded dolomite or anhydrite ("dirty" intervals) within the salt. Figure 4-12 is an example of a well penetrating the F4 Salt in the AOI, where lithologies are identified on the geophysical log, showing thin anhydrite zones and a thicker bed of anhydrite and dolomite interbedded with the salt (halite).

***Table 4-2. Low permeability of salt as compared to other lithologies (Jaeger and others, 2007, and Ehrenberg and Nadeau, 2005).***

| Rock Type | Porosity (%) | Permeability [Darcy (D)] |
|---|---|---|
| Sandstone | 10 - 30 | 0.1 - 5.0 |
| Limestone | 5 - 20 | 0.02 - 0.3 |
| Salt | 0.01 - 1.0 | $10^{-22}$ |

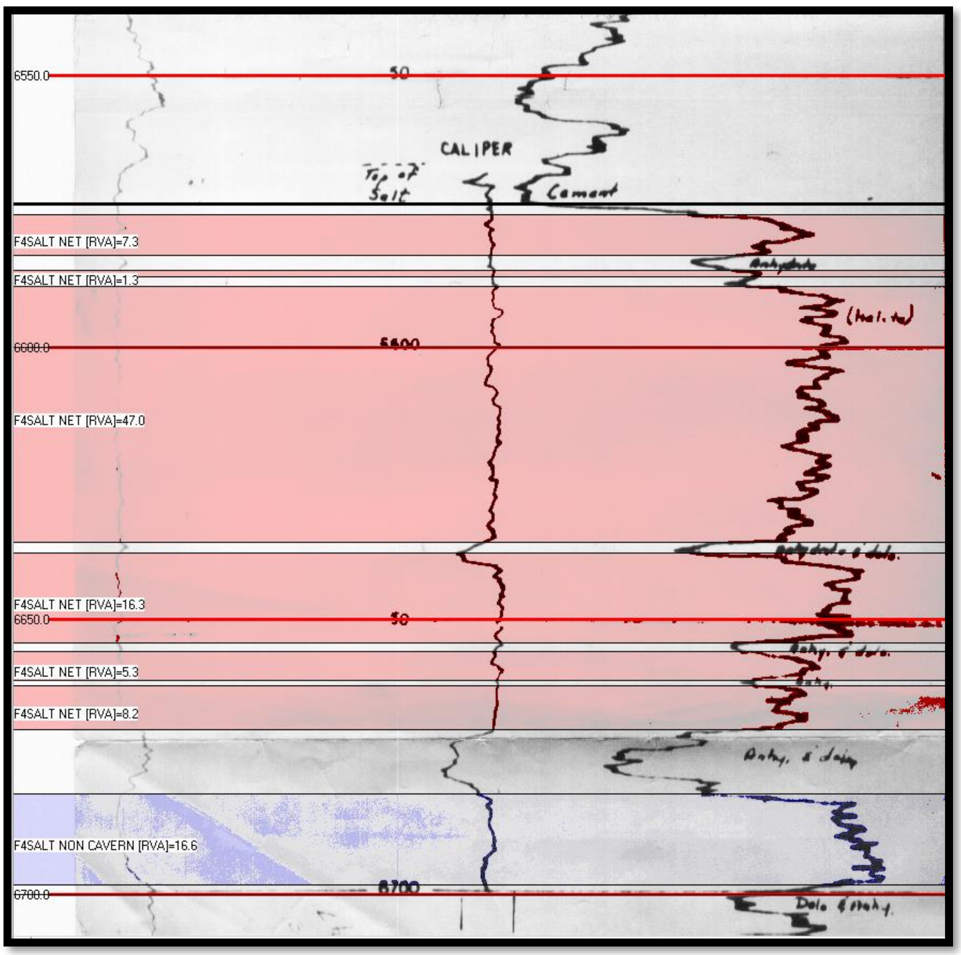



**Figure 4-12. Well penetrating the F4 Salt, where lithologies tied into the geophysical log identify zones of anhydrite and dolomite. The thickness of the upper salt, shown in pink, was used in isopach maps.**

Appendix C includes elemental data for core samples extracted from a PPG Industries well in Marshall County, West Virginia, along with a written description to explain these data. Selected core photographs from this same well are provided in Figures 4-13 through 4-15 to illustrate the interbedded nature of Salina salt units in this area of the AOI.


**Figure 4-13. a: Coarse halite crystals with evenly disseminated black anhydrite pieces that give the sample a dark gray color; b: post-lithification fracture includes some salt crystals along the fracture zone; c: brown-gray calcareous shale, thinly laminated, sometimes wavy, partially replaced by salt and pepper carbonate(?)-anhydrite mixture. The shale is interbedded with the carbonate-anhydrite beds.**

**Figure 4-14. Uniformly coarse (0.25-0.5 inch [in]) halite crystals with evenly disseminated black anhydrite pieces, which give the sample a dark gray color.**


**Figure 4-15. Mix of gray coarse crystalline halite as above and disoriented large (up to 0.8 ft) clasts of thin bedded anhydrite-carbonate plus calcareous shale. Core base is 6,648 ft.**

Even with a relatively pure salt formation, the chemistry and volume of brine produced during the mining process must be carefully considered, as this part of the operation will require careful planning and site management. When producing brine during cavern creation, as well as during routine operation of storage reservoirs, proper water management and environmental health and safety controls are a necessity.

### 4.2.1 Methods

As part of the Study's regional correlation and mapping work, the Research Team determined that the only Salina salt member likely to occur in thicknesses of greater than or equal to 100 ft was the Salina F4 Salt. Subsequent mapping of this particular salt unit identified four areas within the AOI where the F4 Salt has net thicknesses of 100 ft or more; these are illustrated in Figure 4-16 using pale orange to red shading and are centrally located in the panhandle of West Virginia.

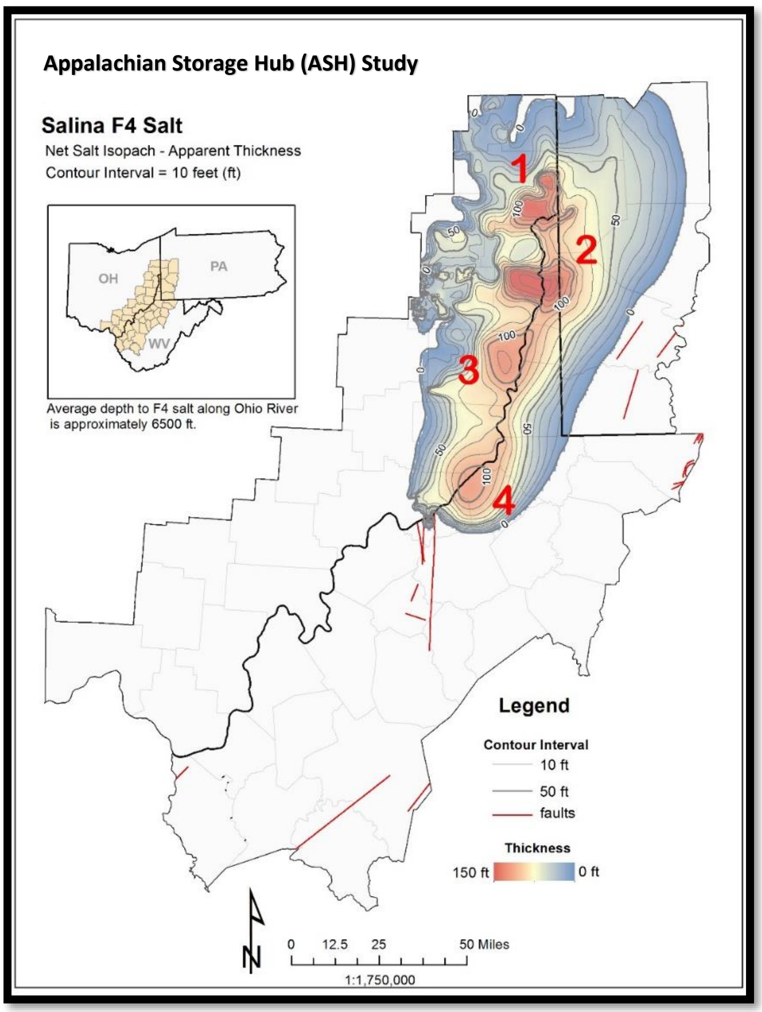



**Figure 4-16. Four areas, numbered from north (1) to south (4) along the Ohio River in the West Virginia panhandle area of the AOI where the net thickness of Salina F4 Salt is ≥ 100 ft.**

## 4.2.2 Depth

In this portion of the AOI, the average approximate measured depth of the clean Salina F4 Salt zone ranges from 5,300 ft in Area 1, to 6,200 ft in Area 2, to 6,650 ft in Area 3 and 6,600 ft in Area 4. Depth relative to MSL is shown in Figure 4-17. The salt is well below the deepest occurrence of fresh drinking water, and has not been penetrated by many deep gas wells that could provide vertical migration pathways. Increase in salt plasticity limits lower cavern depth to less than 7,000 ft. Natural gas caverns are prone to have stability problems because of their great depth (4,000 - 6,700 ft) and rapid changes in internal cavern pressure owing to gas cycling by pressure release (Seni and others, 1984).

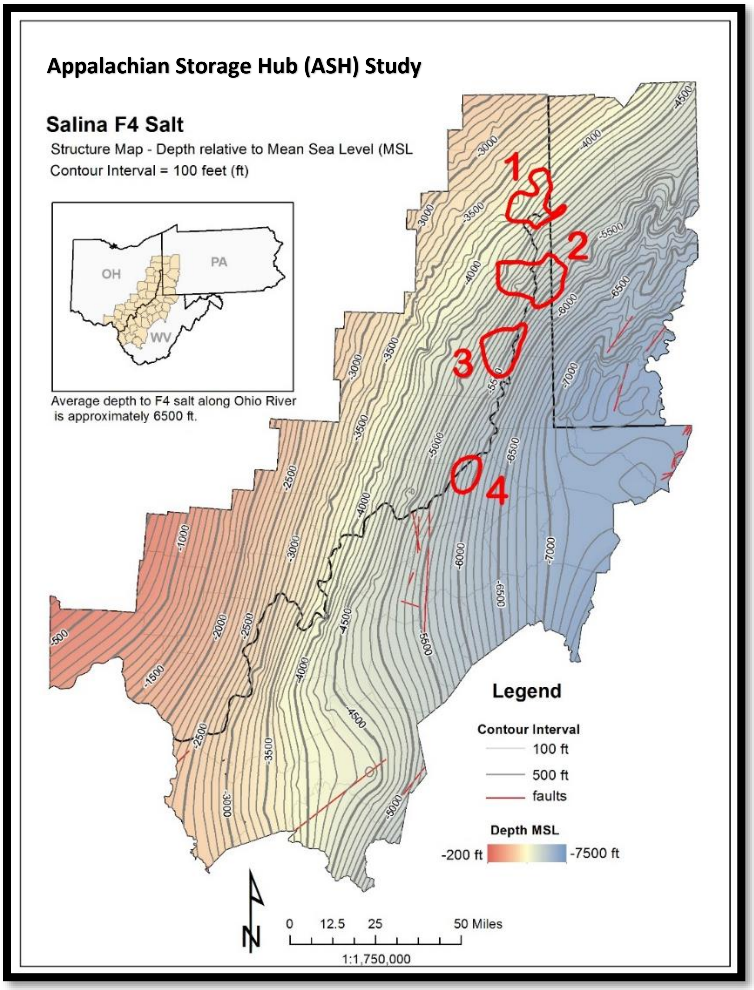



**Figure 4-17. Depths to top of F4 Salt range from -3,700 to -6,000 ft MSL in the West Virginia panhandle.**

## 4.2.3 Thickness

The ability to identify the edge of the salt is important in cavern development, so the extent of a known thick interval of salt is critical. It is necessary to leave a buffer zone between the cavern and the edge of the salt to ensure lateral confinement. Thickness is important because one must leave intervals of salt above the cavern and below the cap rock, and below the cavern to ensure vertical confinement.

Dissolution mining in the Salina Group at these depths is economical when the salt thickness is greater than 100 ft, with minimal amounts of interbedded limestone and shale. There are four areas where the net Salina F4 Salt is greater than 100 ft thick, all located along the Ohio River Valley in the West Virginia panhandle. Some of the thickest F4 Salt areas have better data control than others.

Area 1 is approximately 83,775 acres (ac) and is situated in Columbiana County, Ohio; Beaver County, Pennsylvania; and Hancock County, West Virginia (Figure 4-18). Three wells in the area have a salt thickness greater than 100 ft.

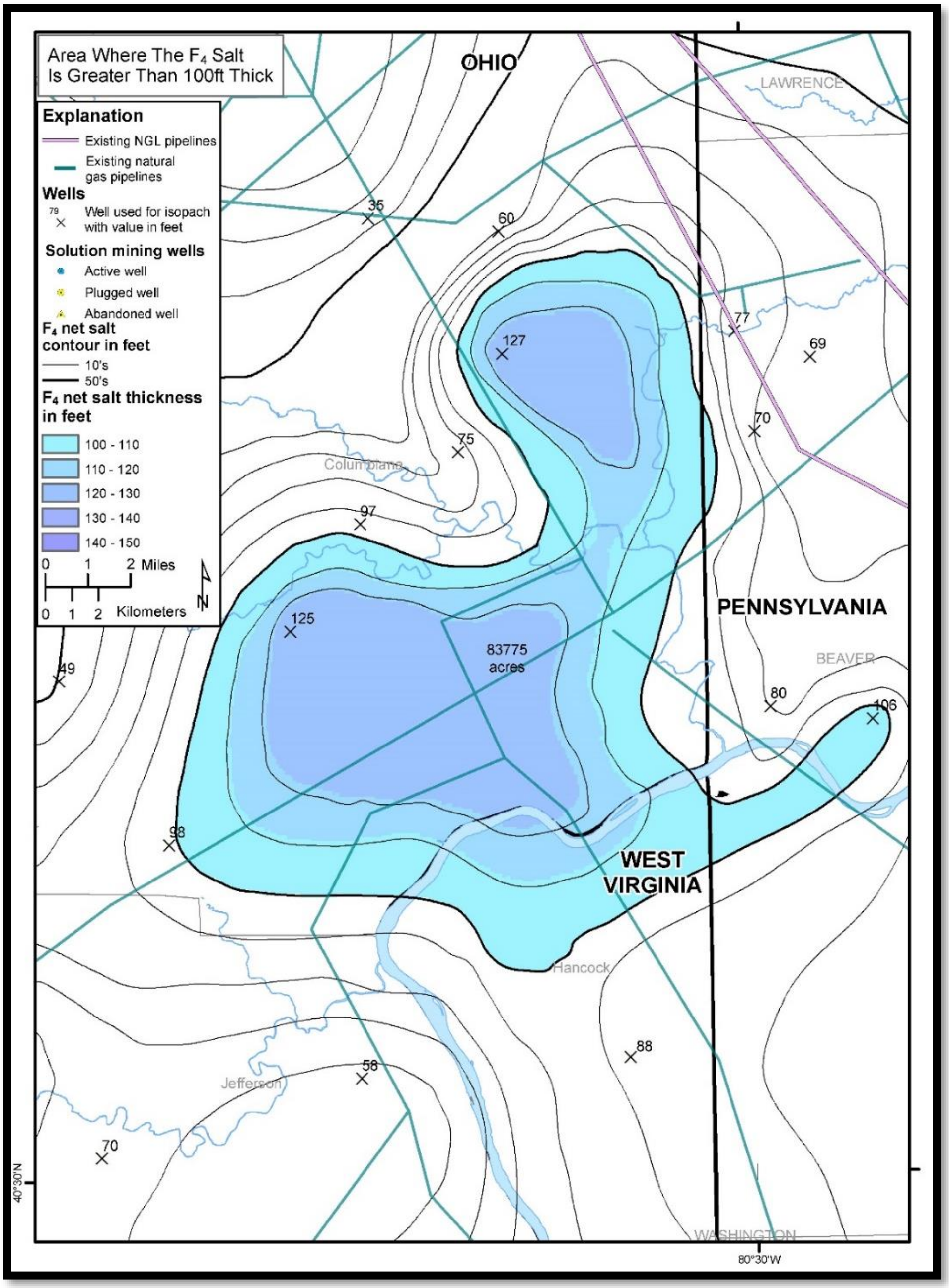



**Figure 4-18. Net thickness map for Salina F4 Salt Area 1.**

Farther south, Area 2 includes Jefferson County, Ohio; Washington County, Pennsylvania; and Brooke and Hancock counties, West Virginia. The area encompasses 129,017 ac. The net thickness of the F4 Salt is constrained by six well data points with more than 100 ft of salt in each (Figure 4-19).

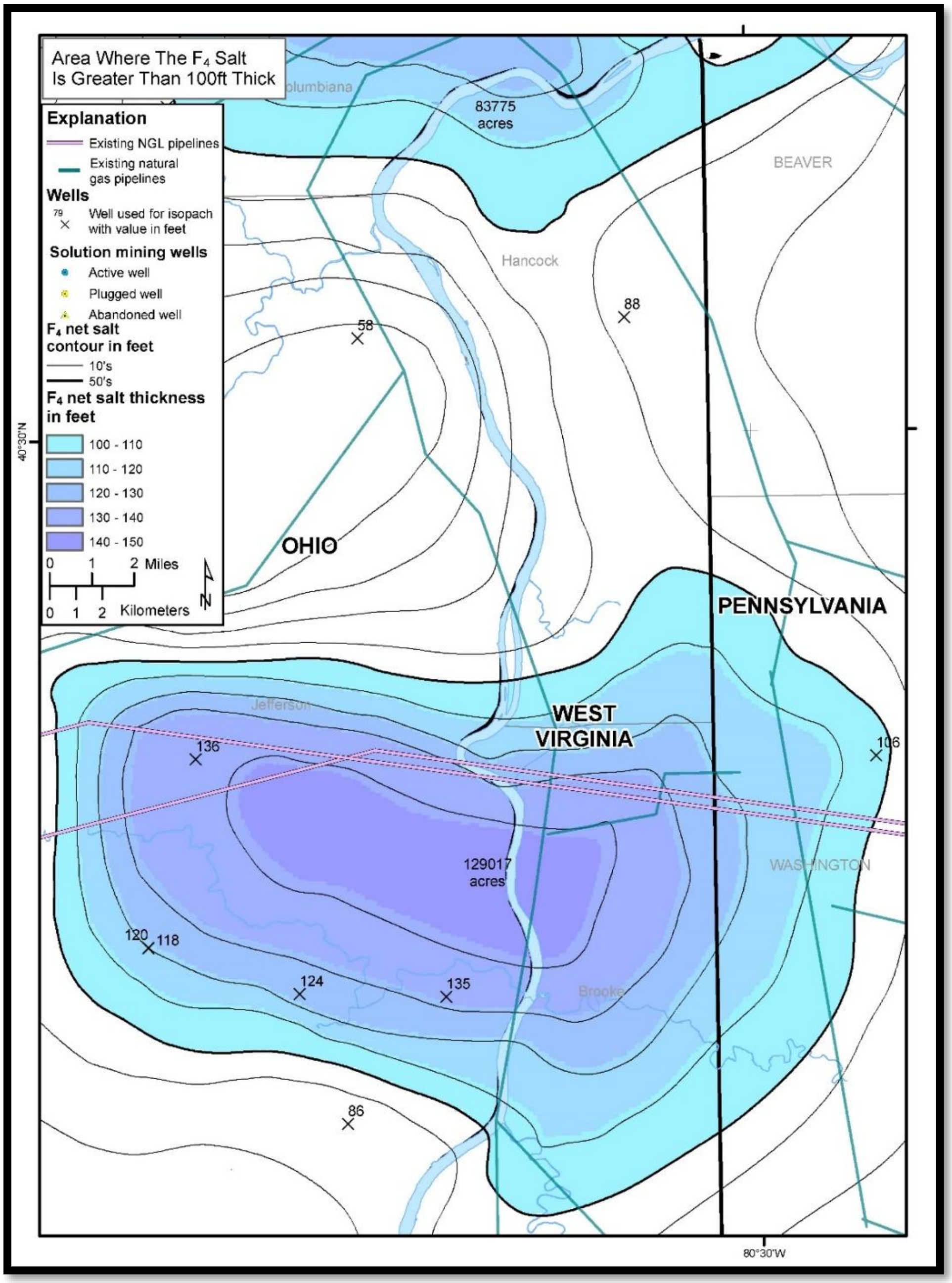



**Figure 4-19. Net thickness map for Salina F4 Salt Area 2.**

Traveling farther to the south, Area 3 is approximately 80,867 ac in size and is situated in Belmont County, Ohio, and Marshall and Ohio counties, West Virginia. The area is constrained by two well data points where the F4 Salt is greater than 100 ft (Figure 4-20).

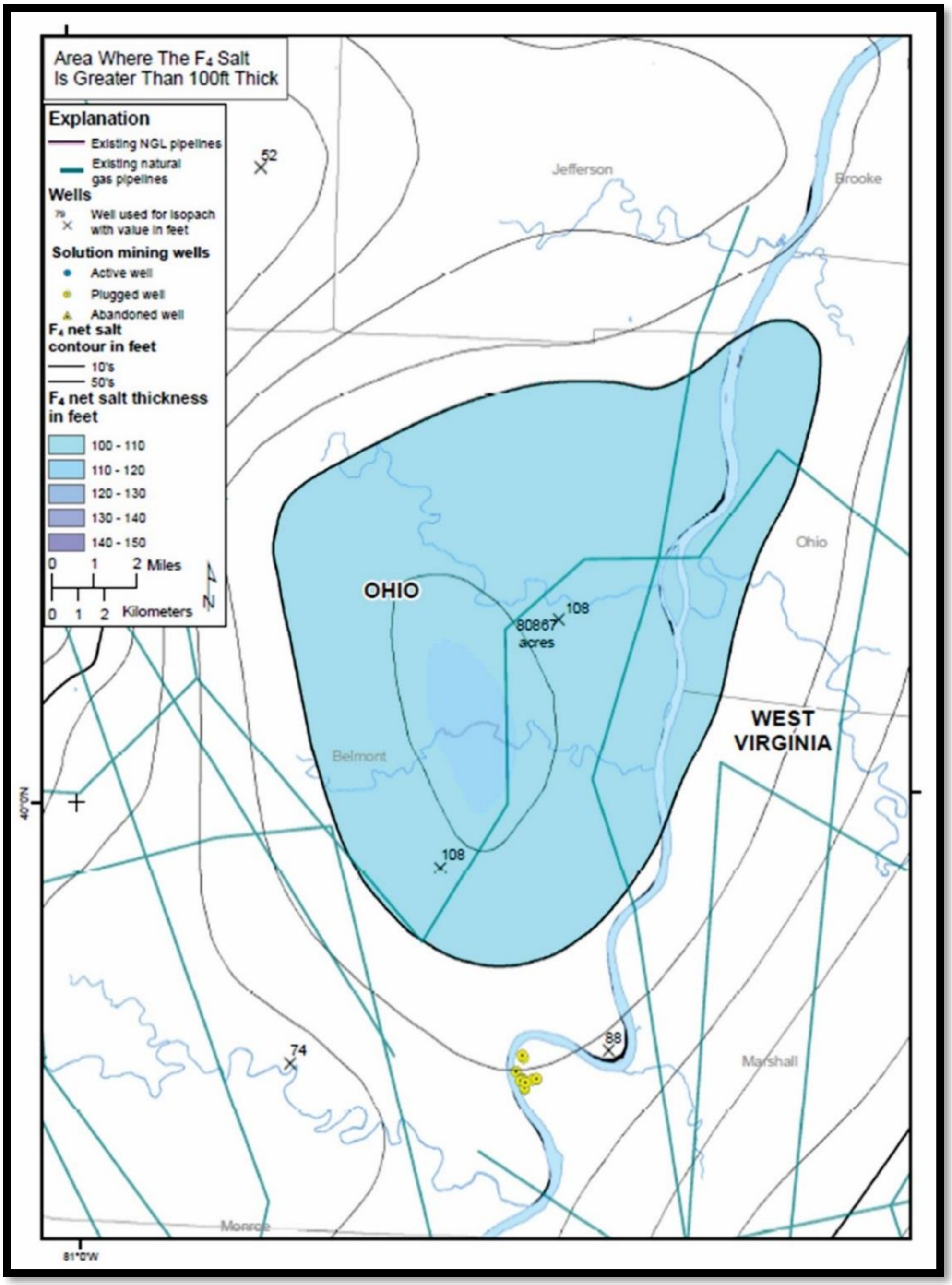



**Figure 4-20. Net thickness map for Salina F4 Salt Area 3.**

The southernmost F4 Salt area with notable thickness is located within Washington and Monroe counties, Ohio, and Tyler and Pleasant counties, West Virginia (Figure 4-21). This area is approximately 40,952 acres. Although it appears to reach thicknesses of 100 ft based on surrounding data control, it should be noted that the footprint of Area 4 is not constrained with well data, and may not actually have a net salt thickness of 100 ft or more.

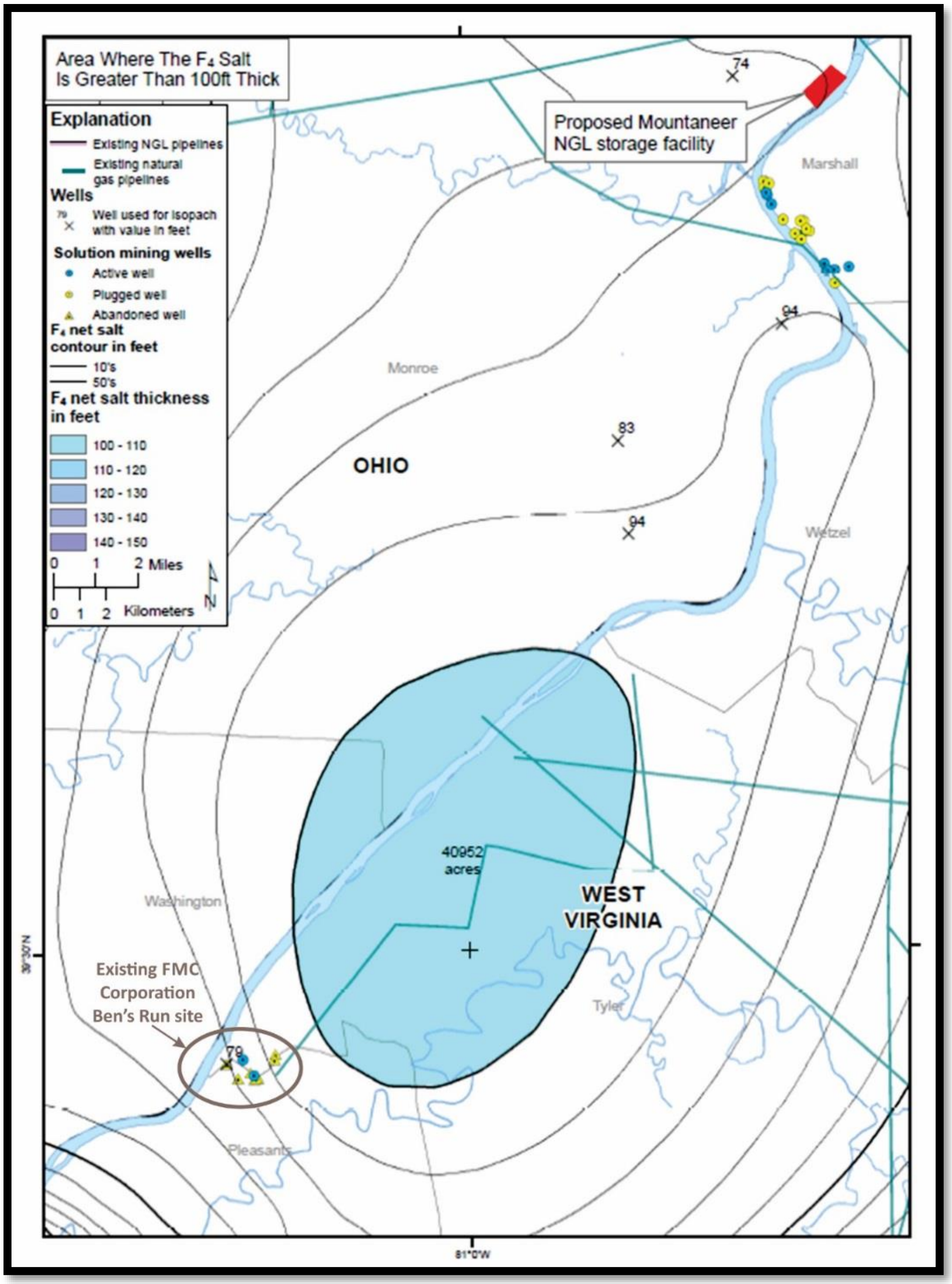



**Figure 4-21. Net thickness map for Salina F4 Salt Area 4.**

Several cross sections were created by the Research Team through the F4 Salt (see Figure 4-22) to show that the interbedded nature of the salt with anhydrite and dolomite increases rapidly outside of the >100-ft footprints laterally, and that there is a persistent dolomite/anhydrite bed immediately below the clean F4 Salt bed, which separates the F4 from an underlying salt bed. The lower salt was not included in the representation of salt thickness for Area 4 in Figure 4-21. If it had been, the >100-ft footprint might differ and/or the net F4 Salt thickness may be greater than what is shown here.

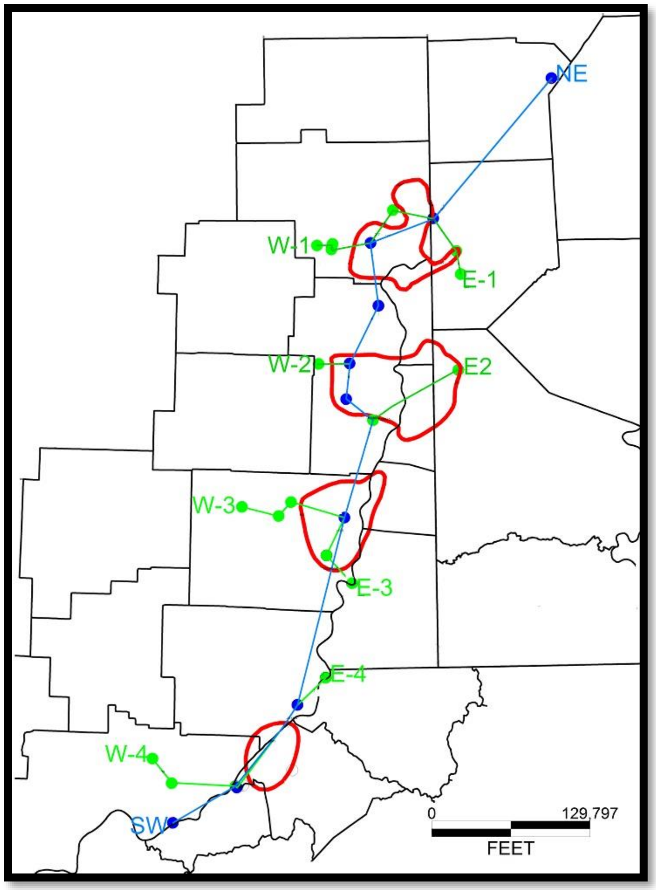



**Figure 4-22. Location of strike (blue) and dip (green) cross sections through the Salina F4 Salt using geophysical log control.**

Although any significant interbedded dolomite or anhydrite within the F4 Salt is uncommon, it does occur in some logs, and therefore its thickness, lateral extent and impact should be considered by the operator.

A strike section along the main trend of the F4 Salt is illustrated in Figure 4-23. A dip section through Area 3 is illustrated in Figure 4-24. Dip sections through the other F4 footprints are illustrated in Chapter 5 as part of the prospect discussion. The stratigraphic datum for these cross sections is the underlying Salina E.

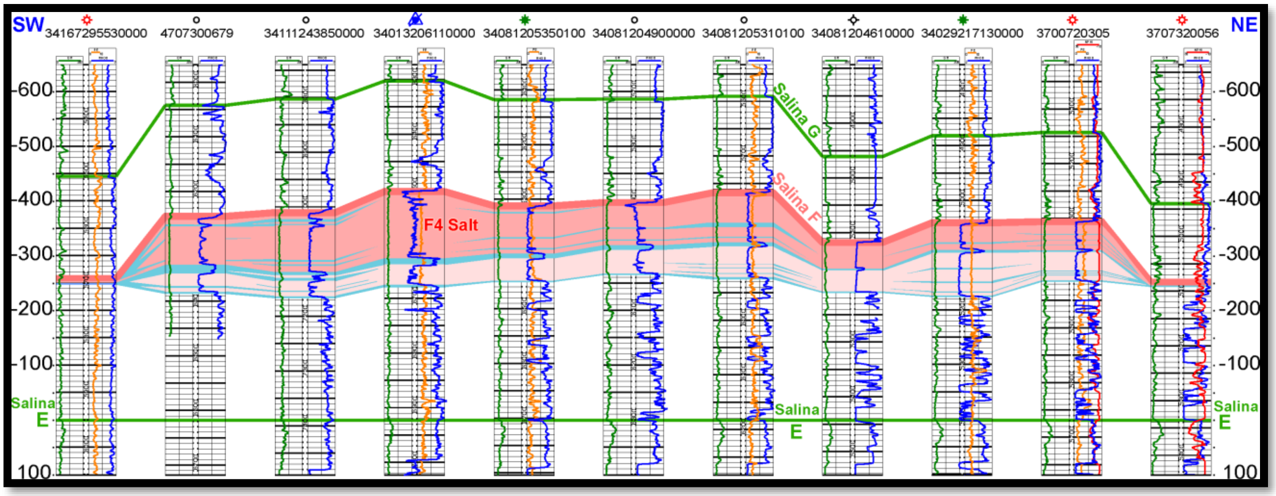



Figure 4-23. Strike (southwest-northeast) cross section through the F4 Salt in the AOI using geophysical log control.

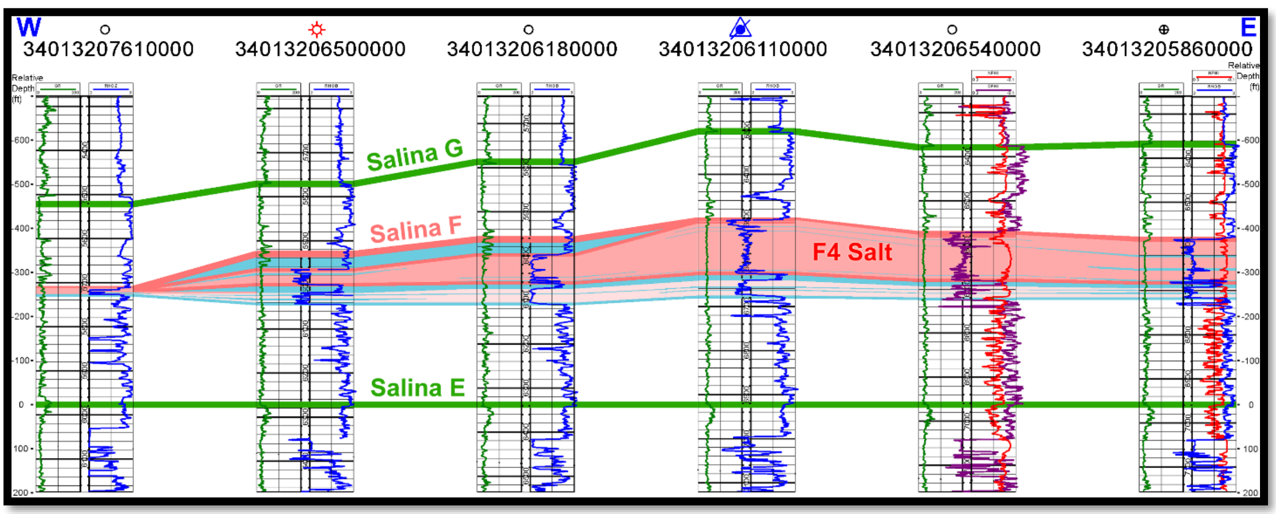



Figure 4-24. Dip (west-east) cross section through the F4 Salt in Area 3 using geophysical log control.

## 4.2.4 Extent

Pure salt has preferable geomechanical properties relative to "dirty" salt, which can lead to roof falls and casing integrity problems. This reiterates the necessity for good internal stratigraphy and the identification of any "dirty" salt intervals or interbedded rock that could lead to lateral migration pathways. Both will increase as one approaches the edge of the salt basin. From the cross sections provided herein, the interbedded nature of the salt with dolomite and anhydrite beds is more extensive outside the 100-ft footprint. There are also a few wells within the footprint that have minor to more significant "dirty" intervals, but these do not appear to have persistent lateral extent, given available well control. A persistent dolomite or anhydrite bed below the clean F4 Salt layer may preclude the inclusion of clean salt below this bed for the purposes of salt cavern storage, depending on the decision of an operator.

Table 4-3 shows leakage frequency from various types of underground natural gas storage facilities (GWPC and IOGCC, 2017). This table does not include facilities that store NGLs. Per Folga and others (2016), most leakage from storage facilities is due to wellbore integrity issues and salt caverns are significantly less likely to have subsurface integrity problems than depleted oi and gas fields or aquifers. According to Seni and others (1984), the three primary factors affecting the stability of salt caverns are pressure, temperature and cavern shape.

***Table 4-3. Leakage frequency from underground natural gas storage facilities (from GWPC and IOGCC, 2017).***

| Facility Type | Cause | Leakage frequency,/facility/year | | Leakage frequency from well-integrity loss/well/year | |
|---|---|---|---|---|---|
| | | Papanikolau and others[1] | Folga and others[2] | Papanikolau and others[1] | Folga and others[2] |
| Depleted oil and gas field | Well integrity | | $6.9 \times 10^{-4}$ to $5.6 \times 10^{-4}$ | | $1.8 \times 10^{-5}$ to $9.8 \times 10^{-6}$ |
| | Subsurface integrity | | $1.6 \times 10^{-3}$ to $1.3 \times 10^{-3}$ | | |
| | Operations | | $1.1 \times 10^{-3}$ to $8.9 \times 10^{-4}$ | | |
| Aquifer | Well integrity | | $9.9 \times 10^{-5}$ to $8.1 \times 10^{-5}$ | | $2.5 \times 10^{-6}$ to $1.4 \times 10^{-6}$ |
| | Subsurface integrity | $5.1 \times 10^{-3}$ | $1.6 \times 10^{-3}$ to $1.3 \times 10^{-3}$ | $2.1 \times 10^{-5}$ | |
| | Operations | | $1.5 \times 10^{-4}$ to $1.2 \times 10^{-4}$ | | |
| Salt cavern | Well integrity | | $3.9 \times 10^{-4}$ to $3.2 \times 10^{-4}$ | | $1.0 \times 10^{-5}$ to $5.6 \times 10^{-6}$ |
| | Subsurface integrity | | $2.5 \times 10^{-4}$ to $2.0 \times 10^{-4}$ | | |
| | Operations | | $3.5 \times 10^{-4}$ to $2.8 \times 10^{-4}$ | | |

(1) Incidents were not broken out into separate causes or degrees of severity.
(2) First value listed uses facility year and well-year frequencies from 2005; second value listed uses estimated frequencies through 2016.

## 4.3 Depleted Gas Reservoirs (Devonian- through Cambrian-Age Sandstones)

### 4.3.1 Reservoir Data Compilation

The Research Team compiled field-level reservoir data for depleted gas reservoirs using information from its previous projects and/or publications with reservoir data specific to the AOI. The Research Team chose to start with the Geographic Information Systems (GIS) database of Appalachian basin gas fields, as prepared by Wickstrom and others (2005) for the Midwest Regional Carbon Sequestration Partnership (MRCSP) and subsequently augmented during Phases II and III of this U.S. Department of Energy-funded research program (Carter and others, 2010; Carter and others, 2012; and Lewis, in preparation). Over the past twelve years, MRCSP has updated and expanded the content of this dataset, based largely on downhole geophysical log data and supplemented using laboratory-derived analyses where available. The GIS database provides field-level reservoir data for such attributes as average depth, porosity, permeability, pressure, net thickness and areal extent. What's more, as the GIS source database was created to evaluate the geologic carbon storage potential for these gas fields, the storage capacity values computed for these fields can be used as a proxy for production where field-level gas production statistics may not be available. The GIS database includes information on fields used for gas production as well as natural gas storage. Based on recommendations from the Consortium's

Advisory Group, the Research Team did not exclude the natural gas storage fields from its analysis. These regional GIS data have been made available on the Study website.

### 4.3.2 Thin Section Examination

A total of 64 geologic samples representing five different geologic intervals were analyzed in thin section to augment the field-level reservoir data compilation effort described above. Thin section sample selection was based not only on the availability of rock core for intervals of interest but also on well location, with proximity to either the Ohio River Valley or areas of sparse reservoir data being the largest drivers for selection (Figure 4-25). The Research Team utilized a combination of existing and newly prepared thin sections for this work (Table 4-4). In summary, 21 Rose Run-Gatesburg thin sections were obtained from wells in southeastern Ohio, and the remaining 43 thin sections were obtained from samples of the Weir (Keener to Berea interval), Venango, Oriskany and Newburg sandstones in northern and western West Virginia (Figure 4-25).

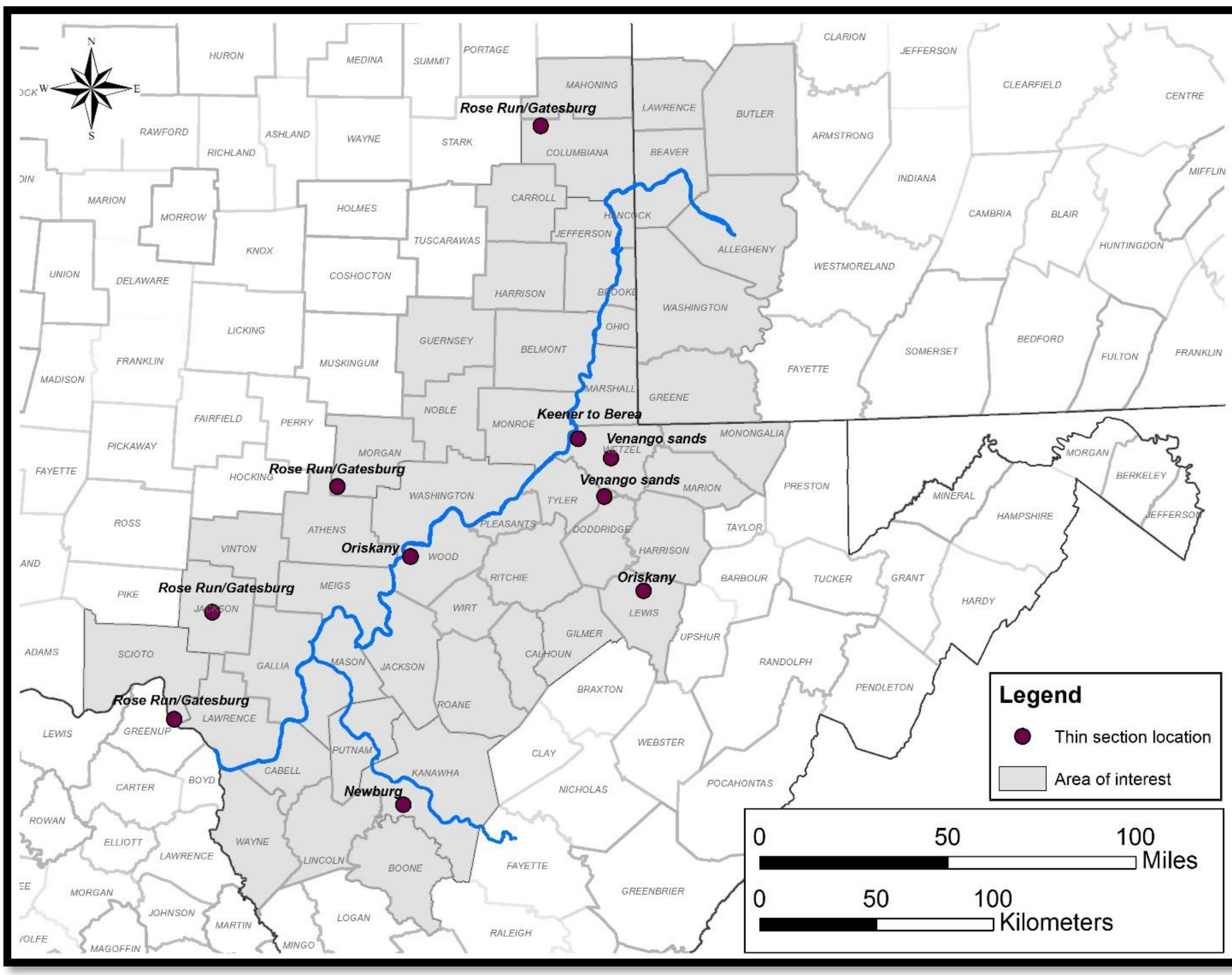



**Figure 4-25. Locations of samples (with corresponding geologic intervals) examined in thin section for the Study.**

*Table 4-4. Thin sections analyzed as part of the Study.*

| State | Thin Sections Existing | Thin Sections New | Well ID/API No. | Geologic Interval(s) |
|---|---|---|---|---|
| OH | | 10 | Denny #1-2468/34-029-20592-0000 | Rose Run-Gatesburg |
| OH | 6 | | Aristech Chemical Co. #4/ 34-145-60141-0000 | Rose Run-Gatesburg |
| | 4 | | Kittle #11125/34-115-21249-0000 | Rose Run-Gatesburg |
| | 1 | | Trepanier #1/34-079-20102-0000 | Rose Run-Gatesburg |
| WV | | 14 | Patty Potts & Gloria Nice #1/47-103-00614 | Keener to Berea |
| | | 11 | Darrell Matheny #2/47-107-01266 | Oriskany Sandstone |
| | | 3 | J.B. Lovett #2/47-041-00057 | Oriskany Sandstone |
| WV | 3 | | Peter Horner #9/47-095-00741 | Venango sandstones |
| | 8 | | L.S. Hoyt #100/47-103-01685 | Venango sandstones |
| | 4 | | J. Woodrum #A-2/47-039-02112 | Newburg sandstone |

Thin sections were analyzed using Leica DM 4500 P microscopes, fitted with either a Leica DFC400 or DFC500 camera, using magnifications of 10x and 25x power under both plane and polarized light (PL and XN, respectively). The typical approach was fourfold: (1) identify and estimate the percentage of mineral groups present; (2) examine textures and grain properties; (3) analyze the cementing materials that hold the rock matrix together; and (4) prepare a visual estimate of porosity. These observations were made using Ulmer-Scholle and others (2014) as a guide, and visual estimates of mineral composition and porosity were based on the comparison chart for visual percentage estimation by Terry and Chilingar (1955).

Observations, estimates and representative photomicrographs prepared for each thin section were recorded on a standard reporting form. These results are summarized in Table 4-5 below and provided in Appendix D.

*Table 4-5. Summary of qualitative thin section analyses for thin sections listed in Table 4-4.*

| API No. | Well ID | Geologic Interval | Lithology | Depth range (ft) | Porosity estimates (%) |
|---|---|---|---|---|---|
| 34-029-20592-0000 | Denny #1-2468 | Rose Run-Gatesburg | Carbonate, dolostone, breccia | 8,098-8,251 | nil - 5% |
| 34-145-60141-0000 | Aristech Chemical Co. #4 | Rose Run-Gatesburg | Sandstone, breccia, sandy carbonate, calcareous sandstone, sandstone | 4,191-4,529 | <1% - 15% |
| 34-115-21249-0000 | Kittle #11125 | Rose Run-Gatesburg | Breccia, sandy carbonate, carbonate, quartz sandstone | 6,484-6,519 | nil to 3% |
| 34-079-20102-0000 | Trepanier #1 | Rose Run-Gatesburg | Carbonate | 4,529 | nil |
| 47-103-00614 | Patty Potts & Gloria Nice #1 | Keener to Berea | Sandstone/graywacke, clayey sandstone | 2,463-2,685 | nil - 2% |
| 47-107-01266 | Darrell Matheny #2 | Oriskany Sandstone | Sandstone | 4,197-4,225 | nil - 13% |
| 47-041-00057 | J.B. Lovett #2 | Oriskany Sandstone | Calcareous sandstone, sandy limestone | 6,963-6,989 | <1% |
| 47-095-00741 | Peter Horner #9 | Venango sandstones | Sandstone, quartz conglomerate | 2,892-2,906 | 4 - 25% |
| 47-103-01685 | L.S. Hoyt #100 | Venango sandstones | Sandstone | 3,136-3,158 | 3 – 30% |
| 47-039-02112 | J. Woodrum #A-2 | Newburg sandstone | Sandstone, calcareous sandstone, quartz sandstone | 5426.5-5432.5 | <1% - 5% |

### 4.3.3 Preliminary Assessment

Using the compiled data, the Research Team identified more than 2,700 fields in the AOI with sandstone reservoir data. Of these, approximately 1,500 fields occur at a depth of 2,000 ft or more. Because this subset represented the large majority of fields with reservoir data for the Study's sandstone intervals of interest (Early Mississippian through Late Cambrian age), this smaller digital dataset was chosen for the siliciclastic reservoir characterization and rating work.

Using the digital dataset of ~1,500 fields, the Research Team identified areas where field-specific reservoir parameters were lacking and reviewed chapters of the Atlas of Major Appalachian Gas Plays (Roen and Walker, 1996) to fill in data gaps wherever possible. The fields were then screened by assigning preliminary rating values (ranging from 0 to 3) for each of a limited list of criteria (Table 4-6). These values were then summed to generate an overall rating value for each field; the higher the rating, the more promising the siliciclastic storage opportunity.

Some of these criteria are reservoir attributes (i.e., average depth, net thickness, porosity, permeability and pressure), while others are related to the location, size and overall likelihood that a field may serve as a viable storage container (i.e., distance to infrastructure in miles [mi], acreage, stacked opportunity and mode carbon dioxide [$CO_2$] storage). As an example, the best siliciclastic storage reservoirs will have porosities of approximately 10 percent (or more), permeabilities of several hundred millidarcy (mD) or more, provide a storage container with adequate thickness and size (ac) and preferably be located proximal to existing or proposed infrastructure. These criteria, data and the preliminary rating workbook used to assess them have also been made available on the Study website.

***Table 4-6. Preliminary rating criteria used to assess depleted gas and natural gas storage fields in the AOI.***

| Criterion | Description | Range of Values |
|---|---|---|
| **Distance to infrastructure**<br>>30 mi<br>>20 mi but <=30 mi<br>>5 mi but <=20 mi<br><=5 mi | Proximity of field to any of the existing or proposed pipeline infrastructure (mi), as illustrated in Figure 4-26 | <br>0<br>1<br>2<br>3 |
| **Acreage**<br><=500 ac<br>>500 ac but <=1,000 ac<br>>1,000 ac but <=5,000 ac<br>>5,000 ac | Measured size (or "footprint") of a field (ac) | <br>0<br>1<br>2<br>3 |
| **Average depth**<br><=2,000 ft<br>>5,000 ft<br>>2,000 ft but <=3,500 ft<br>>3,500 ft but <=5,000 ft | Average depth (ft) at which a field produced natural gas, based on multiple wells completed in that field | <br>0<br>1<br>2<br>3 |
| **Average porosity**<br><=1%<br>>1% but <=5%<br>>5% but <=10%<br>>10% | Porosity is the ratio of void volume in a rock relative to its bulk volume, reported as a percentage; average porosity is determined using data obtained from various depths in the reservoir and/or multiple wells completed in a given reservoir and field | <br>0<br>1<br>2<br>3 |
| **Net thickness**<br><=1 ft<br>>1 ft but <=10 ft<br>>10 ft but <=20 ft<br>>20 ft | Measured thickness (ft) of clean sandstone (i.e., without siltstone and/or shale) in a reservoir rock for a given field | <br>0<br>1<br>2<br>3 |
| **Permeability**<br>No data<br><=10 mD<br>>10 mD but <=1,000 mD<br>>1,000 mD | Capacity of a reservoir rock to transmit a fluid (oil, gas or water), measured in units of mD | <br>0<br>1<br>2<br>3 |
| **Pressure**<br>No data<br>>0 psi but <=900 psi<br>>=1,500 psi<br>>900 psi but <=1,500 psi | Measured pressure (psi) of a reservoir at depth in a given field; the standard lithostatic pressure gradient is 0.433 psi per ft of depth | <br>0<br>1<br>2<br>3 |

| | | |
|---|---|---|
| **Stacked opportunity?**<br>No other intervals in same footprint<br>1 other interval in same footprint<br>2 or 3 other intervals in same footprint<br>4 or more intervals in same footprint | Identification of other storage containers in the general vicinity of the footprint of a given field, at shallower and/or deeper depths | <br>0<br>1<br>2<br>3 |
| **Mode $CO_2$ storage (computed value)**<br><=10,000 tons<br>>10,000 tons but <=100,000 tons<br>>100,000 tons but <=1,000,000 tons<br>>1,000,000 tons | The mode (middle) $CO_2$ storage capacity value reported for a given field, based on sequestration capacity calculations prepared by MRCSP (Lewis, in preparation) | <br>0<br>1<br>2<br>3 |

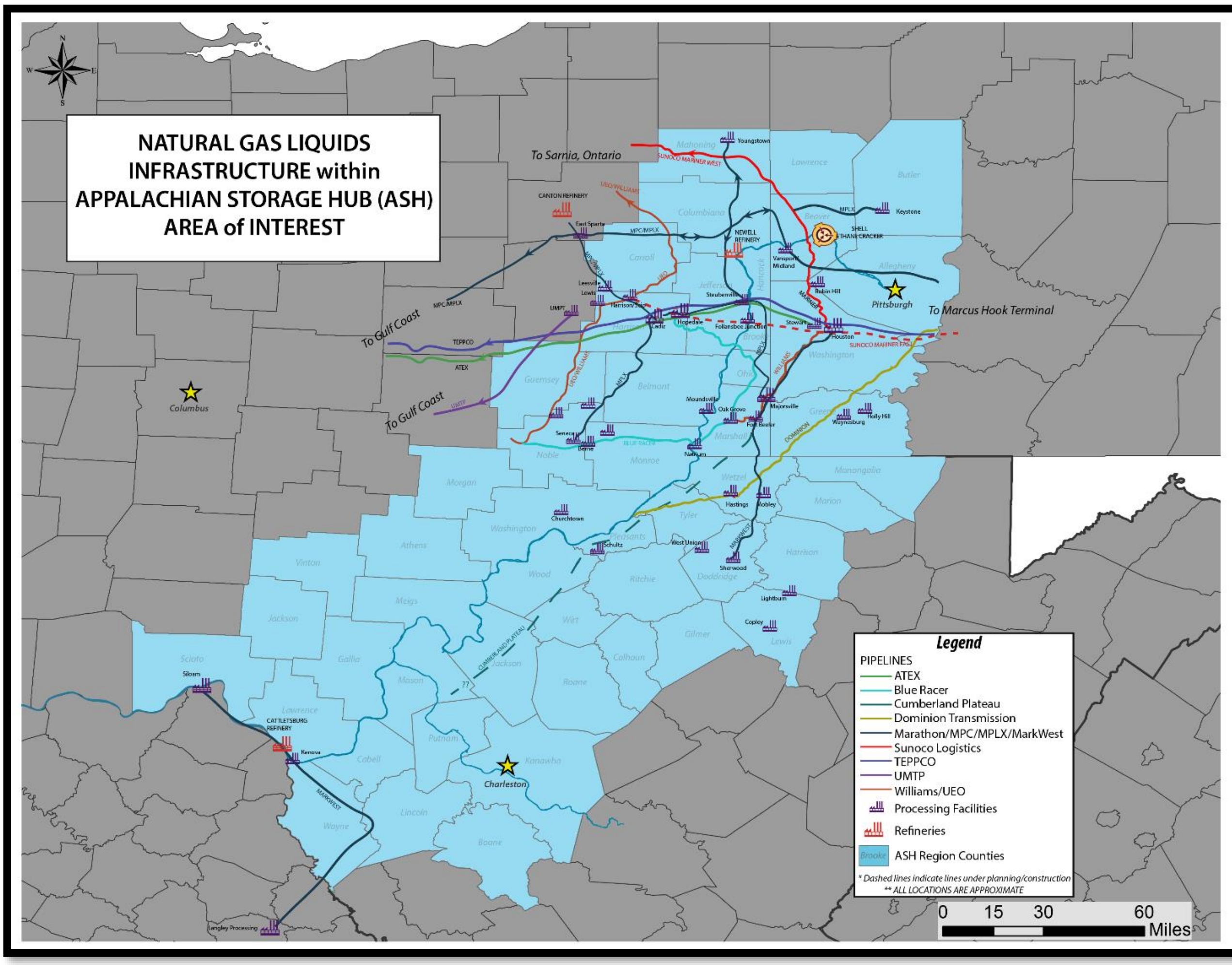



**Figure 4-26. Natural gas liquids infrastructure (existing and planned) within the AOI. All locations are approximate.**

Tables 4-7 and 4-8 list the 113 depleted gas fields and 12 natural gas storage fields with the most favorable reservoir characteristics, respectively, as determined by preliminary rating efforts. Due to the fact that Appalachian basin gas fields can (and often do) produce from multiple reservoirs at different depths (i.e., various geologic intervals), some field names appear more than once in these tables.

***Table 4-7. Top-rated depleted gas fields in the AOI with favorable reservoir characteristics, sorted by geologic interval and in alphabetic order for each interval.***

| Field Name | Geologic Interval(s) | Discovery Year | State |
|---|---|---|---|
| BIG RUN-BURCHFIELD | Keener to Berea | 1902 | WV |
| BURDETT-ST. ALBANS | Keener to Berea | 1906 | WV |
| CAMERON-GARNER | Keener to Berea | 1977 | WV |
| CONDIT-RAGTOWN | Keener to Berea | 1898 | WV |
| HENDERSHOT-OGDIN | Keener to Berea | 1895 | WV |
| MAPLE-WADESTOWN | Keener to Berea | 1905 | WV |
| SIDNEY | Keener to Berea | 1959 | WV |
| STANLEY | Keener to Berea | 1966 | WV |
| WHITES CREEK-GRAGSTON | Keener to Berea | 1930 | WV |
| WILBUR | Keener to Berea | 1971 | WV |
| CAMPBELLS RUN-MIRACLE RUN | Venango | 1929 | WV |
| COBURN-EARNSHAW | Venango | 1913 | WV |
| CONDIT-RAGTOWN | Venango | 1914 | WV |
| FAIRVIEW-STATLER RUN-MOUNT MORRIS | Venango | 1913 | WV |
| HUNDRED | Venango | 1904 | WV |
| JEFFERSON | Venango | 1889 | WV |
| LLEWELLYN RUN-PLUM RUN | Venango | 1925 | WV |
| LOGANSPORT | Venango | 1914 | WV |
| MANNINGTON | Venango | 1893 | WV |
| MAPLE-WADESTOWN | Venango | 1905 | WV |
| MASONTOWN | Venango | 1889 | WV |
| MOORESVILLE | Venango | 1901 | WV |
| SHINNSTON | Venango | 1964 | WV |
| SMITHFIELD | Venango | 1909 | WV |
| WALLACE-FOLSOM | Venango | 1903 | WV |
| WOLF SUMMIT | Venango | 1898 | WV |
| ABBOTT-FRENCH CREEK | Venango, Bradford | 1977 | WV |
| ANTRAM RUN | Venango, Bradford | 1907 | WV |
| AUBURN | Venango, Bradford | 1968 | WV |
| ELK CREEK (OVERFIELD) | Venango, Bradford | 1921 | WV |
| FARMINGTON | Venango, Bradford | 1909 | WV |
| GLENVILLE SOUTH | Venango, Bradford | 1930 | WV |
| LORENTZ | Venango, Bradford | 1977 | WV |
| MEATHOUSE FORK-BRISTOL | Venango, Bradford | 1985 | WV |
| PORTO RICO | Venango, Bradford | 1901 | WV |
| RURAL RIDGE | Venango, Bradford | 1912 | PA |
| SHILOH-WICK AREA | Venango, Bradford | 1979 | WV |

| | | | |
|---|---|---|---|
| STANLEY | Venango, Bradford | 1971 | WV |
| STRAIGHT FORK-BLUESTONE CREEK | Venango, Bradford | 1930 | WV |
| STUMPTOWN-NORMANTOWN-SHOCK | Venango, Bradford | 1985 | WV |
| WHITE ASH | Venango, Bradford | 1910 | PA |
| MCKEESPORT | Bradford | 1919 | PA |
| SOUTH BURNS CHAPEL | Bradford | 1968 | WV |
| ASPINALL-FINSTER | Bradford, Elk | 1975 | WV |
| BRIDGEPORT-PRUNTYTOWN | Bradford, Elk | 1912 | WV |
| BROWN-LUMBERPORT | Bradford, Elk | 1902 | WV |
| ELK CREEK (OVERFIELD) | Bradford, Elk | 1917 | WV |
| GLADE RUN | Bradford, Elk | 1962 | WV |
| HEATERS | Bradford, Elk | 1973 | WV |
| JARVISVILLE | Bradford, Elk | 1901 | WV |
| LORENTZ | Bradford, Elk | 1937 | WV |
| MURPHY CREEK | Bradford, Elk | 1906 | WV |
| SALEM | Bradford, Elk | 1979 | WV |
| SMITHTON-FLINT-SEDALIA | Bradford, Elk | 1936 | WV |
| WESTON-JANE LEW | Bradford, Elk | 1913 | WV |
| ASPINALL-FINSTER | Elk | 1947 | WV |
| AUBURN | Elk | 1973 | WV |
| BEASON RUN | Elk | 1979 | WV |
| BUCKHANNON-CENTURY | Elk | 1916 | WV |
| CONINGS | Elk | 1962 | WV |
| GLENVILLE NORTH | Elk | 1957 | WV |
| GRANTSVILLE-ARNOLDSBURG | Elk | 1992 | WV |
| GREENWOOD | Elk | 1979 | WV |
| HAZEL GREEN-LAWFORD-BEREA | Elk | 1980 | WV |
| HEATERS | Elk | 1968 | WV |
| LORENTZ | Elk | 1940 | WV |
| MAHONE (SMITHVILLE) | Elk | 1981 | WV |
| MURPHY CREEK | Elk | 1917 | WV |
| NEW MILTON SOUTH | Elk | 1962 | WV |
| PORTO RICO | Elk | 1978 | WV |
| PRUNTY | Elk | 1980 | WV |
| STRAIGHT FORK-BLUESTONE CREEK | Elk | 1977 | WV |
| STUMPTOWN-NORMANTOWN-SHOCK | Elk | 1977 | WV |
| THURSDAY | Elk | 1980 | WV |
| WESTON-JANE LEW | Elk | 1909 | WV |
| BLUE CREEK (FALLING ROCK) | Oriskany | 1944 | WV |
| CAMPBELL CREEK | Oriskany | 1935 | WV |
| DEKALB | Oriskany | 1985 | WV |

| | | | |
|---|---|---|---|
| ELK-POCA (SISSONVILLE) | Oriskany | 1967 | WV |
| GLENVILLE NORTH | Oriskany | 1972 | WV |
| HURRICANE CREEK | Oriskany | 1940 | WV |
| KANAWHA FOREST | Oriskany | 1966 | WV |
| LAUREL RUN | Oriskany | 1989 | OH |
| NEW ENGLAND | Oriskany | 1952 | WV |
| PUTNAM | Oriskany | 1951 | OH |
| RED HOUSE | Oriskany | 1954 | WV |
| ROCK CAMP | Oriskany | 1936 | OH |
| COOPER CREEK | Newburg | 1968 | WV |
| GROUNDHOG CREEK | Newburg | 1969 | WV |
| KANAWHA FOREST | Newburg | 1964 | WV |
| NORTH RIPLEY | Newburg | 1969 | WV |
| ROCKY FORK | Newburg | 1966 | WV |
| WHEATON RUN | Newburg | 1971 | WV |
| CANTON CONSOLIDATED | Clinton/Medina | 1921 | OH |
| CANTON CONSOLIDATED | Clinton/Medina | 1921 | OH |
| CANTON CONSOLIDATED | Clinton/Medina | 1921 | OH |
| CANTON CONSOLIDATED | Clinton/Medina | 1921 | OH |
| NORTH ELLSWORTH CONSOLIDATED | Clinton/Medina | 1963 | OH |
| PHILO CONSOLIDATED | Clinton/Medina | 1928 | OH |
| RAVENNA-BEST CONSOLIDATED | Clinton/Medina | 1949 | OH |
| SUFFIELD-SMITH | Clinton/Medina | 1960 | OH |
| TRIADELPHIA CONSOLIDATED | Clinton/Medina | 1927 | OH |
| TRIADELPHIA CONSOLIDATED | Clinton/Medina | 1927 | OH |
| DUMM RIDGE | Rose Run-Gatesburg | 1992 | OH |
| DUMM RIDGE | Rose Run-Gatesburg | 1992 | OH |
| DUMM RIDGE | Rose Run-Gatesburg | 1992 | OH |
| DUMM RIDGE | Rose Run-Gatesburg | 1992 | OH |
| FRAZEYBURG | Rose Run-Gatesburg | 1990 | OH |
| KIRKERSVILLE | Rose Run-Gatesburg | 1992 | OH |
| RANDOLPH | Rose Run-Gatesburg | 1990 | OH |
| ROCKBRIDGE | Rose Run-Gatesburg | 1993 | OH |
| ROCKBRIDGE | Rose Run-Gatesburg | 1993 | OH |
| ROCKBRIDGE | Rose Run-Gatesburg | 1993 | OH |

***Table 4-8. Top-rated natural gas storage fields in the AOI with favorable reservoir characteristics, sorted by geologic interval and in alphabetic order for each interval.***

| Field Name | Geologic Interval(s) | Discovery Year | State |
|---|---|---|---|
| VICTORY "A" (KAUSOOTH-CAMERON) | Greenbrier | 1953 | WV |
| LOGANSPORT | Keener to Berea | 1954 | WV |
| VICTORY "B" (KAUSOOTH-CAMERON) | Keener to Berea | 1957 | WV |
| FINK-KENNEDY-LOST CREEK (MURPHY CREEK) | Venango | 1947 | WV |
| MEHAFFY | Venango | 1934 | PA |
| RACKET-NEWBERNE (SINKING CREEK) | Venango | 1947 | WV |
| MCKEESPORT | Bradford | --- | PA |
| COCO "A" | Oriskany | 1950 | WV |
| COCO "C" | Oriskany | 1957 | WV |
| RIPLEY | Oriskany | 1954 | WV |
| ROCKPORT | Oriskany | 1953 | WV |
| ROCKPORT (DEEP) | Oriskany | 1948 | WV |

The Research Team's preliminary assessment (mapping, compilation and review of field-level reservoir data and petrography) led to the identification of multiple storage opportunities for each category of storage container (i.e., salt cavern, mined-rock cavern, natural gas storage fields and depleted gas reservoirs). These include four areas where the net thickness of the Salina F4 Salt is greater than 100 ft; multiple areas throughout southwestern Pennsylvania and western West Virginia where the Greenbrier Limestone occurs at depths ranging from 1,800 to 2,000 ft; and 12 natural gas storage fields and 66 Upper Devonian depleted gas fields that were selected for further evaluation based on favorable reservoir attributes. The locations of these opportunities are illustrated in Figure 4-27.

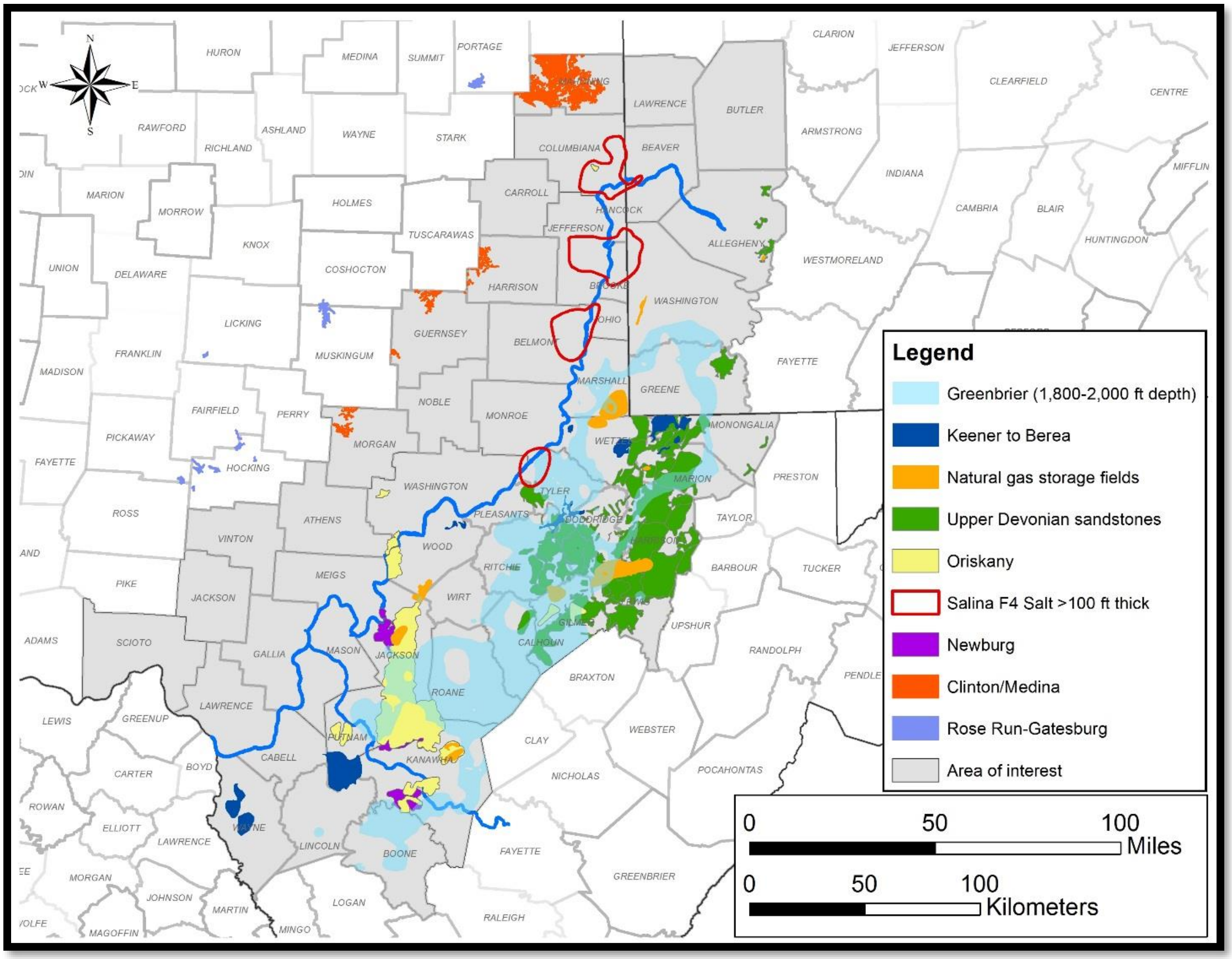



**Figure 4-27. Storage opportunities identified through regional mapping, preliminary field-level assessments and rating.**

## 4.4 Detailed Ratings and Results

Based on the results of the reservoir characterization work presented above, the Research Team took a closer look at the top storage opportunities using a series of detailed rating criteria tailored to each category of storage container. The methods used to assign these detailed ratings are provided below, followed by the results of this work.

### 4.4.1 Methods

Detailed rating efforts involved the assignment of numeric rating values (ranging from 0 to 3) to a set of criteria developed for each of the four types of storage container. The detailed rating criteria used to assess salt caverns, mined-rock caverns, depleted gas fields and natural gas storage fields are given in Tables 4-9 through 4-12, respectively. Rating values were then summed to provide an overall rating value for each storage opportunity for comparison purposes. Once again, the higher the rating, the more promising the storage opportunity.

***Table 4-9. Detailed rating criteria used to assess salt caverns in the AOI.***

| Criterion | Description | Range of Values |
|---|---|---|
| **Distance to infrastructure**<br>>30 mi<br>>20 mi but <=30 mi<br>>5 mi but <=20 mi<br><=5 mi | Proximity of area to any of the existing or proposed pipeline infrastructure (mi), as illustrated in Figure 4-26 | <br>0<br>1<br>2<br>3 |
| **Acreage**<br><25,000 ac<br>>=25,000 ac but <50,000 ac<br>>=50,000 ac but <100,000 ac<br>>=100,000 ac | Measured size (or "footprint") of an area (ac) | <br>0<br>1<br>2<br>3 |
| **Average depth**<br><=2,000 ft<br>>5,000 ft but <=7,000 ft<br>>3,000 ft but <=5,000 ft<br>>2,000 ft but <=3,000 ft | Average depth (ft) at which an area has a thick accumulation of salt | <br>0<br>1<br>2<br>3 |
| **Net thickness**<br><=10 ft<br>>10 ft but <=50 ft<br>>50 ft but <=100 ft<br>>100 ft | Measured thickness (ft) of relatively pure salt (i.e., without interlayers of siltstone, dolostone or shale) that can be solution-mined to create a salt cavern | <br>0<br>1<br>2<br>3 |
| **Pressure**<br>No data<br>>0 psi but <=900 psi<br>>900 psi but <=1,500 psi<br>>1,500 psi | Measured pressure (psi) of a salt layer at depth in a given area; the standard lithostatic pressure gradient is 0.433 psi per ft of depth | <br>0<br>1<br>2<br>3 |
| **Trap integrity**<br>No data<br>Limited data on trap characteristics<br>Inferred lithologic and/or structural closure<br>Documented lithologic and/or structural closure | Four levels of data control/confidence, as listed to the left and illustrated in Figure 4-28 | <br>0<br>1<br>2<br>3 |
| **Legacy well penetrations**<br>No data or >=20 wells per 1,000 ac<br>>=5 wells per 1,000 ac but <20 wells per 1,000 ac<br>>=2 wells per 1,000 ac but <5 wells per 1,000 ac<br><2 well per ac | Four levels of data density with respect to well penetrations in a given area | <br>0<br>1<br>2<br>3 |
| **Stacked opportunity?**<br>No other intervals in same footprint<br>1 other interval in same footprint<br>2 or 3 other intervals in same footprint<br>4 or more intervals in same footprint | Identification of other storage containers in the general vicinity of an area, at shallower and/or deeper depths | <br>0<br>1<br>2<br>3 |

***Table 4-10. Detailed rating criteria used to assess mined-rock caverns in the AOI.***

| Criterion | Description | Range of Values |
|---|---|---|
| **Distance to infrastructure**<br>>30 mi<br>>20 mi but <=30 mi<br>>5 mi but <=20 mi<br><=5 mi | Proximity of area to any of the existing or proposed pipeline infrastructure (mi), as illustrated in Figure 4-26 | <br>0<br>1<br>2<br>3 |
| **Acreage**<br><25,000 ac<br>>=25,000 ac but <75,000 ac<br>>=75,000 ac but <125,000 ac<br>>=125,000 ac | Measured size (or "footprint") of an area (ac) | <br>0<br>1<br>2<br>3 |
| **Average depth**<br><1,800 ft<br>>=1,800 ft but <=2,000 ft | Average depth (ft) at which an area has mineable thicknesses of Greenbrier Limestone | <br>0<br>3 |
| **Net thickness**<br><40 ft<br>>=40 ft | Measured thickness (ft) of lime mudstone, within the depth range of 1,800 – 2,000 ft, that can be mined to create a mined-rock cavern | <br>0<br>3 |
| **Trap integrity**<br>No data<br>Limited data on trap characteristics<br>Inferred lithologic and/or structural closure<br>Documented lithologic and/or structural closure | Four levels of data control/confidence, as listed to the left and illustrated in Figure 4-28 | <br>0<br>1<br>2<br>3 |
| **Legacy well penetrations**<br>No data or >=20 wells per 1,000 ac<br>>=5 wells per 1,000 ac but <20 wells per 1,000 ac<br>>=2 wells per 1,000 ac but <5 wells per 1,000 ac<br><2 well per ac | Four levels of data density with respect to well penetrations in a given area | <br>0<br>1<br>2<br>3 |
| **Stacked opportunity?**<br>No other intervals in same footprint<br>1 other interval in same footprint<br>2 or 3 other intervals in same footprint<br>4 or more intervals in same footprint | Identification of other storage containers in the general vicinity of an area, at shallower and/or deeper depths | <br>0<br>1<br>2<br>3 |

***Table 4-11. Detailed rating criteria used to assess depleted gas reservoirs in the AOI.***

| Criterion | Description | Range of Values |
|---|---|---|
| **Distance to infrastructure**<br>>30 mi<br>>20 mi but <=30 mi<br>>5 mi but <=20 mi<br><=5 mi | Proximity of field to any of the existing or proposed pipeline infrastructure (mi), as illustrated in Figure 4-26 | <br>0<br>1<br>2<br>3 |
| **Acreage**<br><=500 ac<br>>500 ac but <=1,000 ac<br>>1,000 ac but <=5,000 ac<br>>5,000 ac | Measured size (or "footprint") of a field (ac) | <br>0<br>1<br>2<br>3 |
| **Average depth**<br><=2,000 ft<br>>5,000 ft<br>>2,000 ft but <=3,500 ft | Average depth (ft) at which a field produced natural gas, based on multiple wells completed in that field | <br>0<br>1<br>2 |

| | | |
|---|---|---|
| >3,500 ft but <=5,000 ft | | 3 |
| **Average porosity**<br><=1%<br>>1% but <=5%<br>>5% but <=10%<br>>10% | Porosity is the ratio of void volume in a rock relative to its bulk volume, reported as a percentage; average porosity is determined using data obtained from various depths in the reservoir and/or multiple wells completed in a given reservoir and field | <br>0<br>1<br>2<br>3 |
| **Net thickness**<br><=1 ft<br>>1 ft but <=10 ft<br>>10 ft but <=20 ft<br>>20 ft | Measured thickness (ft) of clean sandstone (i.e., without siltstone and/or shale) in a reservoir rock for a given field | <br>0<br>1<br>2<br>3 |
| **Permeability**<br>No data<br><=10 mD<br>>10 mD but <=1,000 mD<br>>1,000 mD | Capacity of a reservoir rock to transmit a fluid (oil, gas or water), measured in units of mD | <br>0<br>1<br>2<br>3 |
| **Pressure**<br>No data<br>>0 psi but <=900 psi<br>>=1,500 psi<br>>900 psi but <=1,500 psi | Measured pressure (psi) of a reservoir at depth in a given field; the standard lithostatic pressure gradient is 0.433 psi per ft of depth | <br>0<br>1<br>2<br>3 |
| **Trap integrity**<br>No data<br>Limited data on trap characteristics<br>Inferred lithologic and/or structural closure<br>Documented lithologic and/or structural closure | Four levels of data control/confidence, as listed to the left and illustrated in Figure 4-28 | <br>0<br>1<br>2<br>3 |
| **Legacy well penetrations**<br>No data or >=20 wells per 1,000 ac<br>>=5 wells per 1,000 ac but <20 wells per 1,000 ac<br>>=2 wells per 1,000 ac but <5 wells per 1,000 ac<br><2 well per ac | Four levels of data density with respect to well penetrations in a given field | <br>0<br>1<br>2<br>3 |
| **Stacked opportunity?**<br>No other intervals in same footprint<br>1 other interval in same footprint<br>2 or 3 other intervals in same footprint<br>4 or more intervals in same footprint | Identification of other storage containers in the general vicinity of a field, at shallower and/or deeper depths | <br>0<br>1<br>2<br>3 |
| **Mode $CO_2$ storage (computed value)**<br><=10,000 tons<br>>10,000 tons but <=100,000 tons<br>>100,000 tons but <=1,000,000 tons<br>>1,000,000 tons | The mode (middle) $CO_2$ storage capacity value reported for a given field, based on sequestration capacity calculations prepared by MRCSP (Lewis, in preparation) | <br>0<br>1<br>2<br>3 |
| **Estimated cumulative gas production (BCF)**<br>No data<br><=1 BCF<br>>1 BCF but <=10 BCF<br>>10 BCF | The cumulative volume of gas produced in a given field, in units of billion cubic feet (BCF), based on aggregate data tabulated from Roen and Walker (1996) | <br>0<br>1<br>2<br>3 |

***Table 4-12. Detailed rating criteria used to assess natural gas storage fields in the AOI.***

| Criterion | Description | Range of Values |
|---|---|---|
| **Distance to infrastructure**<br>>30 mi<br>>20 mi but <=30 mi<br>>5 mi but <=20 mi<br><=5 mi | Proximity of field to any of the existing or proposed pipeline infrastructure, as illustrated in Figure 4-26 | <br>0<br>1<br>2<br>3 |
| **Acreage**<br><=500 ac<br>>500 ac but <=1,000 ac<br>>1,000 ac but <=5,000 ac<br>>5,000 ac | Measured size (or "footprint") of a field (ac) | <br>0<br>1<br>2<br>3 |
| **Average depth**<br><=2,000 ft<br>>5,000 ft<br>>2,000 ft but <=3,500 ft<br>>3,500 ft but <=5,000 ft | Average depth (ft) at which a field stores/stored natural gas, based on multiple wells completed in that field | <br>0<br>1<br>2<br>3 |
| **Average porosity**<br><=1%<br>>1% but <=5%<br>>5% but <=10%<br>>10% | Porosity is the ratio of void volume in a rock relative to its bulk volume, reported as a percentage; average porosity is determined using data obtained from various depths in the reservoir and/or multiple wells completed in a given reservoir and field | <br>0<br>1<br>2<br>3 |
| **Net thickness**<br><=1 ft<br>>1 ft but <=10 ft<br>>10 ft but <=20 ft<br>>20 ft | Measured thickness (ft) of clean sandstone (i.e., without siltstone and/or shale) in a reservoir rock for a given field | <br>0<br>1<br>2<br>3 |
| **Permeability**<br>No data<br><=10 mD<br>>10 mD but <=1,000 mD<br>>1,000 mD | Capacity of a reservoir rock to transmit a fluid (oil, gas or water), measured in units of mD | <br>0<br>1<br>2<br>3 |
| **Pressure**<br>No data<br>>0 psi but <=900 psi<br>>=1,500 psi<br>>900 psi but <=1,500 psi | Measured pressure (psi) of a reservoir at depth in a given field; the standard lithostatic pressure gradient is 0.433 psi per ft of depth | <br>0<br>1<br>2<br>3 |
| **Trap integrity**<br>No data<br>Limited data on trap characteristics<br>Inferred lithologic and/or structural closure<br>Documented lithologic and/or structural closure | Four levels of data control/confidence, as listed to the left and illustrated in Figure 4-28 | <br>0<br>1<br>2<br>3 |
| **Legacy well penetrations**<br>No data or >=20 wells per 1,000 ac<br>>=5 wells per 1,000 ac but <20 wells per 1,000 ac<br>>=2 wells per 1,000 ac but <5 wells per 1,000 ac<br><2 well per ac | Four levels of data density with respect to well penetrations in a given field | <br>0<br>1<br>2<br>3 |

| | | |
|---|---|---|
| **Stacked opportunity?**<br>No other intervals in same footprint<br>1 other interval in same footprint<br>2 or 3 other intervals in same footprint<br>4 or more intervals in same footprint | Identification of other storage containers in the general vicinity of a field, at shallower and/or deeper depths | <br>0<br>1<br>2<br>3 |
| **Mode $CO_2$ storage (computed value)**<br><=10,000 tons<br>>10,000 tons but <=100,000 tons<br>>100,000 tons but <=1,000,000 tons<br>>1,000,000 tons | The mode (middle) $CO_2$ storage capacity value reported for a given field, based on sequestration capacity calculations prepared by MRCSP (Lewis, in preparation) | <br>0<br>1<br>2<br>3 |
| **Working gas capacity (MCF)**<br><=1,000,000 MCF (or no data)<br>>1,000,000 MCF but <=5,000,000 MCF<br>>5,000,000 MCF but <=10,000,000 MCF<br>>10,000,000 MCF | Total gas storage capacity minus base gas (i.e., volume of gas that is not withdrawn from the field in order to maintain pressures and deliverability), in units of thousand cubic feet (MCF) | <br>0<br>1<br>2<br>3 |

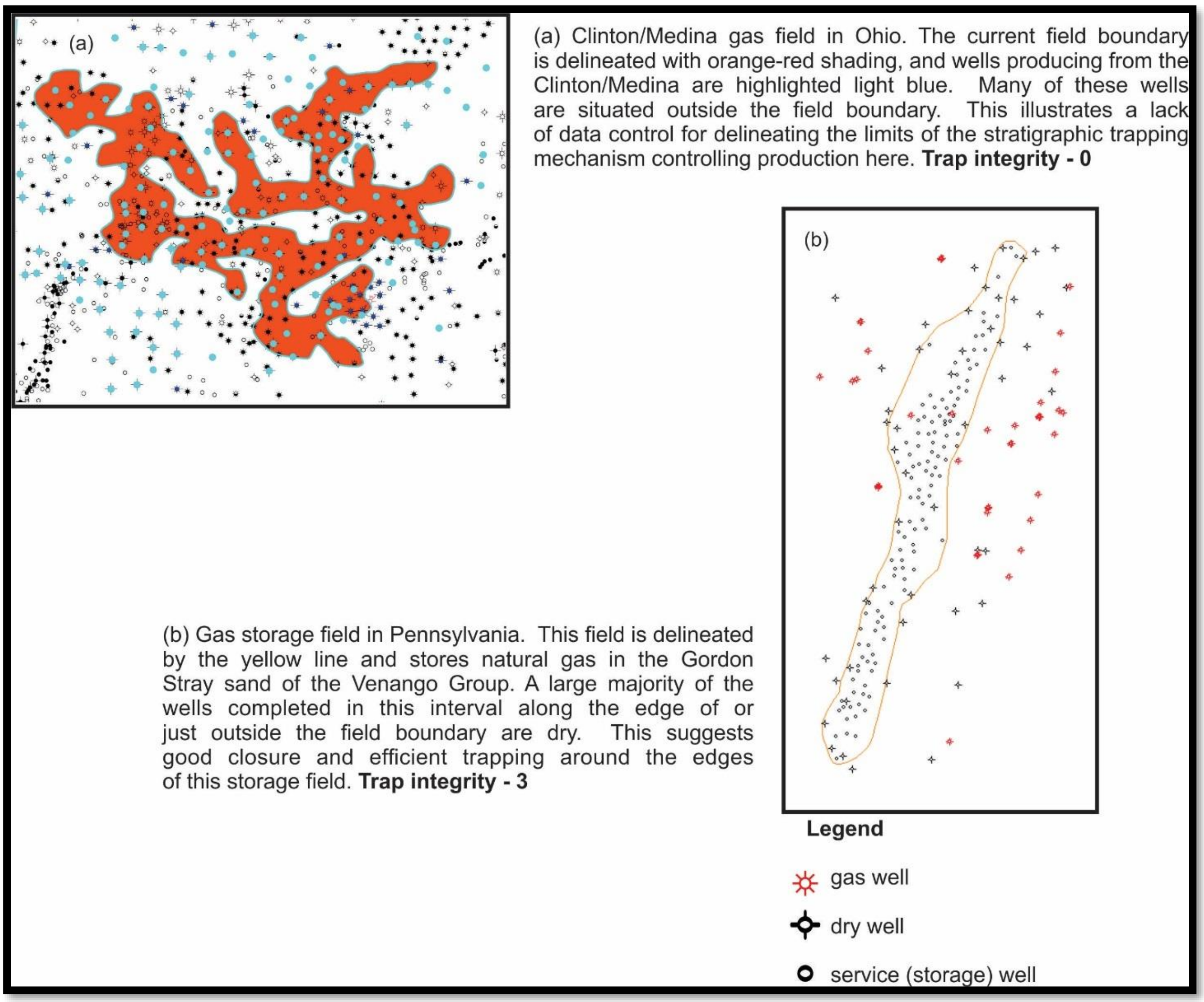



**Figure 4-28. Two end-member examples of trap integrity ratings using field-level data from Ohio and Pennsylvania.**

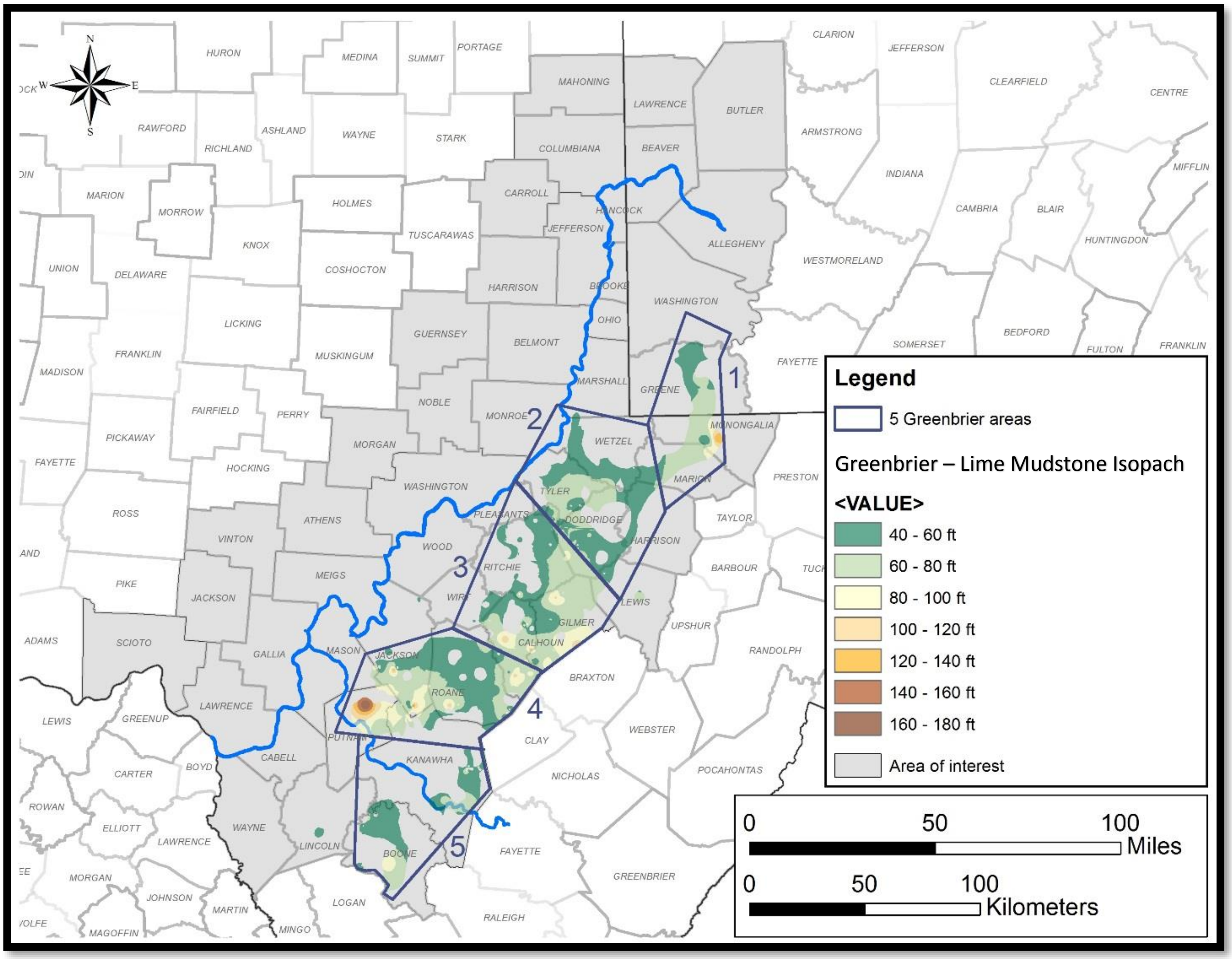



**Figure 4-29. Five geographic areas where the Greenbrier Limestone's mudstone facies was evaluated using the detailed rating criteria provided in Table 4-10.**

Consistent with the preliminary assessment of siliciclastic reservoirs, some of the rating criteria are reservoir attributes, and others are related to the location, size and overall likelihood that a geologic interval may serve as a viable storage container. An additional component of this effort, however, involved the application of criteria related to certain potential risks associated with the operation of underground ethane storage facilities – trap integrity and well penetrations. The detailed rating workbook used to evaluate these options are provided as Appendix E and have been made available on the Study website.

### 4.4.2 Rating Results

The Research Team's detailed rating efforts were used to generate a short list of 30 locations with the greatest potential to facilitate underground storage (Table 4-13). In particular, three areas of thick Salina F4 Salt are situated in the northern and central areas of the AOI along the Ohio River. The top-rated areas where the Greenbrier's lime mudstone facies was at least 40 ft thick and has a substantial footprint (acreage) are located in West Virginia. In addition, the top two natural gas storage fields and highest ranked depleted gas reservoirs are located in West Virginia.

***Table 4-13. Detailed rating results for the top 30 opportunities, summarized by storage container type and geologic interval.***

| Container Type | Field/Location | Geologic Interval | Rating Result |
|---|---|---|---|
| Mined-Rock Cavern | 5 | Greenbrier | 19 |
| | 4 | Greenbrier | 16 |
| | 2 | Greenbrier | 15 |
| Salt Cavern | 1 | Salina F4 Salt | 15 |
| | 2 | Salina F4 Salt | 15 |
| | 4 | Salina F4 Salt | 15 |
| Natural Gas Storage Field | RIPLEY | Oriskany | 24 |
| | RACKET-NEWBERNE (SINKING CREEK) | Venango | 22 |
| Depleted Gas Reservoirs | MAPLE-WADESTOWN | Keener to Berea | 23 |
| | BURDETT-ST. ALBANS | Keener to Berea | 22 |
| | CONDIT-RAGTOWN | Keener to Berea | 22 |
| | ABBOTT-FRENCH CREEK | Venango | 25 |
| | WESTON-JANE LEW | Elk | 24 |
| | CAMPBELL CREEK | Oriskany | 25 |
| | ELK-POCA (SISSONVILLE) | Oriskany | 24 |
| | NORTH RIPLEY | Newburg | 27 |
| | ROCKY FORK | Newburg | 27 |
| | KANAWHA FOREST | Newburg | 27 |
| | COOPER CREEK | Newburg | 25 |
| | CANTON CONSOLIDATED | Clinton/Medina | 25 |
| | CANTON CONSOLIDATED | Clinton/Medina | 24 |
| | CANTON CONSOLIDATED | Clinton/Medina | 24 |
| | RAVENNA-BEST CONSOLIDATED | Clinton/Medina | 24 |
| | DUMM RIDGE | Rose Run-Gatesburg | 18 |
| | DUMM RIDGE | Rose Run-Gatesburg | 18 |
| | FRAZEYBURG | Rose Run-Gatesburg | 18 |
| | RANDOLPH | Rose Run-Gatesburg | 18 |
| | KIRKERSVILLE | Rose Run-Gatesburg | 17 |
| | DUMM RIDGE | Rose Run-Gatesburg | 17 |
| | ROCKBRIDGE | Rose Run-Gatesburg | 17 |

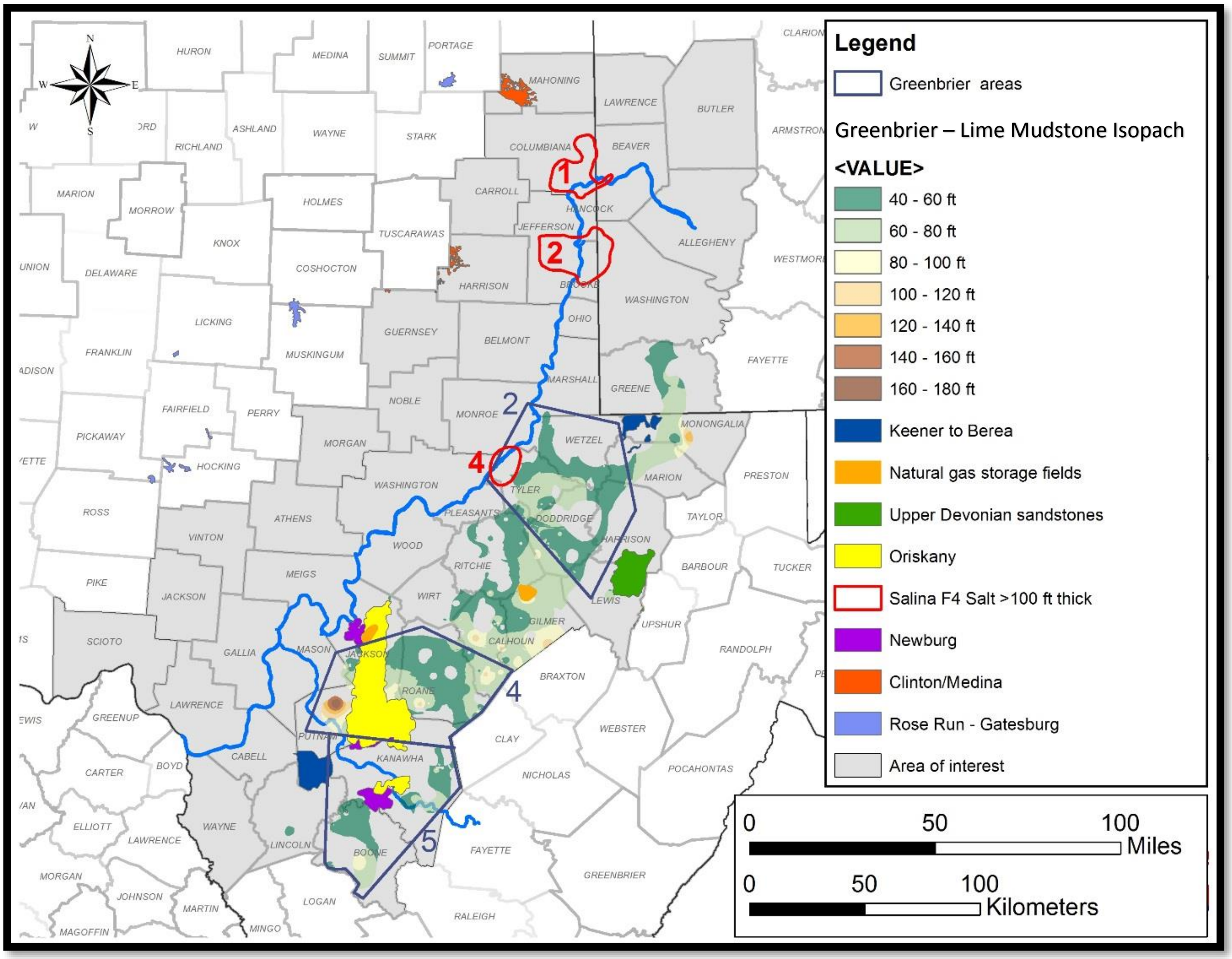



**Figure 4-30. Top-rated storage opportunities identified by the Study.**

# 5.0 RANKING RESULTS, STACKED OPPORTUNITIES AND FIELD-LEVEL PROSPECTS

This chapter represents the culmination of the Research Team's collaboration on regional geologic mapping, field-level reservoir characterization and rating and ranking efforts to identify the most prospective ethane storage opportunities in the AOI. This chapter presents the Research Team's ranking work, followed by a discussion of stacked opportunities and the presentation of field-level prospects using selected reservoir data.

## 5.1 Ranking Efforts

The purpose of the Study's ranking efforts was to identify the "best of the best" NGL storage opportunities irrespective of storage container type. The detailed rating values used to evaluate these opportunities (see Chapter 4) offer a robust means for ranking which fields or areas might serve as the best option for underground storage. However, because the rating criteria applied to each of the four categories were not identical, the Research Team could not use the rating values for ranking purposes as they were. The Research Team decided to normalize these rating criteria by using only those criteria common to each container type – specifically, distance to infrastructure, acreage, average depth, net thickness, trap integrity, legacy well penetrations and stacked opportunities. The ranking workbook used to evaluate the top 30 storage options are provided as Appendix F and have been made available on the Study website.

Table 5-1 summarizes the results of the Research Team's ranking efforts using normalized rating values for each of the top 30 storage opportunities. Using these data, nine of the 30 fields/locations yielded rankings of 1, 2 or 3. These top nine (highlighted green) include a combination of all four types of storage containers, and are generally consistent with the highest rated storage opportunities presented in Chapter 4.

*Table 5-1. Final ranking results for the top 30 ethane storage opportunities in the AOI.*

| Ranking | Container Type | Field/Location | Geologic Interval | Normalized Rating |
|---|---|---|---|---|
| 1 | mined-rock cavern | 5 | Greenbrier | 19 |
| 2 | depleted gas reservoir | NORTH RIPLEY | Newburg | 16 |
| 2 | depleted gas reservoir | ROCKY FORK | Newburg | 16 |
| 2 | depleted gas reservoir | KANAWHA FOREST | Newburg | 16 |
| 2 | mined-rock cavern | 4 | Greenbrier | 16 |
| 3 | depleted gas reservoir | CAMPBELL CREEK | Oriskany | 15 |
| 3 | mined-rock cavern | 2 | Greenbrier | 15 |
| 3 | salt cavern | 1 | Salina F4 Salt | 15 |
| 3 | salt cavern | 2 | Salina F4 Salt | 15 |
| 4 | depleted gas reservoir | WESTON-JANE LEW | Elk | 14 |
| 4 | depleted gas reservoir | CANTON CONSOLIDATED | Clinton/Medina | 14 |
| 4 | depleted gas reservoir | COOPER CREEK | Newburg | 14 |
| 4 | depleted gas reservoir | ABBOTT-FRENCH CREEK | Venango | 14 |
| 4 | natural gas storage field | RIPLEY | Oriskany | 14 |
| 5 | depleted gas reservoir | MAPLE-WADESTOWN | Keener to Berea | 13 |
| 5 | depleted gas reservoir | ELK-POCA (SISSONVILLE) | Oriskany | 13 |
| 5 | gas storage field | RACKET-NEWBERNE (SINKING CREEK) | Venango | 13 |
| 5 | salt cavern | 4 | Salina F4 salt | 13 |
| 4 | depleted gas reservoir | CANTON CONSOLIDATED | Clinton/Medina | 13 |
| 5 | depleted gas reservoir | CANTON CONSOLIDATED | Clinton/Medina | 13 |
| 5 | depleted gas reservoir | RAVENNA-BEST CONSOLIDATED | Clinton/Medina | 13 |
| 6 | depleted gas reservoir | BURDETT-ST. ALBANS | Keener to Berea | 12 |
| 6 | depleted gas reservoir | CONDIT-RAGTOWN | Keener to Berea | 12 |
| 7 | depleted gas reservoir | DUMM RIDGE | Rose Run-Gatesburg | 11 |
| 7 | depleted gas reservoir | FRAZEYBURG | Rose Run-Gatesburg | 11 |
| 8 | depleted gas reservoir | KIRKERSVILLE | Rose Run-Gatesburg | 10 |
| 8 | depleted gas reservoir | DUMM RIDGE | Rose Run-Gatesburg | 10 |
| 8 | depleted gas reservoir | DUMM RIDGE | Rose Run-Gatesburg | 10 |
| 8 | depleted gas reservoir | ROCKBRIDGE | Rose Run-Gatesburg | 10 |
| 8 | depleted gas reservoir | RANDOLPH | Rose Run-Gatesburg | 10 |

Figure 5-1 provides a visual comparison of the individual rating values for these opportunities. A majority of the fields/locations have comparable rating values for distance to infrastructure, acreage, net thickness and number of well penetrations. What sets the highest ranked opportunities apart are the following: average depth, favorable trap integrity and presence of stacked opportunities.

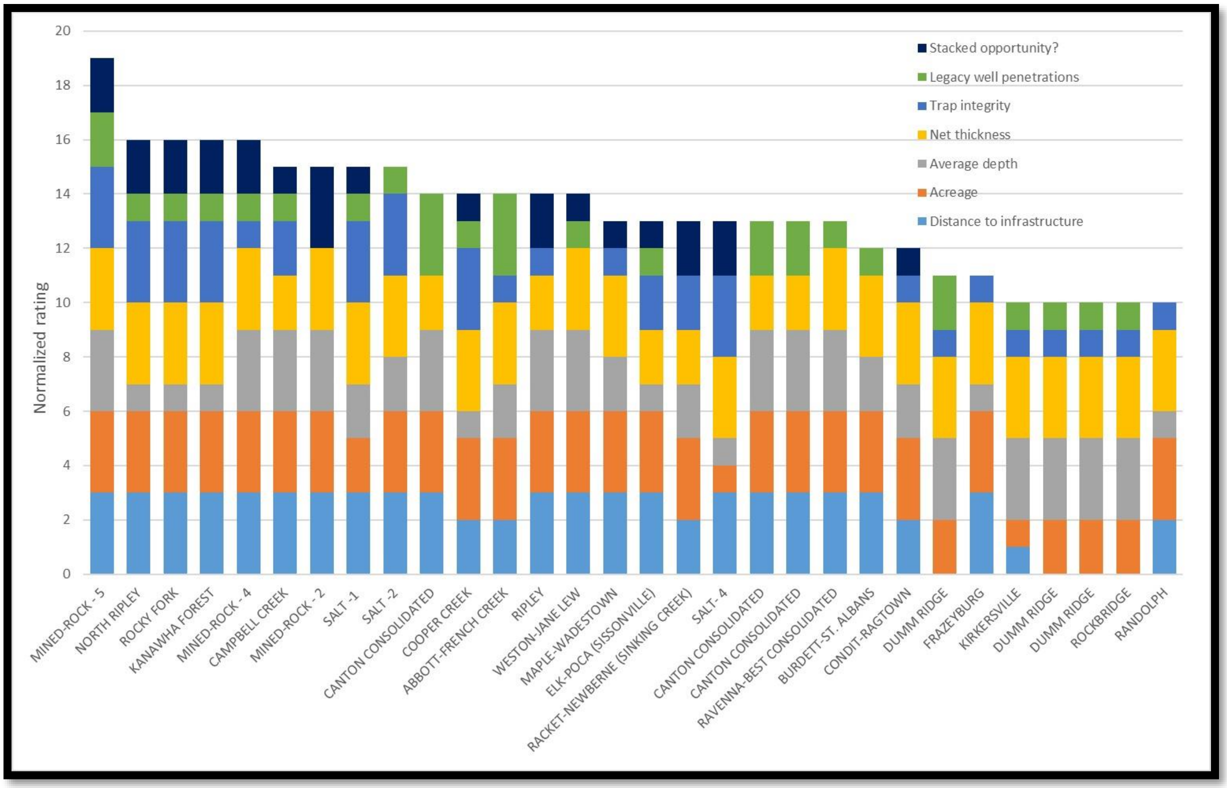



**Figure 5-1. Comparison of normalized ratings for seven criteria among top-rated fields/locations in the Study area.**

## 5.2 Importance of Stacked Opportunities

Stacked opportunities are defined as multiple subsurface geologic formations or intervals that occur at different depths within a given geographic area. Stacked opportunities provide many benefits, most notably flexibility with respect to the amount and kind of products that could potentially be stored at a site and the actual placement of pipeline infrastructure relative to a site's footprint. In addition, stacked opportunities may reduce risks related to site acquisition and/or access to subsurface mineral rights and pore space, and could offer economies of scale relative to site preparation, number of wells to be drilled and logistics. Finally, the availability of multiple storage options in a given area allows an operator to tailor its underground storage portfolio to suit its business needs, financial position and any potential environmental safety concerns.

## 5.3 Field-Level Prospects

The Research Team has identified three storage prospects in the AOI that contain top-rated geologic intervals/reservoirs and exhibit varying degrees of stacked potential. The blue circles outlining these areas each have a radius of 20 mi (Figure 5-2). These prospects have been identified by general geographic area – northern, central and southern –and are discussed in the following sections as examples of how end users may apply the subsurface geologic and reservoir data prepared for the current Study to their own underground storage considerations.

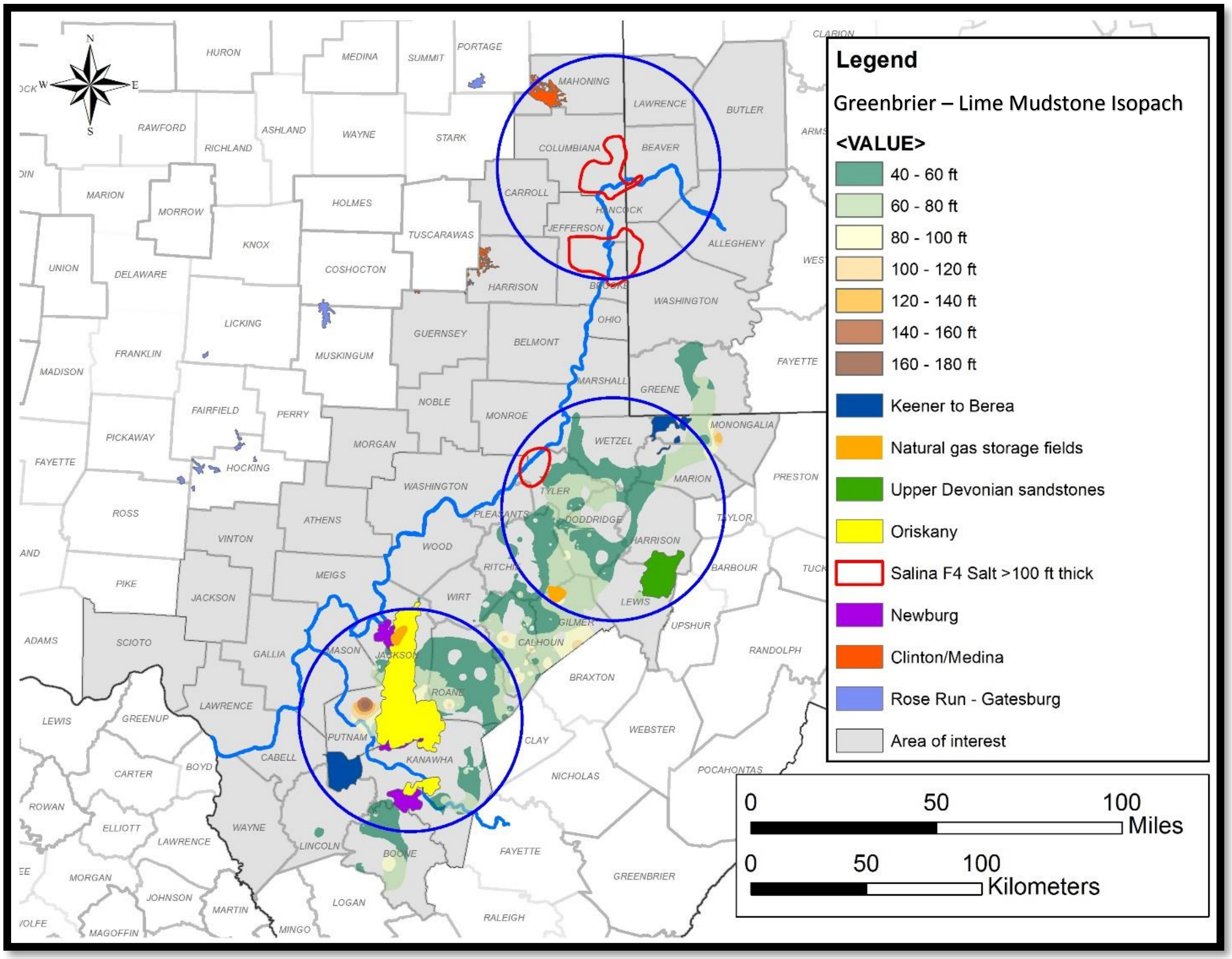



**Figure 5-2. Three prospects evaluated using reservoir characterization data prepared for this Study.**

### 5.3.1 Northern Prospect

The Northern Prospect encompasses the northern panhandle of West Virginia and adjacent portions of eastern Ohio and western Pennsylvania, presenting storage opportunities (Figure 5-3) in Clinton/Medina sandstones in Ohio's Ravenna-Best Consolidated Field and two Salina F4 Salt cavern opportunities straddling the Ohio River. In addition, Oriskany Sandstone core data from Beaver County, Pennsylvania, can be extrapolated to, and used to aid in the evaluation of, Oriskany fields of specific interest to the operator.

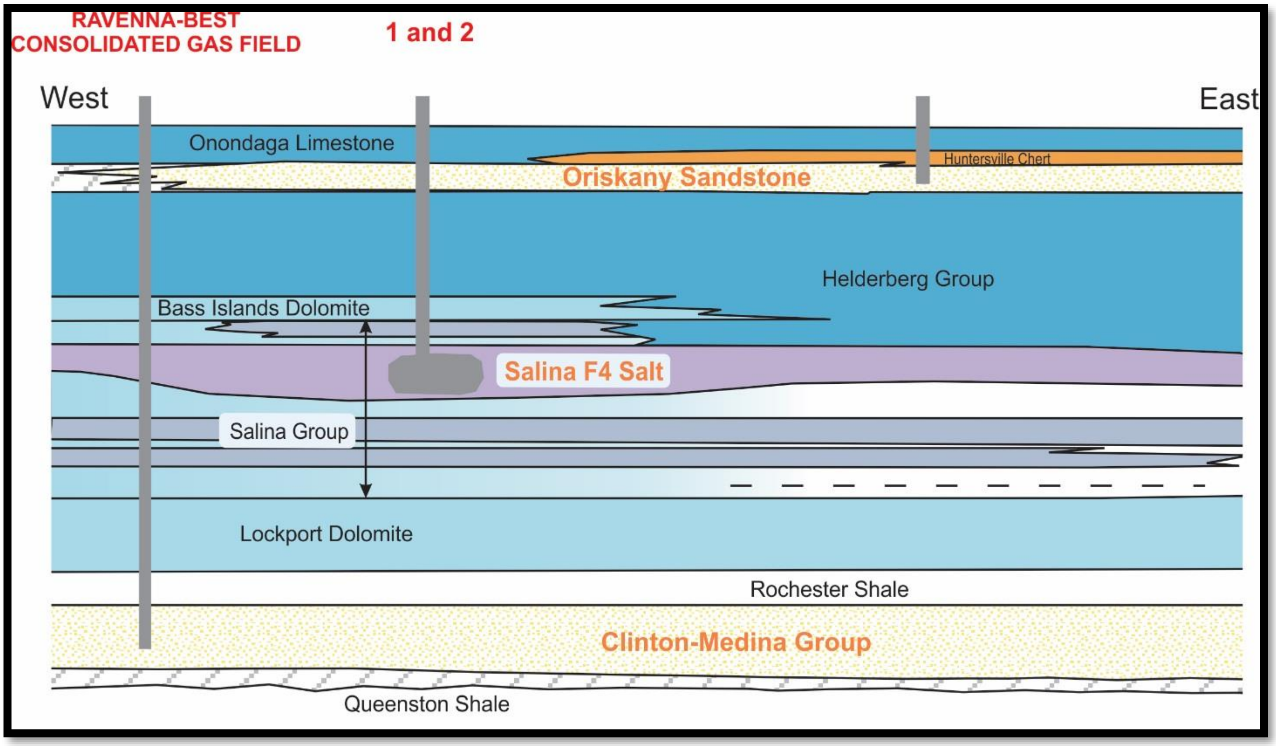



**Figure 5-3. Cartoon of the subsurface geology associated with the Northern Prospect, which has three storage opportunities (generalized and not to scale).**

##### *5.3.1.1 Oriskany Sandstone Interval*

The Oriskany Sandstone has been produced in the Ohio portion of the Northern Prospect and tested in the Pennsylvania portion of the prospect area. Even though the current Study did not rate any Oriskany gas fields high enough to warrant mention here, core-derived laboratory analytical data obtained from a well in Beaver County, Pennsylvania, suggest that an operator considering this prospect area for underground storage options should include this geologic interval as part of any site-specific investigation.

As presented in Chapter 3, the Oriskany Sandstone persists throughout most of the AOI. In the Northern Prospect area, it's shallowest in the northwest (-2,500 ft MSL) and deepens toward the southeast (-6,500 ft MSL) (Figure 5-4a), with gross thicknesses ranging from 0 to 70 ft or more (Figure 5-4b).

The Research Team prepared an Oriskany measured depth map for the Northern Prospect area to illustrate the wide range of depths at which this unit occurs here (i.e., approximately 3,000 – 7,000 ft) (Figure 5-5).

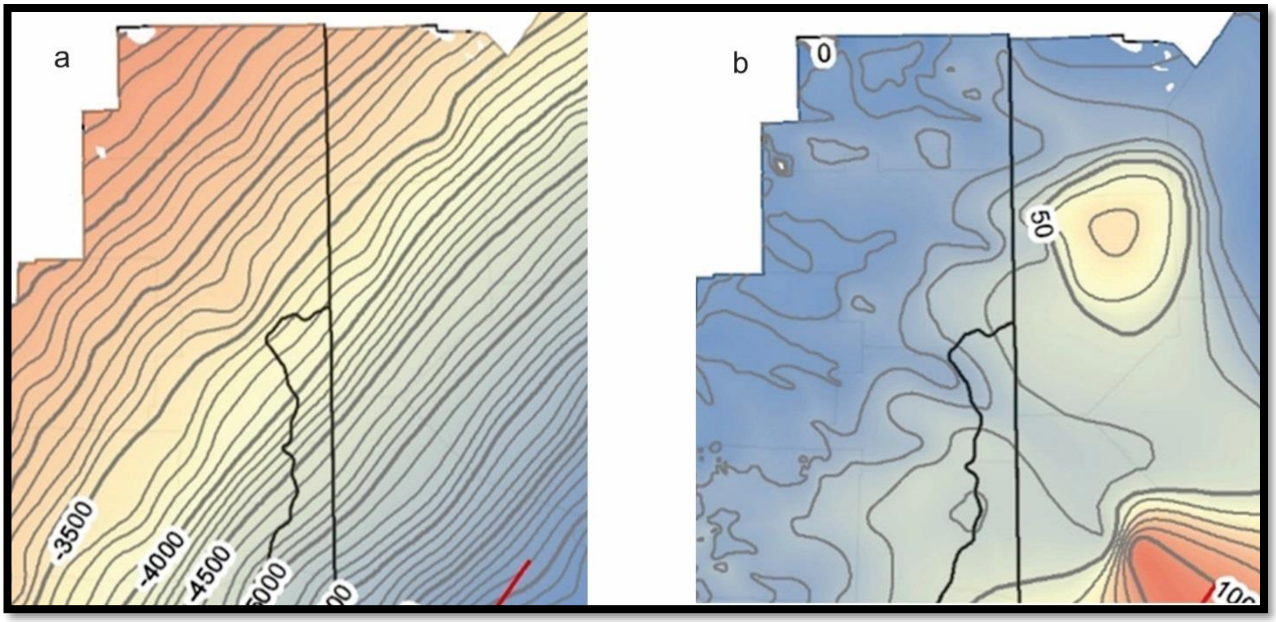



**Figure 5-4. Regional structure (ft MSL) and gross thickness (ft) maps of the Oriskany Sandstone in the Northern Prospect (excerpted from Figures 3-15 and 3-16).**

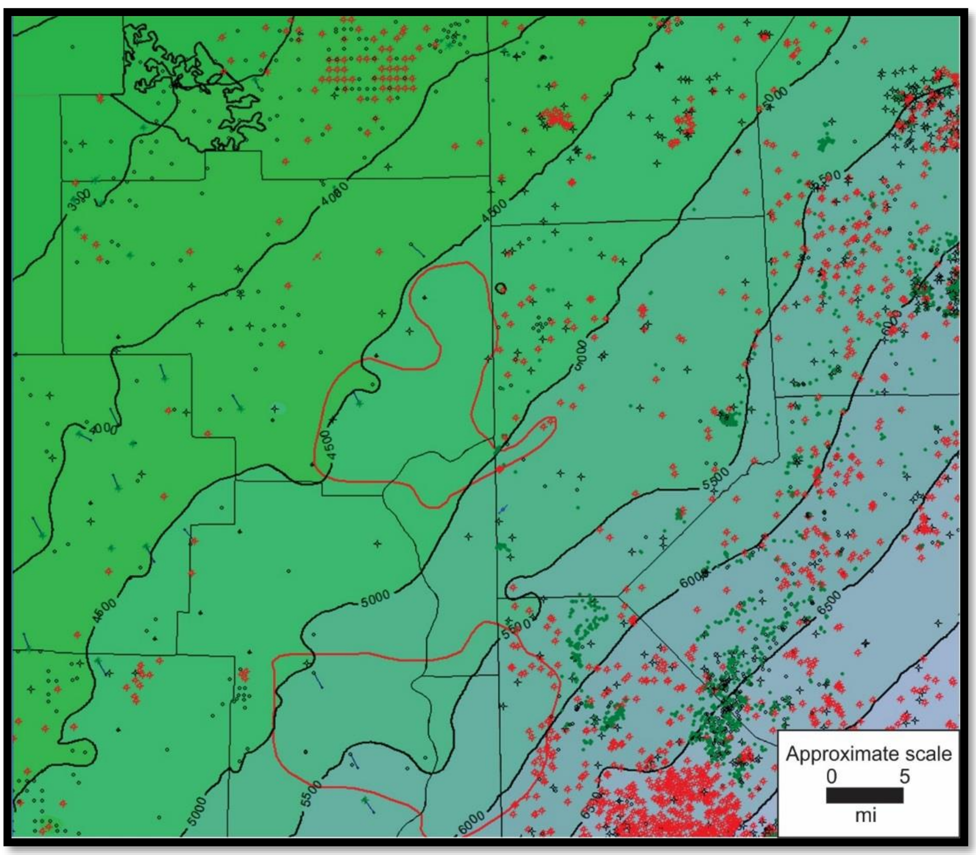



**Figure 5-5. Contour map on top of the Oriskany Sandstone (depth below ground surface in ft) in the Northern Prospect. The color-ramped grid varies from green (shallow) to purple (deep), and the contour interval is 500 ft.**

Oriskany Sandstone core data are available from a wastewater well drilled in the early 1960s (API No. 37-007-00007) in Beaver County, Pennsylvania. Figure 5-6 presents a capillary pressure curve from a sidewall core sample taken at 5,404 ft depth. This curve plots percent water saturation versus mercury capillary pressure values to provide insight as to how well the pore space in the sample is interconnected by way of pore throats. Here, the curve indicates good interconnectivity because the pore throats are very well sorted. The porosity and permeability of the Oriskany in this sample was 7.9 percent and 8.35 mD, respectively.

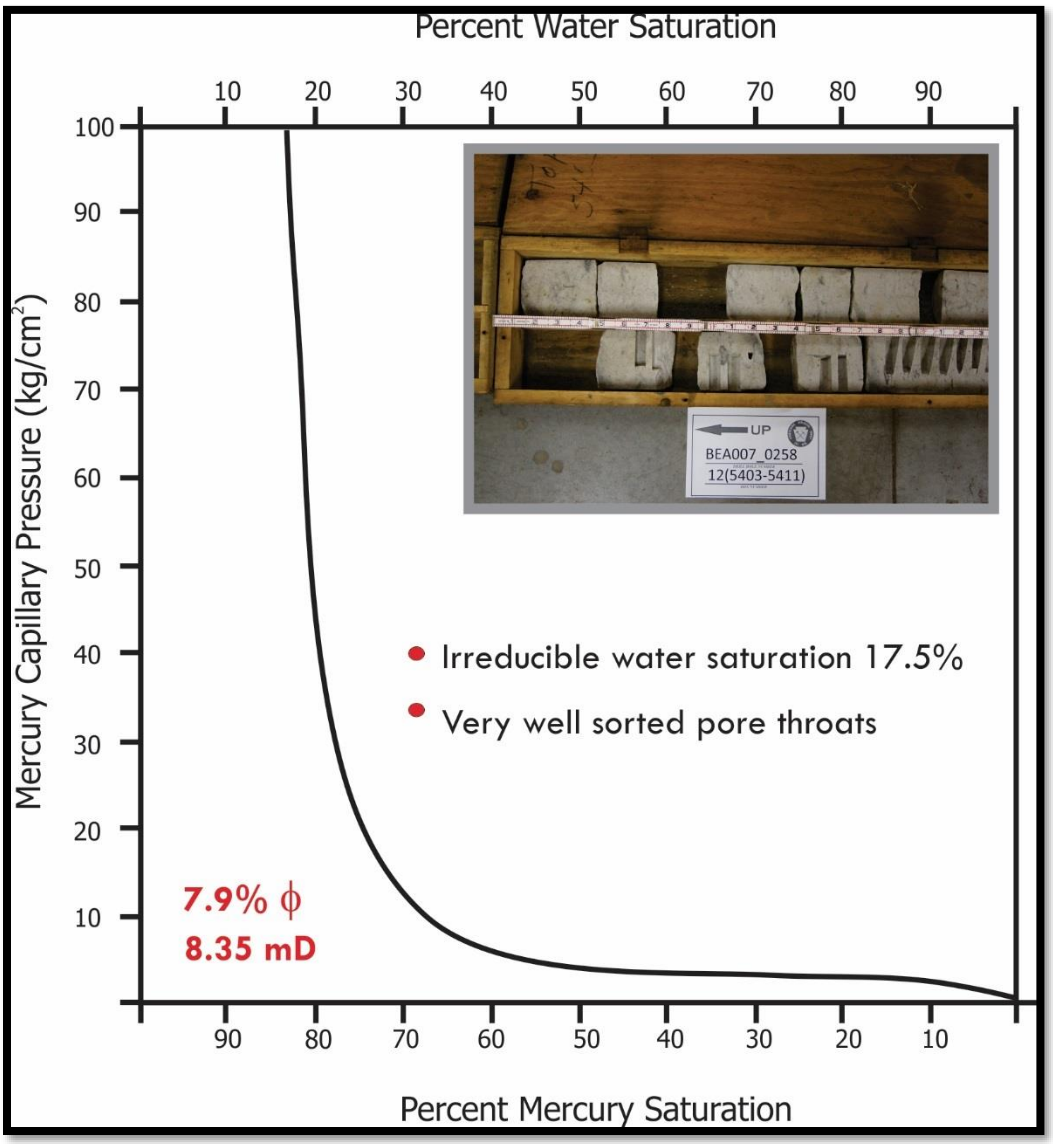



**Figure 5-6. Capillary pressure curve for the Oriskany Sandstone at 5,404 ft in the Jones & Laughlin #1 (API No. 37-007-00007).**

Figures 5-7 and 5-8 plot porosity versus depth and porosity vs. permeability, respectively, based on the entire laboratory-analytical dataset for the Jones & Laughlin #1 core (Appendix G). Figure 5-7 illustrates that higher porosities are associated with the Oriskany Sandstone than the overlying Huntersville Chert, so the chert may act as a partial seal above the sandstone in this area of the AOI. Figure 5-8 illustrates that the highest permeabilities in the Oriskany Sandstone at this location are associated with porosities greater than 4 percent.

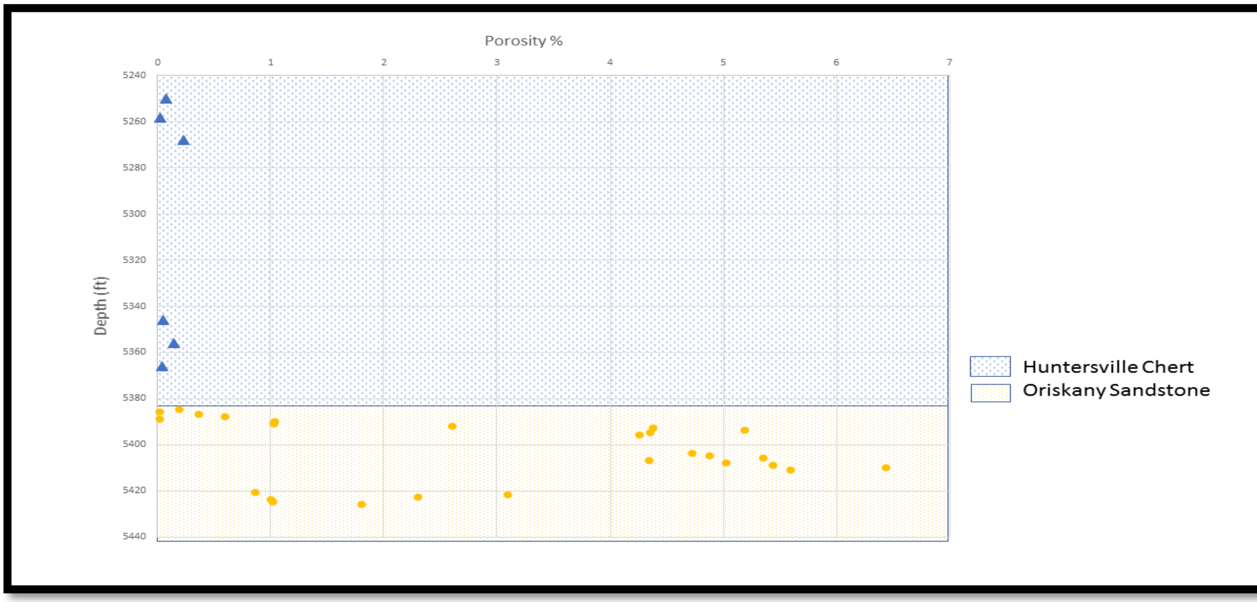



**Figure 5-7. Porosity vs. depth plot for the Jones & Laughlin #1 (API No. 37-007-00007).**

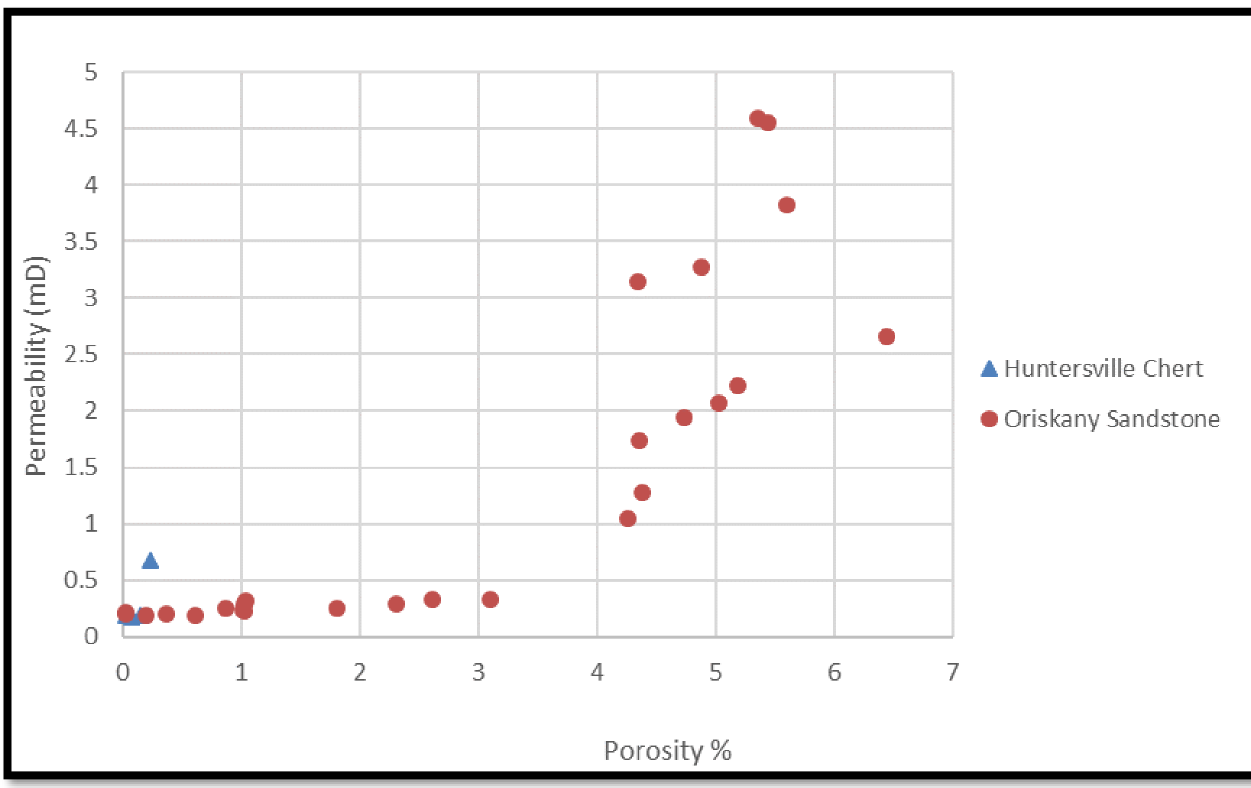



**Figure 5-8. Porosity vs. permeability plot for the Jones & Laughlin #1 (API No. 37-007-00007).**

### *5.3.1.2 Salina F4 Salt Interval: Salt Caverns*

The F4 Salt within the Salina Group has been identified as the preferred interval for salt cavern storage, where the pure salt exceeds 100 ft in thickness. There are two such thick areas in the Northern Prospect, illustrated in Figures 5-9 and 5-10.

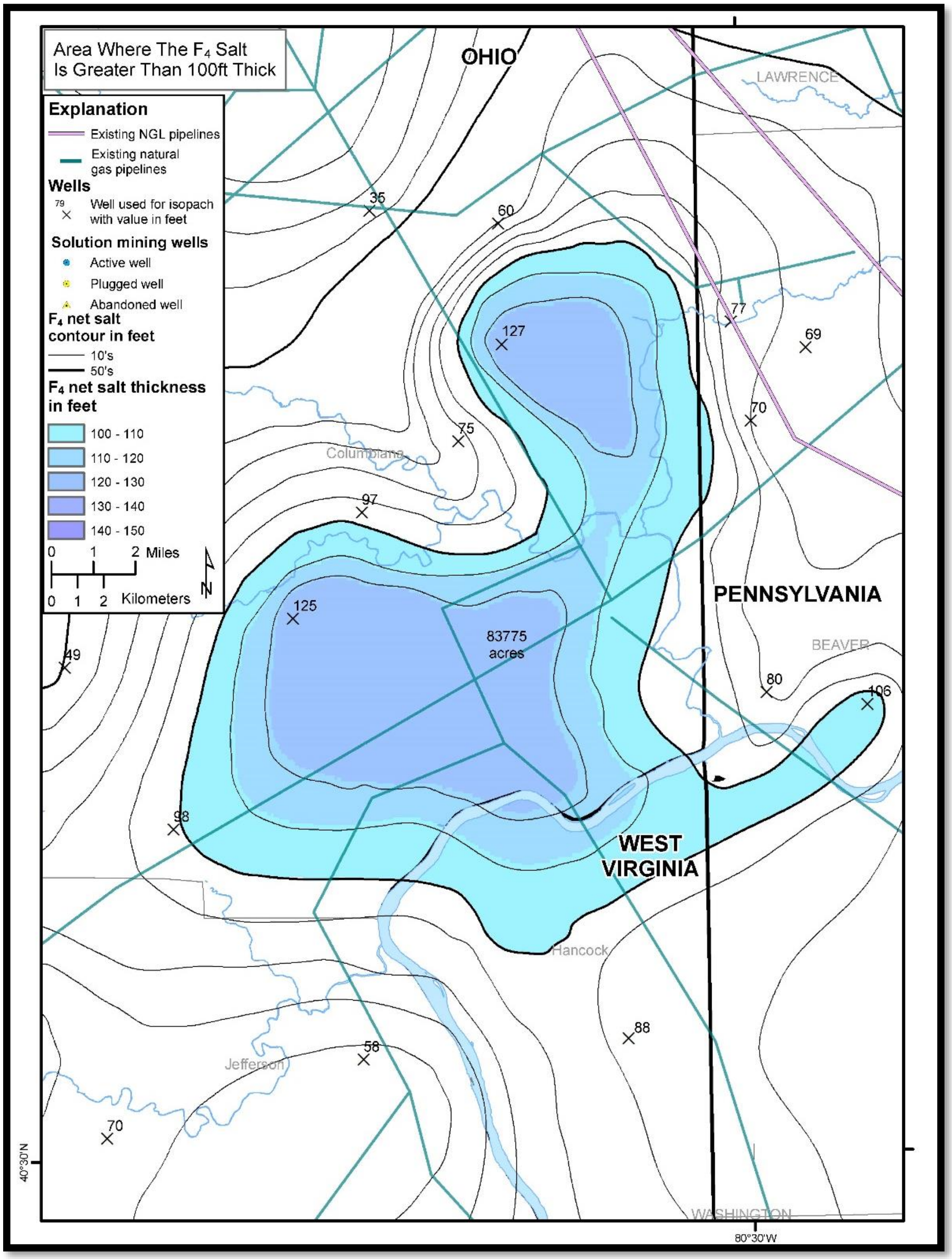



**Figure 5-9. Area 1 of the Northern Prospect, where the Salina F4 Salt is greater than 100 ft thick.**

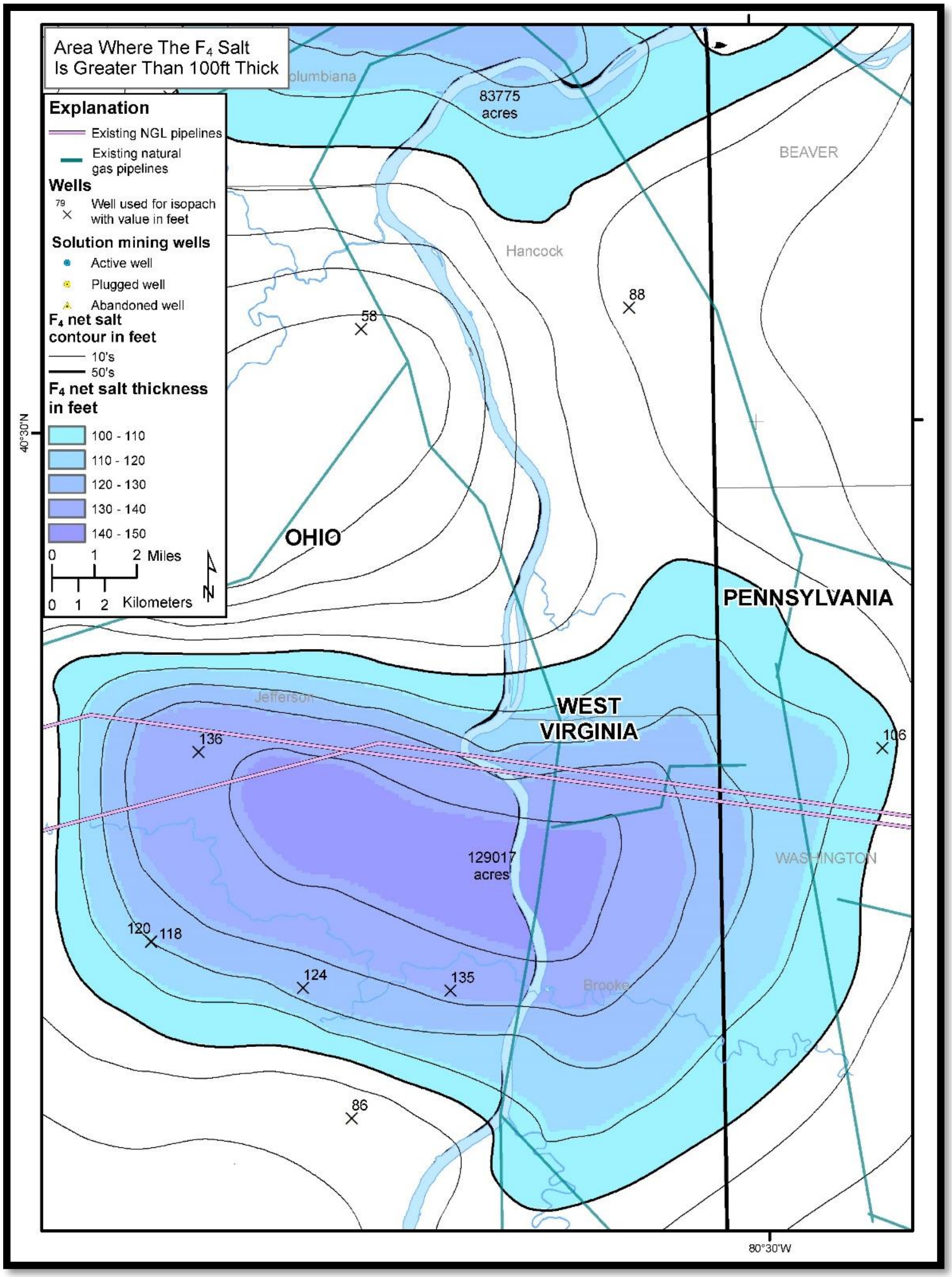



**Figure 5-10. Area 2 of the Northern Prospect, where the Salina F4 Salt is greater than 100 ft thick.**

The Research Team prepared cross sections through each of these areas along dip (i.e., west to east; Figure 5-11).

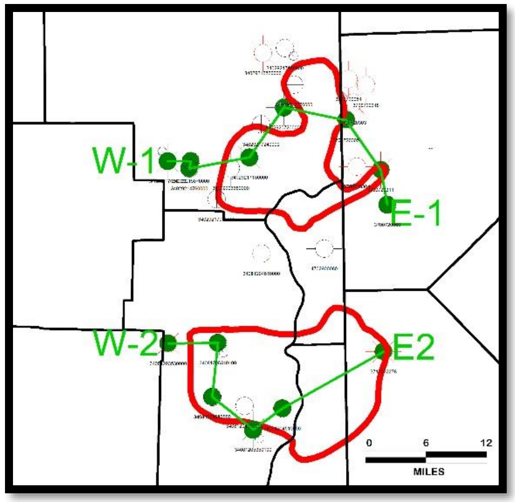



**Figure 5-11. Location of cross sections through the Salina F4 Salt along dip in the Northern Prospect.**

Cross sections are hung on top of the Salina E unit below the F salts to best illustrate areas of greatest thickening in the F4 Salt. In each area, the main F4 Salt is separated from underlying salt by a persistent layer of anhydrite and dolomite. Figures 5-12 and 5-13 show the subsurface geology through Areas 1 and 2, respectively. While several wells in the heart of each area have a solid thickness of salt, some wells do have occasional thin layers of interbedded anhydrite or dolomite of which the operator should be aware. The interbedded nature of the salt becomes more prevalent toward the margin of the salt just outside the areas' footprints, where the anhydrite and dolomite beds can increase rapidly, so it is best to stay well within the border of each footprint.

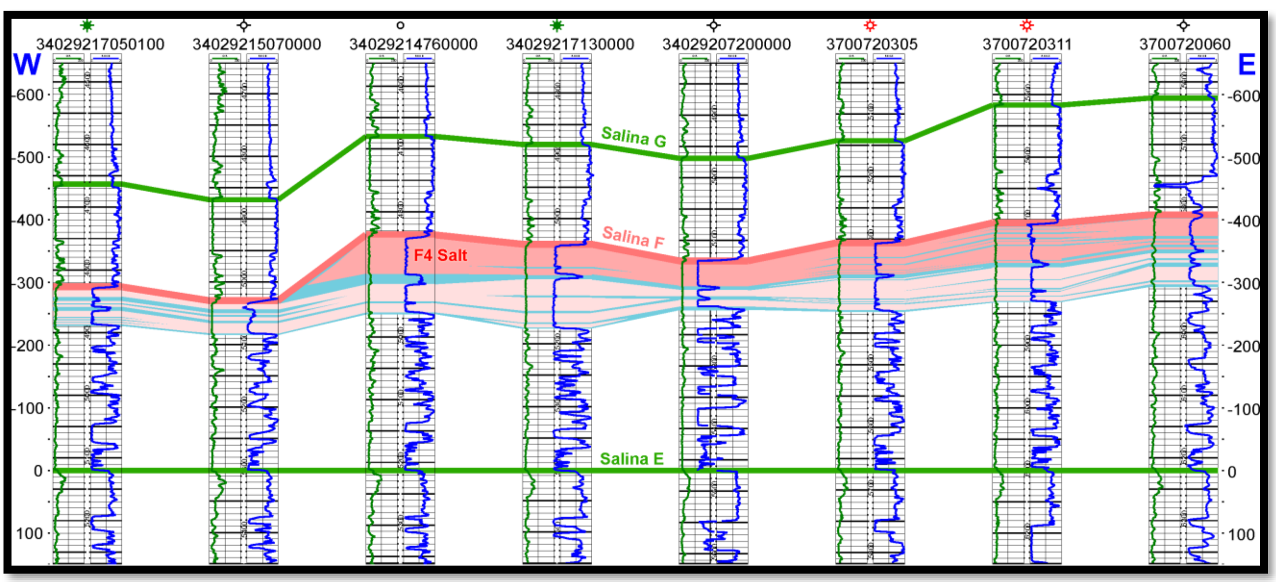



**Figure 5-12. Area 1 cross section through Salina F4 Salt (salmon). F4 Salt is separated from underlying salt beds (light pink) by calcareous interbeds (blue).**

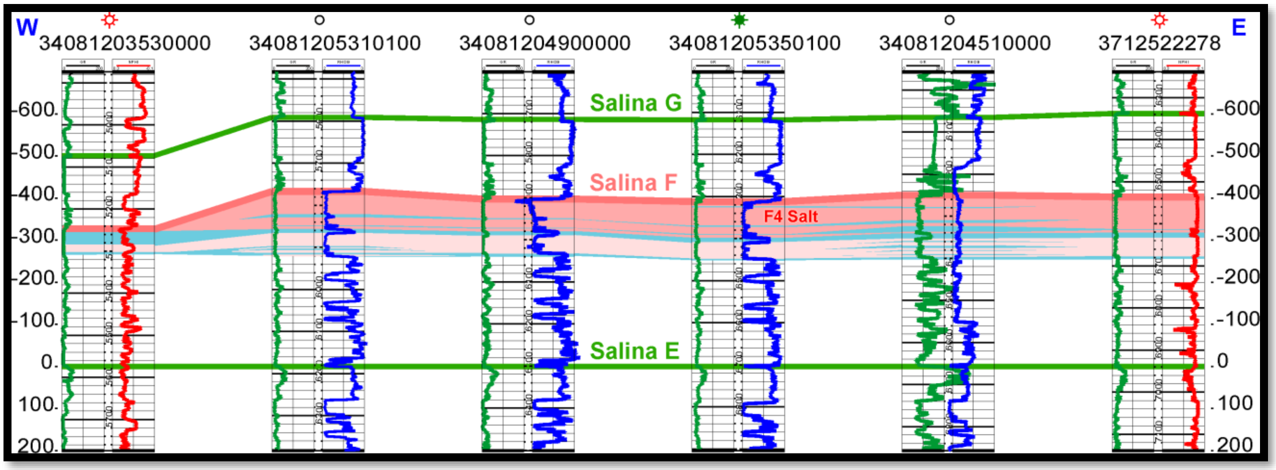



**Figure 5-13. Area 2 cross section through Salina F4 Salina Salt (salmon). F4 Salt is separated from underlying salt beds (light pink) by calcareous interbeds (blue).**

### *5.3.1.3 Clinton/Medina Group Interval: Depleted Gas Field*

The Ravenna-Best Consolidated Field is located just within the northwestern boundary of the Northern Prospect (Figure 5-2) in Ohio, and has produced from the fluvial-deltaic sandstones of the Clinton/Medina Group. Although the play is considered primarily stratigraphic, localized structure has been shown to influence gas production. Production mapping in the Ravenna-Best Consolidated Field shows trends of wells averaging more than 20 million cubic feet (MMCF) gas, roughly parallel to the East Ohio fault system, with two wells reporting more than 1 BCF gas (McCormac and others, 1996).

Maps prepared by the Research Team show that the top of the Clinton/Medina Group ranges from about 4,100 to 6,300 ft below ground surface (Figure 5-14), and that net sandstone thicknesses range from 25 to about 160 ft (Figure 5-15).

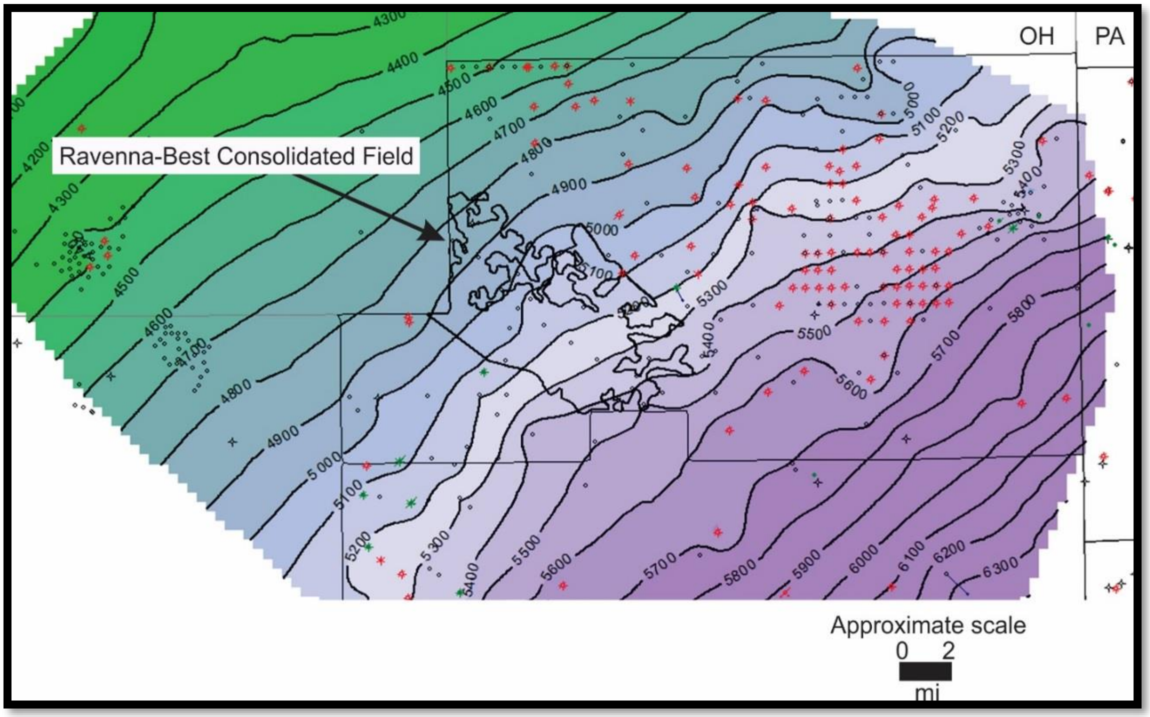



**Figure 5-14. Contour map on top of the Clinton/Medina Group (depth below ground surface in ft) in Ravenna-Best Consolidated Field (black outline). The color-ramped grid varies from green (shallow) to purple (deep), and the contour interval is 100 ft.**

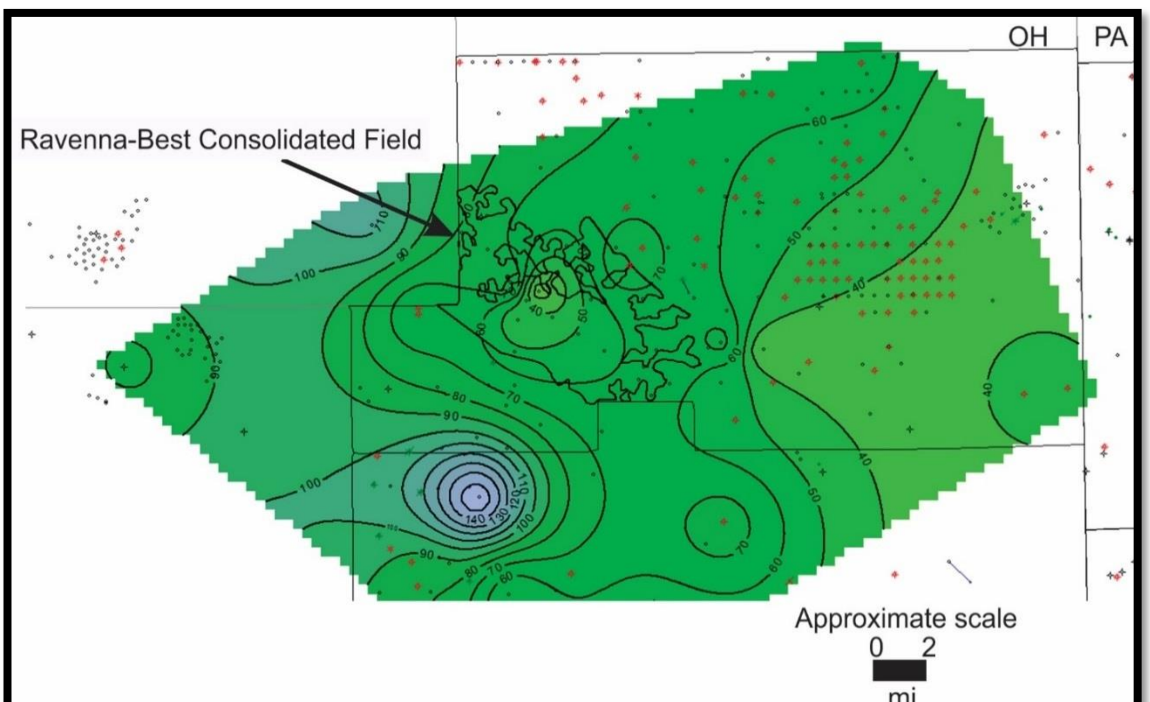



**Figure 5-15. Net thickness map of the Clinton/Medina Group in the Ravenna-Best Consolidated Field (black outline). The color-ramped grid varies from green (thin areas) to purple (thick areas), and the contour interval is 10 ft.**

Field-specific reservoir data were prepared for these fields by compiling pre-existing MRCSP GIS field-level data and interpreting downhole geophysical log data for the Clinton/Medina interval using IHS PETRA® software for the current Study. These data are provided in Tables 5-2 and 5-3, respectively.

***Table 5-2. Ravenna-Best Consolidated field-level reservoir data (MRCSP GIS database).***

| Average producing depth (ft) | Net thickness (ft) | Pressure (psi) | Porosity (%) | Initial pressure (psi) | Trap type |
|---|---|---|---|---|---|
| 4,850 | 40 | 1,500 | 8.3 | 2,100 | Stratigraphic |

***Table 5-3. Reservoir data prepared for the Ravenna-Best Consolidated Field as part of the current Study.***

| Values | Depth (ft) | Gross thickness (ft) | Net thickness (ft) | Average neutron porosity (%) |
|---|---|---|---|---|
| Minimum | 4,107 | 116 | 25 | 2.0 |
| Maximum | 6,497 | 226 | 156 | 3.6 |
| Average | 5,264 | 178 | 67 | 3.0 |

Based on reservoir data for this field, the Clinton/Medina Group occurs at optimal depths for NGL storage (in the 3,500 – 5,000 ft range), has a sizeable footprint (nearly 69,000 ac) and is within five mi of proposed/existing infrastructure. In addition, the sandstones of this interval have an average net thickness of 40 to 76 ft, with reservoir pressures between 1,500 and 2,100 psi and porosities ranging from 2 to 8.3 percent (depending on the data source consulted). The relatively wide range in porosities should not dissuade an operator from considering the Ravenna-Best Consolidated Field for storage opportunities, as it is commonly reported by industry that the Clinton/Medina Group can be a reliable (and large) producer, given the proper treatment and stimulation techniques. As an example, the Ravenna-Best Consolidated Field had produced nearly 33.5 BCF gas by 1996 (Roen and Walker, 1996) even though the porosity values calculated for this Study did not exceed 4 percent. Finally, this field offers stacked opportunities with both the Oriskany Sandstone and Salina F4 Salt, which were discussed earlier in this section.

The Ravenna-Best Consolidated Field received low to poor (i.e., 0-1) ratings for well penetrations and trap integrity. In this portion of eastern Ohio, there has been much oil and gas production (both conventional and unconventional) over the past few decades, which means that site-specific reconnaissance and detailed site preparation will be a must for this prospect. The poor trap integrity rating for this field is due to the fact that Clinton/Medina Group production has occurred beyond the boundaries of this field, with little to no documentation as to where the stratigraphic and/or localized structural trapping limits may occur. Figure 5-16 provides a generalized cross section through this field to illustrate subsurface stratigraphy and the persistent nature of Clinton/Medina sandstones here.

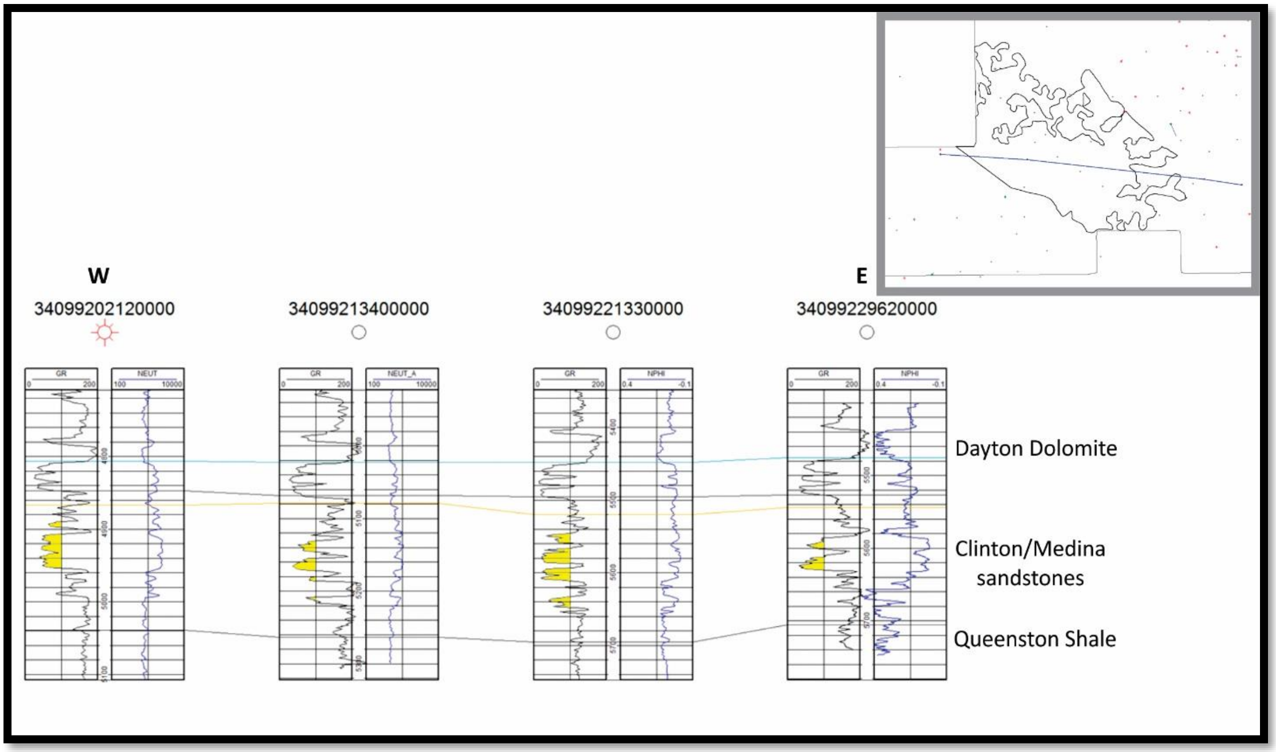



**Figure 5-16. West-east cross section through the central portion of Ravenna-Best Consolidated Field, hung on the Dayton Dolomite.**

### 5.3.2 Central Prospect

The Central Prospect encompasses portions of southeastern Ohio, southwestern Pennsylvania and north-central West Virginia (Figure 5-2) and contains multiple storage opportunities, five of which are presented below: Greenbrier Limestone mined-rock cavern options throughout the area; depleted gas reservoirs in the Keener to Berea interval in and between the Maple-Wadestown and Condit-Ragtown fields; a depleted gas reservoir in the Upper Devonian Venango Group in the Racket-Newberne (Sinking Creek) gas storage field; depleted gas reservoirs in in Upper Devonian sandstones in the Weston-Jane Lew Field; and a Salina F4 Salt opportunity near Ben's Run (Figure 5-17).

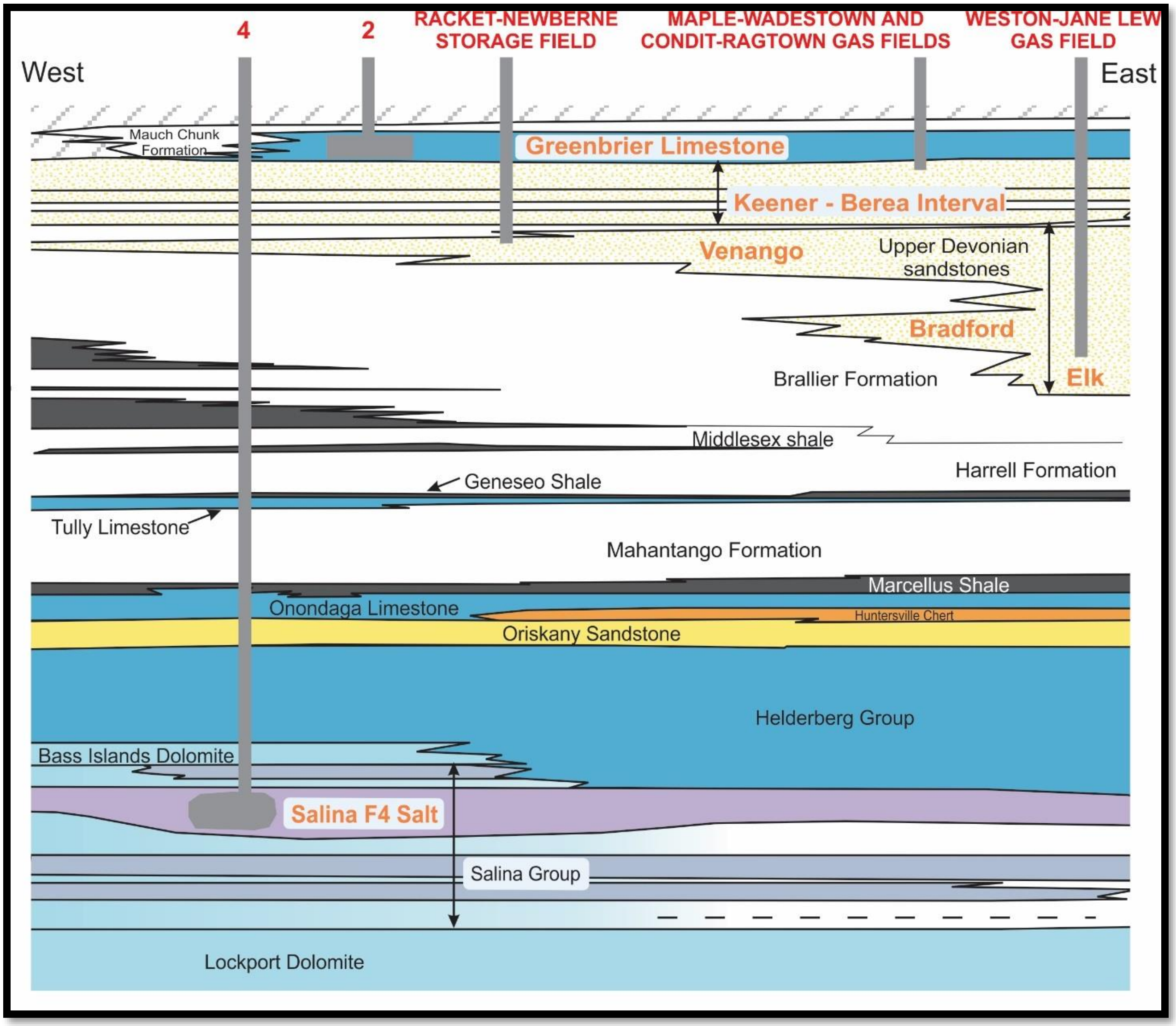



**Figure 5-17. Cartoon of the subsurface geology associated with the Central Prospect, where five storage opportunities have been identified (generalized and not to scale).**

### *5.3.2.1 Greenbrier Limestone Interval: Mined-Rock Caverns*

The lime mudstone facies of the Greenbrier Limestone, identified as the preferred interval to mine for underground NGL storage, has been mapped throughout the West Virginia portion of the Central Prospect area in thicknesses ranging from 40 to 60 ft (dark green) to 60 to 80 ft (light green) within the depth interval of 1,800 – 2,000 ft (Figure 5-18).

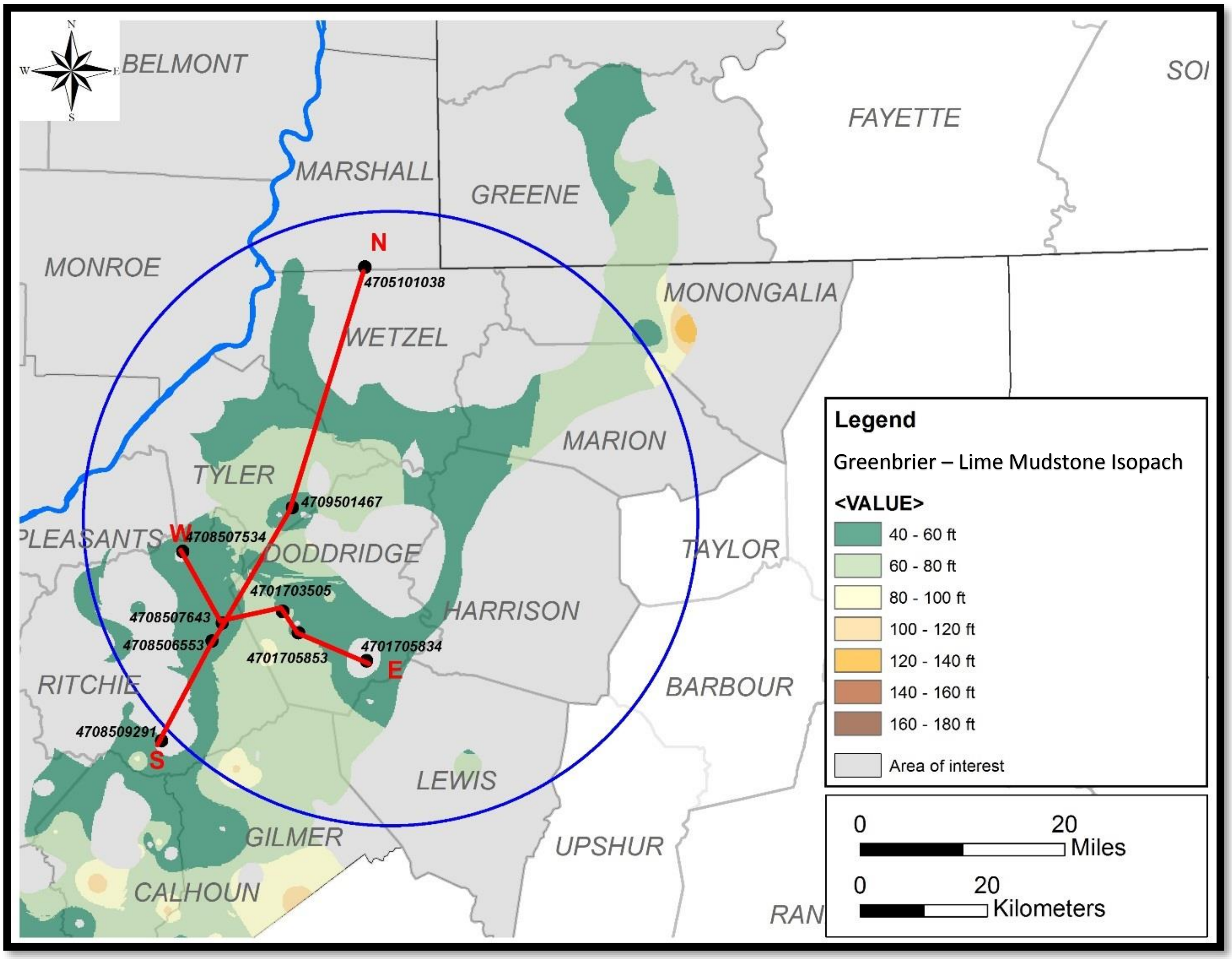



**Figure 5-18. Net thickness map of the Greenbrier's lime mudstone facies in the Central Prospect. Red lines indicate cross section locations through the Greenbrier interval for the Central Prospect.**

Not only does the Greenbrier exist at optimal depths and thicknesses here, it has a relatively large footprint (>300,000 ac) and is very close to the Ohio River and proposed/existing infrastructure (in some places, less than 5 mi away). In addition, it rated high as a stacked opportunity, because at least four other geologic intervals occupy the same general area as the Greenbrier in this prospect.

The only criteria for which the Greenbrier Limestone interval received poor ratings (i.e., 0) were for well penetrations and trap integrity. North-central West Virginia is home to thousands of existing, abandoned and/or plugged oil and gas wells, so preparing a site to develop mined-rock caverns here will require site-specific reconnaissance and detailed site preparation. As for trap integrity, the downhole geophysical log data used by the Research Team to delineate the depth and thickness of grainstone and mudstone facies in the Greenbrier was relatively limited throughout the tri-state area (265 locations for the entire AOI). Geologic cross sections, presented below, are used as a means of illustrating the concept of trap integrity.

Two geologic cross sections were prepared using geophysical logs and subsurface Greenbrier facies tops data to illustrate the varying thickness of mudstone (dark blue) from north to south and west to east (Figures 5-19 and 5-20, respectively). Also displayed in these sections are the upper and lower grainstone facies (light blue) that bound the mudstone in the Greenbrier Limestone interval. The GR, RHOB and Pe log curves were utilized to delineate the depths and thicknesses of these facies, with the Pe curves (shown in red) providing essential lithologic data control to pick these tops. As presented in Section 4.1, the best areas for mining a cavern from the Greenbrier's lime mudstone facies will be found where the lime mudstone facies is relatively thick and juxtaposed between upper and lower grainstone facies with bound water and water-filled porosity, which will assure hydraulic containment of stored NGLs.

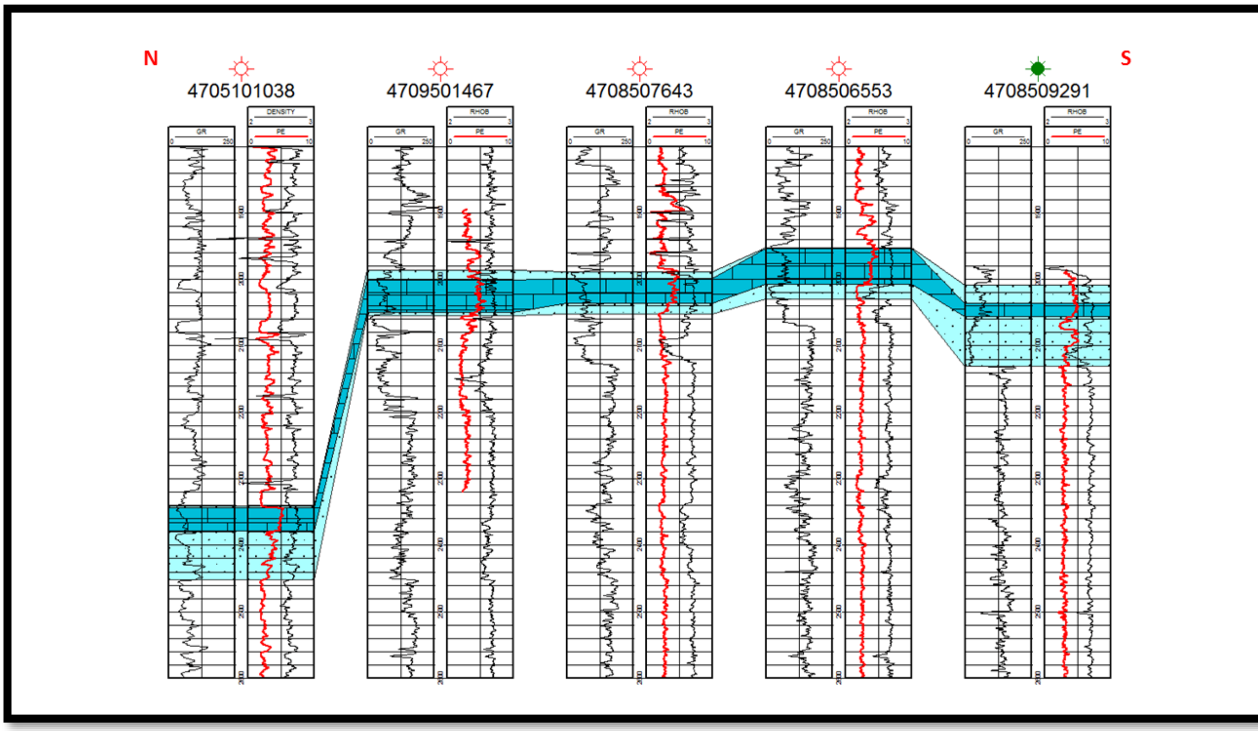



**Figure 5-19. North-south geologic cross section through the Greenbrier Limestone interval in the Central Prospect.**

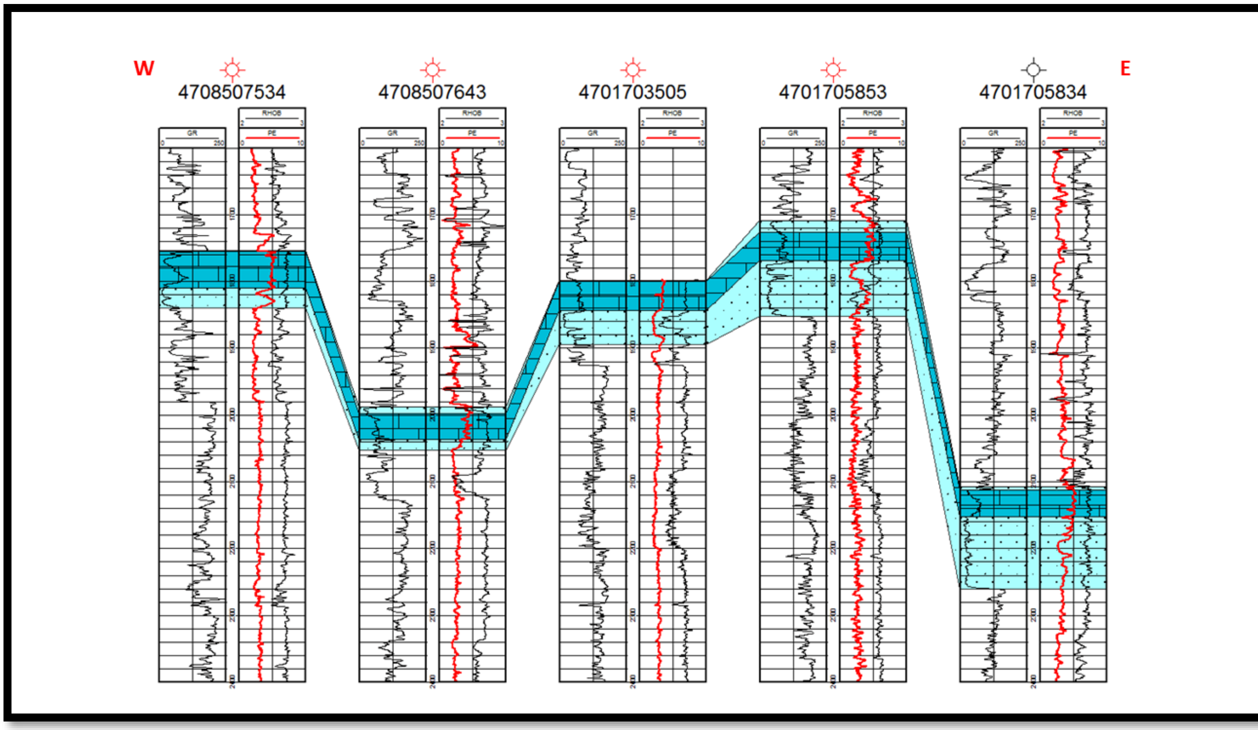



**Figure 5-20. West-east geologic cross section through the Greenbrier Limestone interval in the Central Prospect.**

### *5.3.2.2 Keener to Berea Interval: Depleted Gas Fields*

The Maple-Wadestown and Condit-Ragtown fields, which skirt the Mason-Dixon line in north-central West Virginia, produced gas from sandstones of the Keener to Berea interval (Figure 5-21). Maps prepared by the Research Team show that the top of this interval ranges from about 2,000 to 2,600 ft below ground surface (Figure 5-22), and that net sandstone thicknesses range from approximately 20 to 170 ft as shown in Figure 5-23.

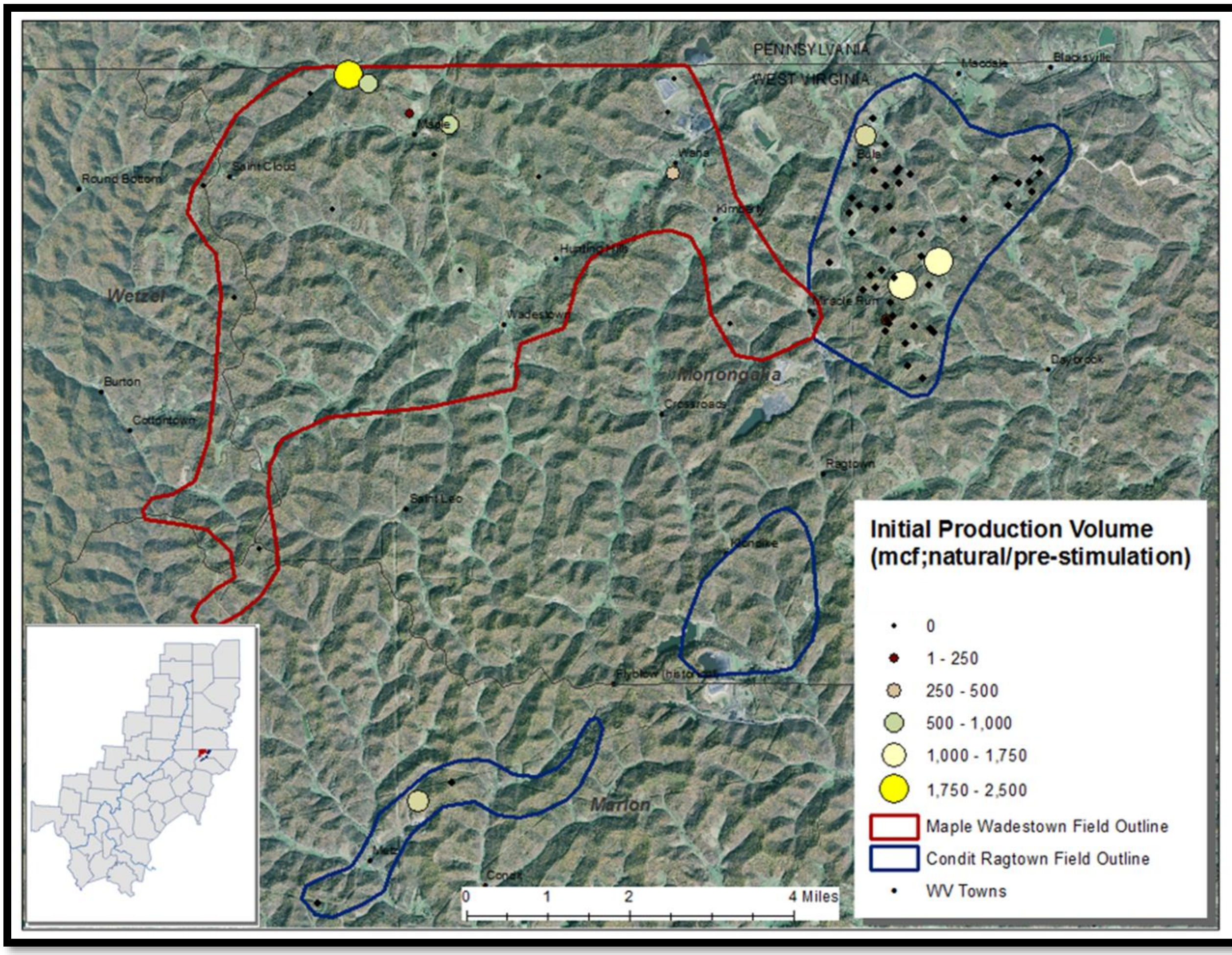



**Figure 5-21. Maple-Wadestown and Condit-Ragtown fields, Initial gas production (MCF) natural/pre-stimulation.**

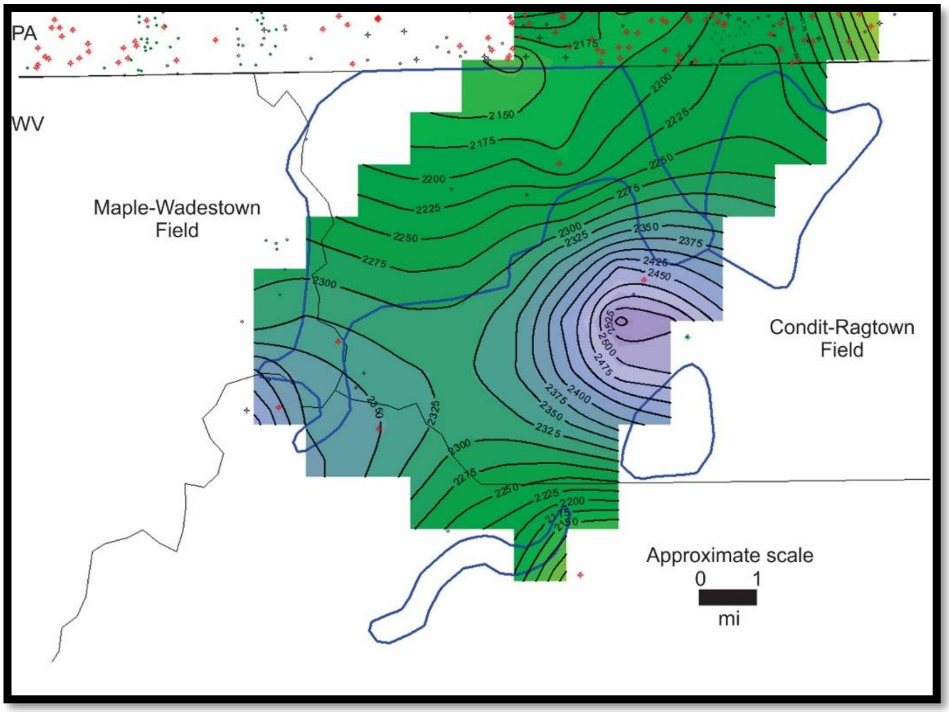



**Figure 5-22. Contour map on top of the Keener to Berea interval (depth below ground surface in ft) in the Maple-Wadestown/Condit-Ragtown fields area (blue outlines). The color-ramped grid varies from green (shallow) to purple (deep), and the contour interval is 25 ft.**

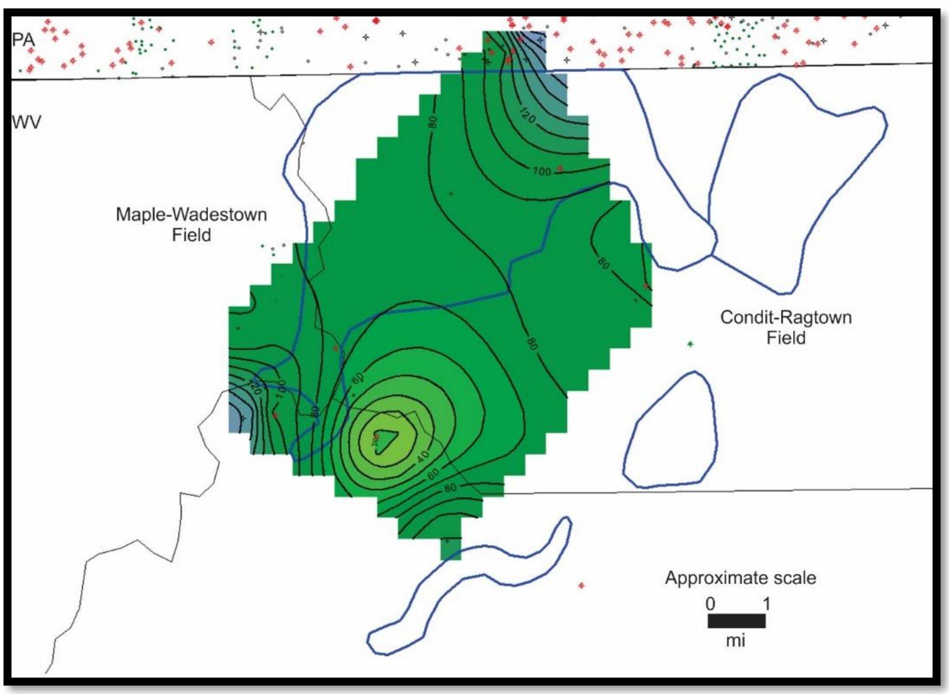



**Figure 5-23. Net thickness map of the Keener to Berea interval in the Maple-Wadestown/Condit-Ragtown fields area (blue outlines). The color-ramped grid varies from green (thin areas) to purple (thick areas), and the contour interval is 10 ft.**

Reservoir data were prepared for these fields by compiling pre-existing MRCSP GIS field-level data and interpreting downhole geophysical log data for the Keener to Berea interval using IHS PETRA® software for the current Study. Tables 5-4 and 5-5 provide this information.

***Table 5-4. Maple-Wadestown and Condit-Ragtown field-level reservoir data (MRCSP GIS database).***

| Field | Average producing depth (ft) | Net thickness (ft) | Pressure (psi) | Porosity (%) | Initial pressure (psi) | Trap type |
|---|---|---|---|---|---|---|
| Maple-Wadestown | 2,345 | 47 | 1,000 | 11.0 | 1,015 | Stratigraphic |
| Condit-Ragtown | 2,035 | 25 | 1,000 | 17.6 | 881 | Structural/ Stratigraphic |

***Table 5-5. Reservoir data prepared for the Maple-Wadestown and Condit-Ragtown fields and immediate vicinity as part of the current Study.***

| Values | Depth (ft) | Gross thickness (ft) | Net thickness (ft) | Average density porosity (%) | Average neutron porosity (%) |
|---|---|---|---|---|---|
| Minimum | 1,988 | 420 | 17 | 4.0 | 5.0 |
| Maximum | 2,595 | 546 | 170 | 9.0 | 7.0 |
| Average | 2,253 | 498 | 99 | 6.0 | 6.0 |

Based on these data, the Keener to Berea interval occurs at suitable depths (2,000 – 3,500-ft range), has a large footprint (more than 28,000 ac) in the vicinity of the two fields and is within 20 mi of proposed/existing infrastructure. Furthermore, previous and existing work confirm that the sandstones of this interval are commonly greater than 20 ft thick, with reservoir pressures between 900 and 1,500 psi and porosities ranging from 4 to 18 percent (depending on the data source).

These two Keener to Berea interval fields received low to poor ratings (i.e., 0-1) for well penetrations, trap integrity and stacked opportunities. As stated previously, north-central West Virginia is home to thousands of existing, abandoned and/or plugged oil and gas wells, so preparing a site to develop underground NGL storage will need site-specific reconnaissance and detailed site preparation. The ability to assess trap integrity for the fields was hampered by the lack of penetrations through the interval with adequate downhole geophysical log coverage to compute reservoir parameters. Finally, this part of the Central Prospect offers only the Greenbrier and Keener to Berea intervals as stacked opportunities.

#### *5.3.2.3 Upper Devonian Venango Group: Natural Gas Storage Field*

The Racket-Newberne (Sinking Creek) Field, situated near the southern edge of Central Prospect (Figure 5-2) in West Virginia, is an existing facility storing natural gas in the Gantz sandstone of the Upper Devonian Venango Group. There are many well penetrations in this field, but not all of them are associated with the current gas storage operations (Figure 5-24).

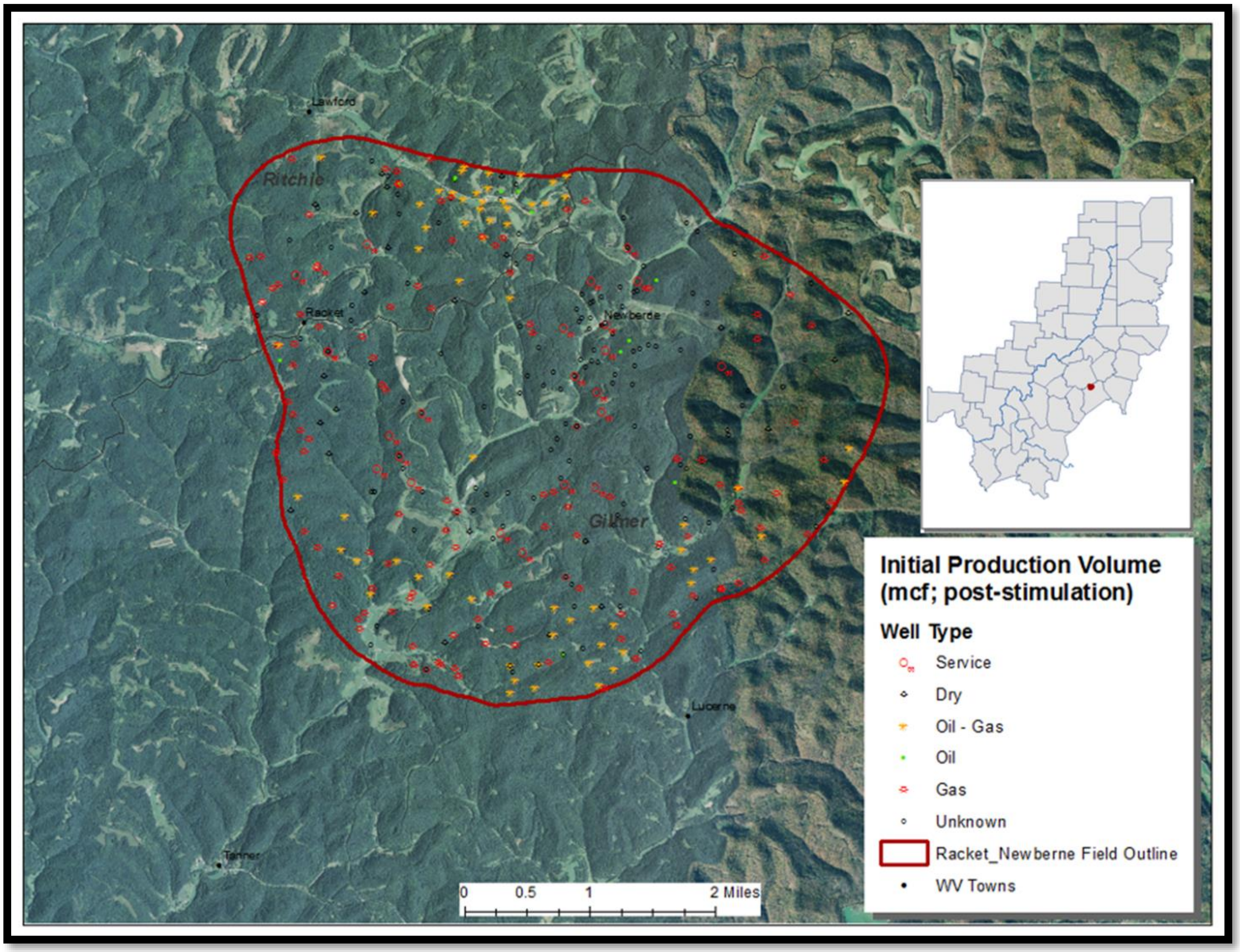



**Figure 5-24. Racket-Newberne (Sinking Creek) Field (existing natural gas storage), with well locations.**

The Research Team had no geophysical log control within the boundary of the Racket-Newberne (Sinking Creek) Field, so no maps of depth or net thickness were prepared for this area. Instead, the Research Team identified a limited number of geophysical logs within a one-mile buffer of the field boundary to calculate field-specific reservoir attribute data, including depth to the top of the Gantz sandstone. Compilation of pre-existing MRCSP GIS data for this field and data interpreted from geophysical logs using IHS PETRA® software for the current Study are provided in Tables 5-6 and 5-7, respectively.

***Table 5-6. Racket-Newberne (Sinking Creek) field-level reservoir data (MRCSP GIS database).***

| Average producing depth (ft) | Net thickness (ft) | Pressure (psi) | Porosity (%) | Initial pressure (psi) | Trap type |
|---|---|---|---|---|---|
| 2,400 | 13 | 1,000 | 8.7 | Not available | Stratigraphic |

***Table 5-7. Reservoir data prepared for the Racket-Newberne (Sinking Creek) Field as part of the current Study.***

| Values | Depth (ft) | Gross thickness (ft) | Net thickness (ft) | Average density porosity (%) | Average neutron porosity (%) |
|---|---|---|---|---|---|
| Minimum | 2,010 | 14 | 4 | 3.0 | 6.0 |
| Maximum | 2,643 | 39 | 20 | 3.0 | 13.0 |
| Average | 2,428 | 23 | 11 | 3.0 | 8.8 |

Based on data prepared for the Study, the Gantz sandstone occurs at suitable depths (in the 2,000-3,500-ft range), has a respectable footprint (approximately 11,000 ac) and is within 20 mi of proposed/existing infrastructure. Previous and existing work confirm that the reservoir pressures, porosities and net sandstone thickness range from 900 to 1,500 psi, 6 to 13 percent and 10 to 20 ft, respectively. This field is also considered a stacked opportunity with the Greenbrier's lime mudstone facies. In addition, there were enough existing subsurface geologic data for this area that the Research Team rated the trap integrity for this field as 2 – inferred lithologic and/or structural closure. The only criterion for which Racket-Newberne (Sinking Creek) Field received a poor rating (i.e., 0) was for well penetrations, a characteristic that is relatively common in this part of the AOI.

#### *5.3.2.4 Upper Devonian Elk Group: Depleted Gas Field*

The Weston-Jane Lew Field is situated near the eastern edge of Central Prospect (Figure 5-2) in West Virginia, and has produced from numerous Upper Devonian Bradford and Elk sandstone/siltstone reservoirs over several decades (Roen and Walker, 1996). There are thousands of well penetrations in this field, and production data provided by the state of West Virginia indicate that many of these experienced initial flows (post-stimulation) in the range of 500 – 1,000 MCF (Figure 5-25).

In this area, most of the Elk Group production originates from the Benson siltstone (Donaldson and others, 1996), which correlates to the E4 interval of the current Study. It also happens to be the largest producing interval in Weston-Jane Lew Field (Table 5-8).

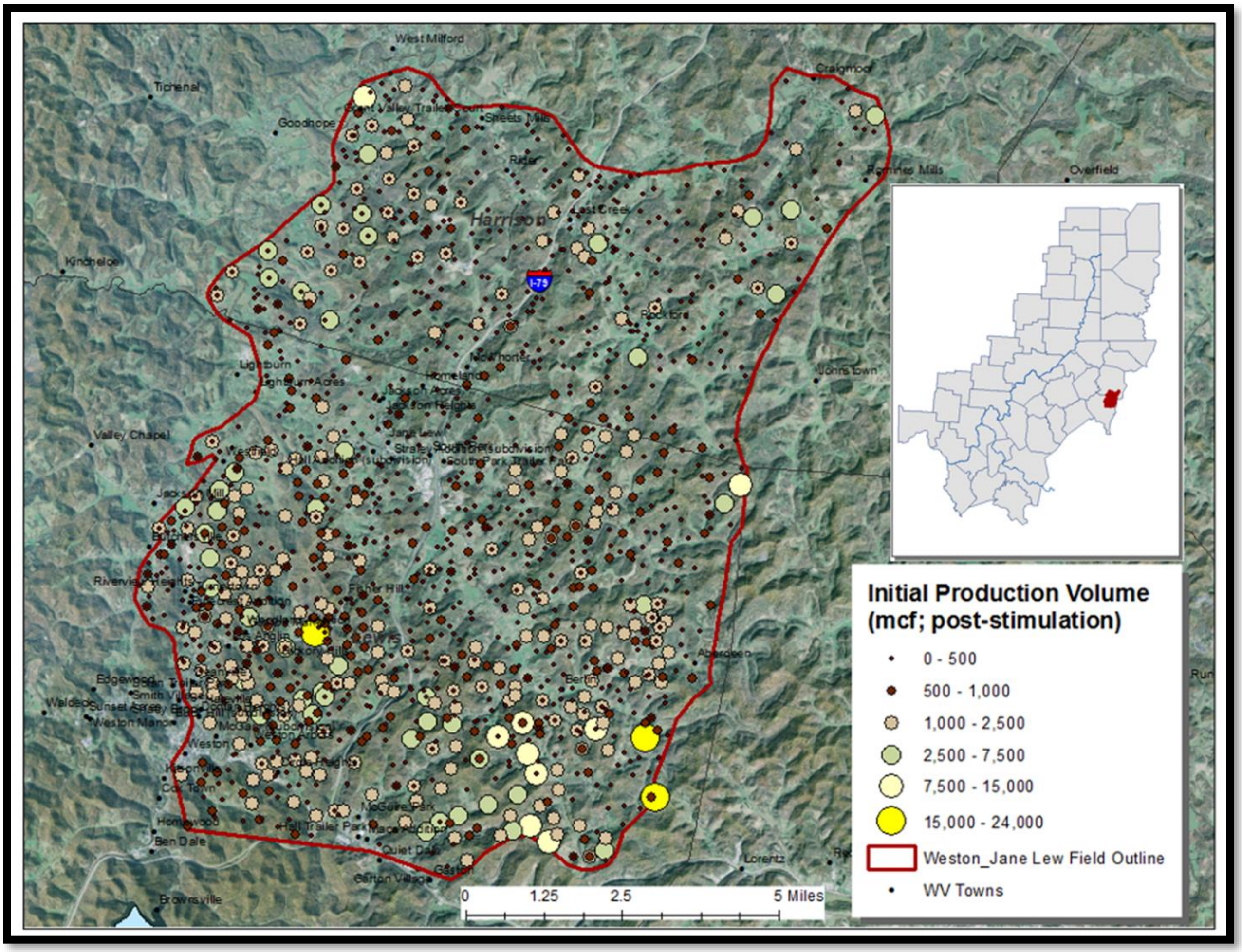



**Figure 5-25. Weston-Jane Lew Field, initial gas production (MCF) post-stimulation.**

***Table 5-8. Production data for specific Bradford- and Elk-producing units in Weston-Jane Lew Field (modified from Roen and Walker, 1996).***

| Geologic Interval | Producing Unit | Cumulative Production (BCF) |
|---|---|---|
| Bradford Group | Speechley | 0.1508 |
| Bradford Group | Balltown | 0.5754 |
| Bradford Group | Bradford | 0.193 |
| Bradford Group | Riley | 0.4432 |
| Elk Group | Benson | 19.743 |
| Elk Group | Alexander | 0.1652 |
| Elk Group | Brallier | 0.1129 |

Maps prepared by the Research Team show that the top of the Benson interval ranges from about 4,000 to 4,900 ft below ground surface (Figure 5-26), and that net thicknesses range from less than 10 to 18 ft, as shown in Figure 5-27.

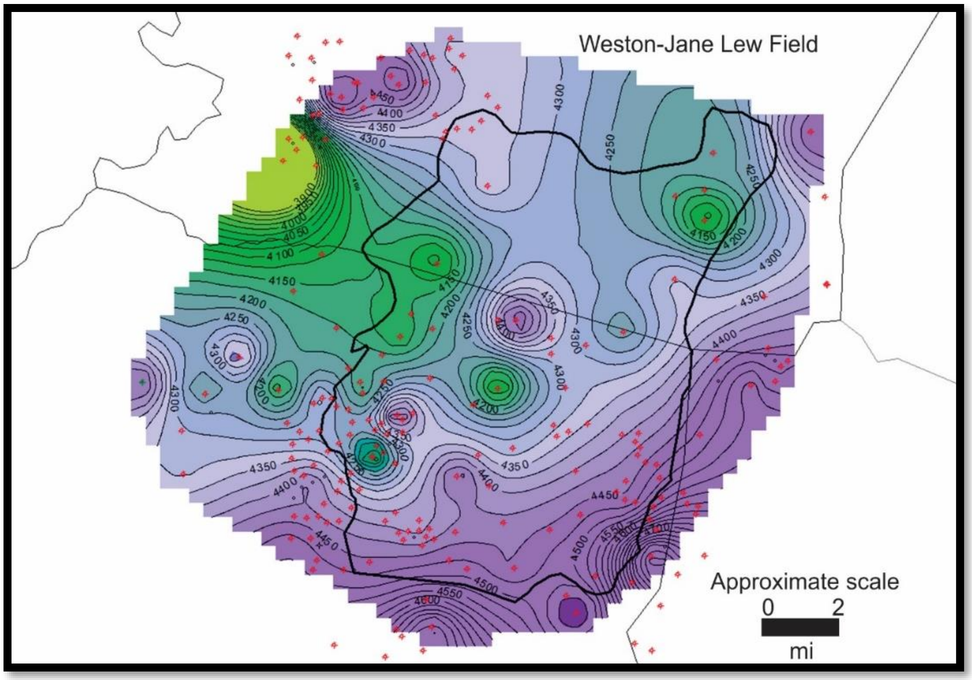



**Figure 5-26. Contour map on top of the Benson siltstone (depth below ground surface in ft) in Weston-Jane Lew Field (black outline). The color-ramped grid varies from green (shallow) to purple (deep), and the contour interval is 25 ft.**

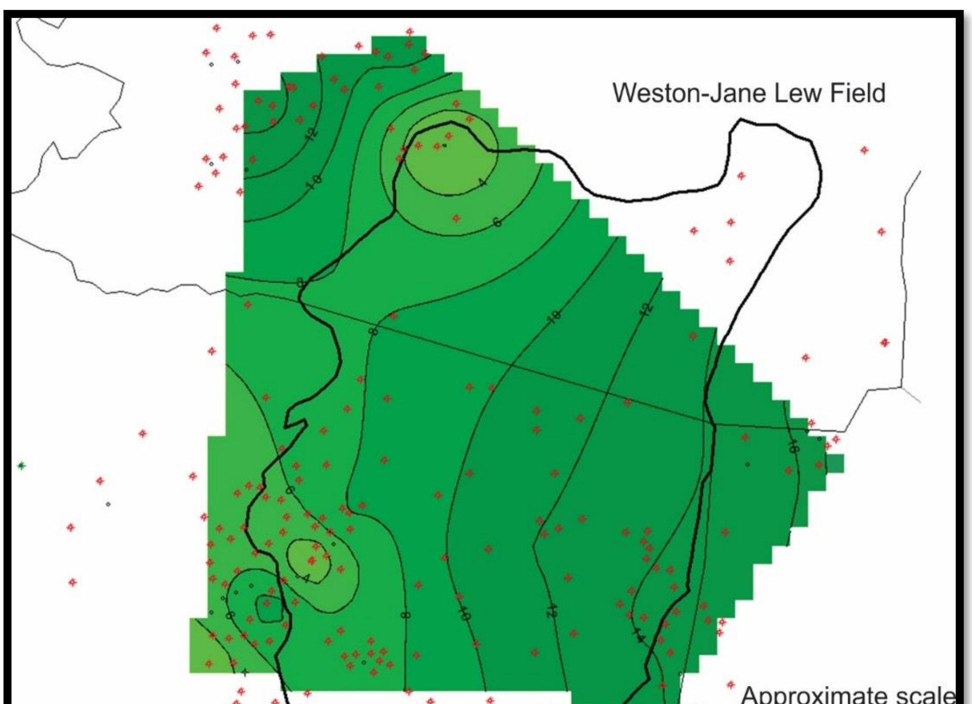



**Figure 5-27. Net thickness map of the Benson siltstone in Weston-Jane Lew Field (black outline). The contour interval is 2 ft.**

Compilation of pre-existing MRCSP GIS field-level data for the Weston-Jane Lew Field and data interpreted specifically for the Benson siltstone from geophysical logs using IHS PETRA® software for the current Study are provided in Tables 5-9 and 5-10, respectively.

***Table 5-9. Weston-Jane Lew field-level (Elk Group) reservoir data (MRCSP GIS database).***

| Average producing depth (ft) | Net thickness (ft) | Pressure (psi) | Porosity (%) | Initial pressure (psi) | Trap type |
|---|---|---|---|---|---|
| 4,336 | 66 | 1,900 | 8.0 | 1,877 | Stratigraphic |

***Table 5-10. Reservoir data prepared for the Weston-Jane Lew Field (Benson siltstone) as part of the current Study.***

| Values | Depth (ft) | Gross thickness (ft) | Net thickness (ft) | Average density porosity (%) | Average neutron porosity (%) |
|---|---|---|---|---|---|
| Minimum | 4,089 | 10 | 2 | 3.0 | 5.0 |
| Maximum | 4,880 | 84 | 18 | 20.0 | 10.0 |
| Average | 4,371 | 23 | 10 | 7.0 | 8.0 |

Two geologic cross sections were prepared using geophysical logs and subsurface tops data to illustrate the general character of siliciclastic reservoirs (and the Benson siltstone in particular) from north to south and west to east (Figures 5-28 through 5-30). Here, the Elk Group is comprised of sandy siltstones, so the GR log alone is a poor tool for identifying individual sandstone units. Due to their size, these cross sections are also provided as plates in Appendix H. The Benson is distinguished by its high resistivity, low density, and often shows a temperature deflection (see Figure 5-31).

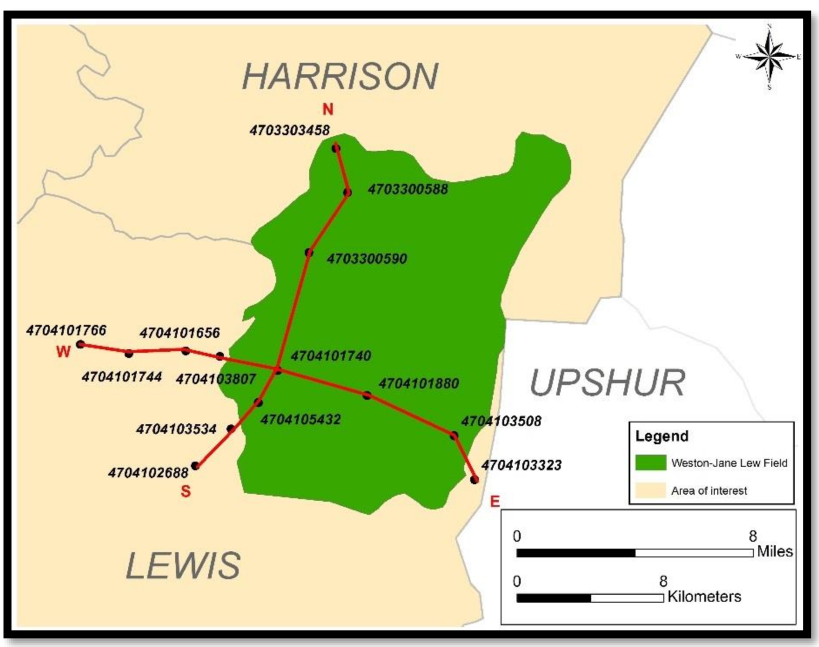



**Figure 5-28. Upper Devonian geologic cross section locations (red lines) through Weston-Jane Lew Field.**

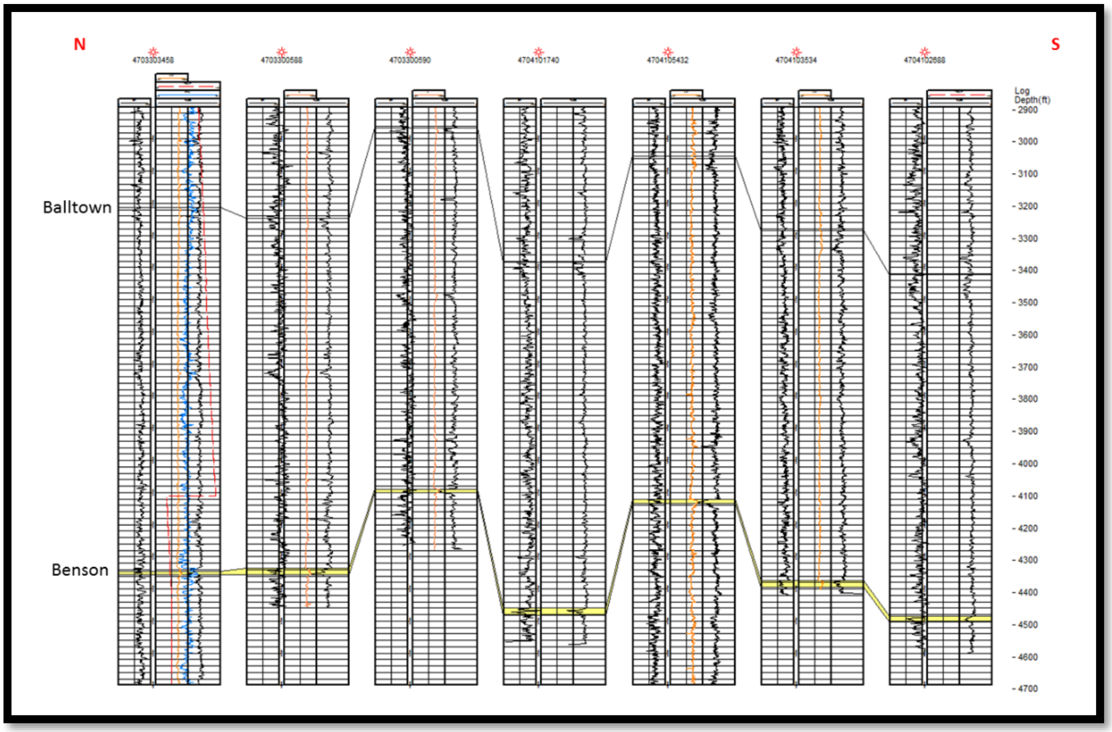



**Figure 5-29. North-south geologic cross section through Weston-Jane Lew Field, illustrating Upper Devonian units in the Central Prospect.**

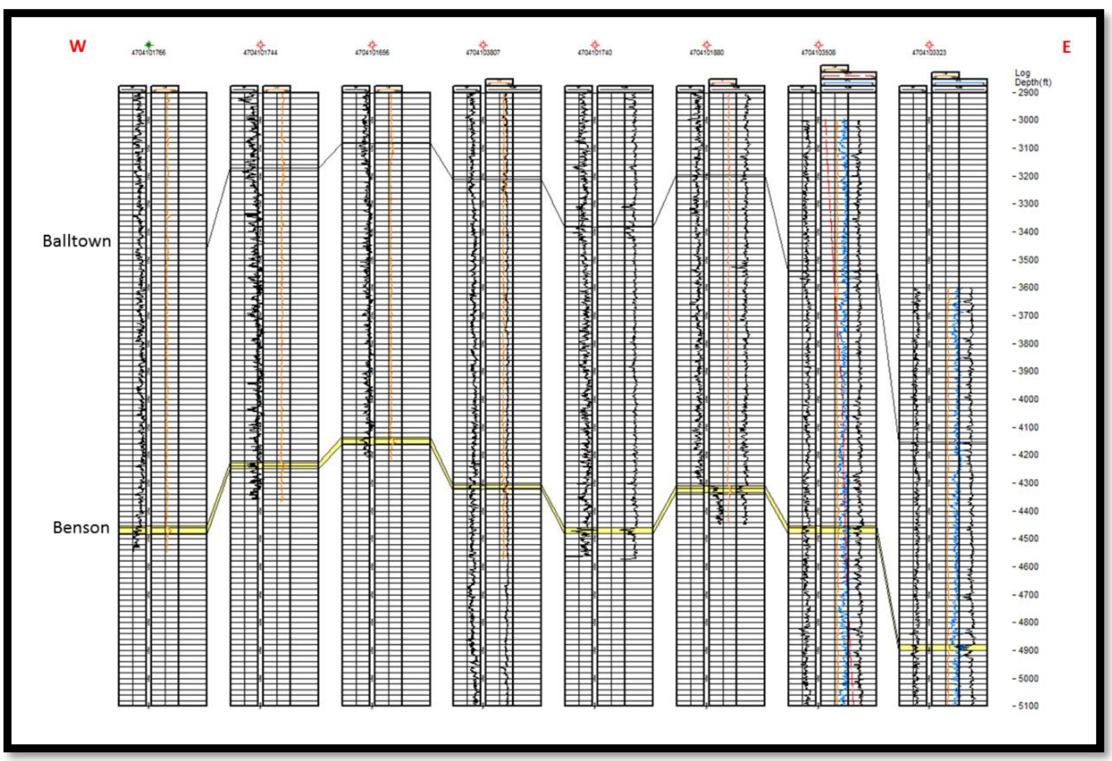



**Figure 5-30. West-east geologic cross section through Weston-Jane Lew Field, illustrating Upper Devonian units in the Central Prospect.**

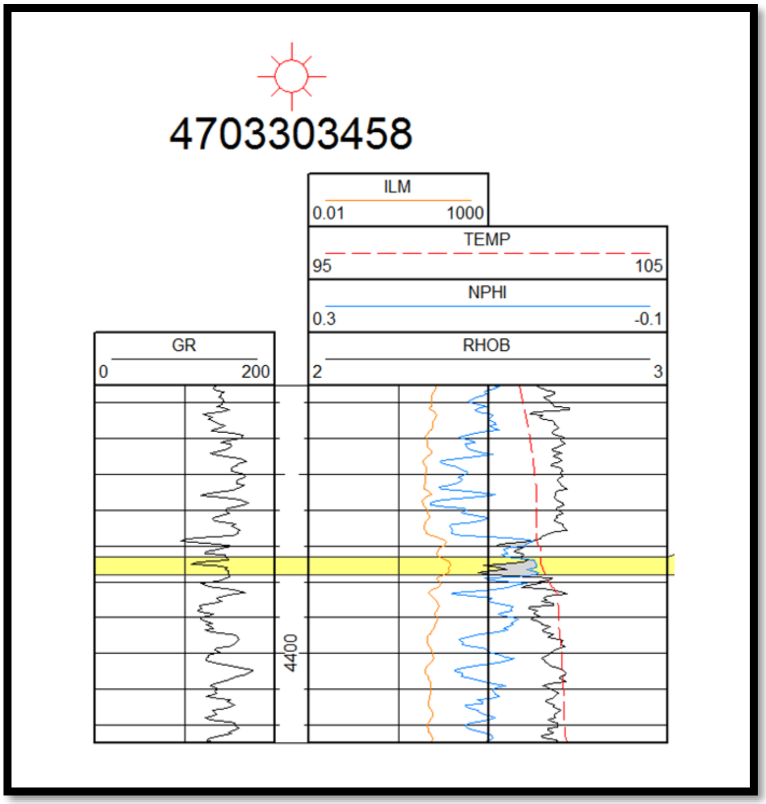



**Figure 5-31. Geophysical log signature of the Benson siltstone (highlighted yellow) in Weston-Jane Lew Field (API No. 47-033-03458). The crossover between the NPHI and RHOB curves is shaded gray. This NPHI peak and density drop along with a resistivity (ILM) log peak is characteristic of the Benson siltstone.**

The Weston-Jane Lew Field comprises multiple depleted gas reservoirs that could be evaluated for suitability to store NGLs, but for the purposes of the current Study, the Research Team chose to assess the Elk Group's Benson interval. Here, the Benson siltstone occurs at optimal depths (3,500 – 5,000 ft range), is proximal to existing/proposed infrastructure (i.e., processing facilities) and has a relatively large footprint (about 64,000 ac). The average net thickness of the Benson interval is 10 ft, and porosity ranges from 3 to 20 percent, averaging 7 to 8 percent.

The only criteria for which the Elk Group interval received low or poor ratings (i.e., 0-1) were for well penetrations, trap integrity and stacked opportunities. In Weston-Jane Lew Field alone, more than 2,000 well penetrations were identified, and based on subsurface data provided by these wells, the potential extent of the stratigraphic trapping mechanism associated with Upper Devonian units (including the Benson) is not well constrained. Finally, as illustrated in Figure 5-2, The Weston-Jane Lew Field offers only limited stacked opportunities, as it just barely overlaps with a small area of Greenbrier lime mudstone facies (>60 ft thickness) in Lewis County, West Virginia.

### *5.3.2.5 Salina F4 Salt: Salt Caverns*

The Central Prospect is home to an area of relatively thick Salina F4 Salt adjacent to existing/proposed infrastructure along the western edge of the prospect area (Figure 5-2). Here, the Salina F4 Salt is approximately 6,600 ft deep and has an interpreted net Salina F4 Salt thickness of at least 100 ft in an >40,000-ac area (Figure 5-32). Reported pressures for this area are within the 900 – 1,500 psi range, and stacked opportunities are present. The only criterion for which Salina F4 Salt received a poor rating (i.e., 0) was for well penetrations, for the same reasons previously mentioned for other storage opportunities in this prospect.

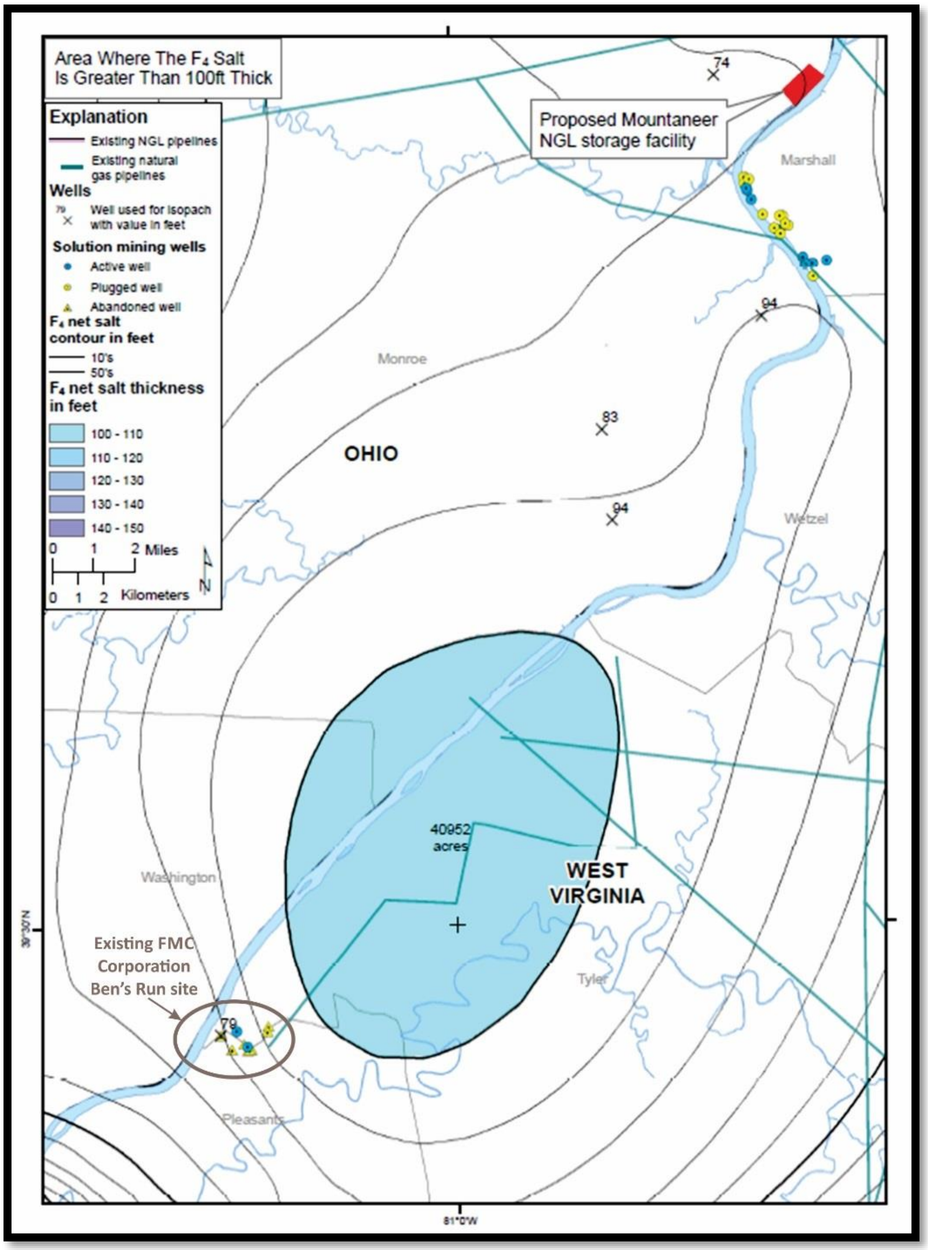



**Figure 5-32. Ben's Run area of the Central Prospect, where the Salina F4 Salt is interpreted to be greater than 100 ft thick.**

As reported in Section 4.2, anhydrite and dolomite are interbedded with the F4 Salt beyond the 100-ft footprint laterally, and there is a bed of dolomite/anhydrite immediately below the F4 Salt. A west-east dip cross section was prepared for this area (Figure 5-33) to illustrate this detailed stratigraphy (Figure 5-34). Because this thick salt area thins to the west and east, is underlain by dolomite/anhydrite and overlain by younger Salina anhydrite and dolomite and Helderberg Group carbonates, trap integrity was highly rated, and the Research Team considers this to represent documented trap closure. For more detail, see the rating results in Appendix E.

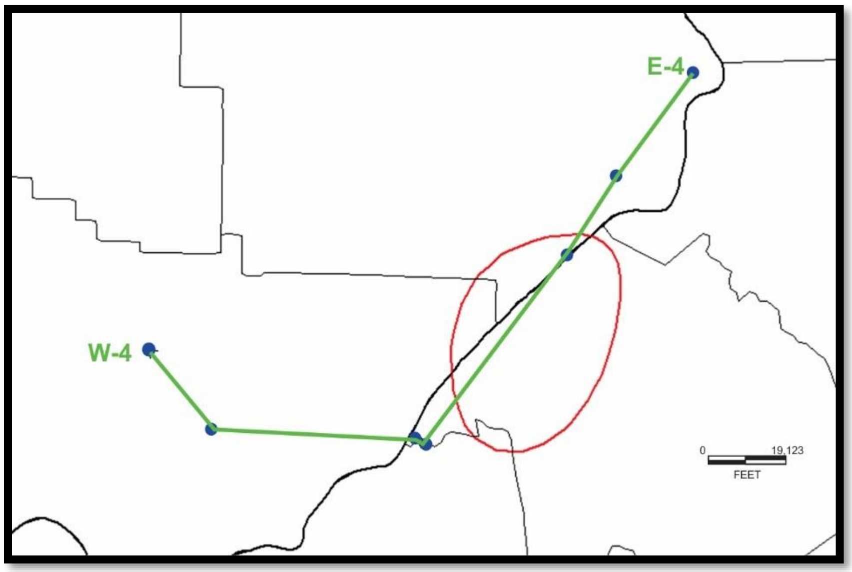



**Figure 5-33. Location of dip cross section through the Salina F4 Salt in the Central Prospect.**

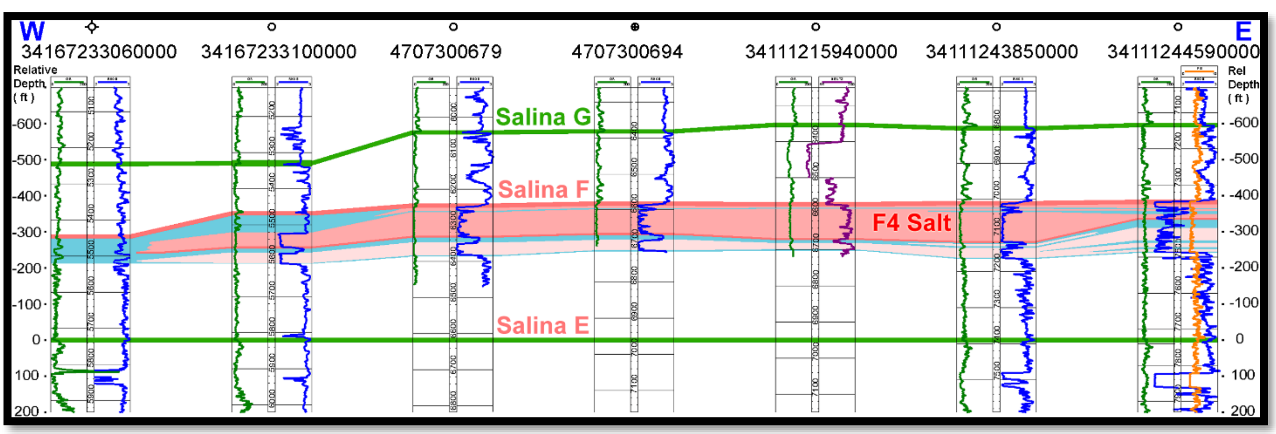



**Figure 5-34. West-east dip cross section through Salt Area 4, hung on the underlying Salina E unit, which illustrates thickening of the F4 Salt over the prospect area.**

### 5.3.3 Southern Prospect

The Southern Prospect is situated in the Kanawha River Valley of West Virginia and includes multiple storage opportunities, from mined-rock caverns in the Greenbrier Interval to various depleted gas fields in the Keener to Berea, Oriskany Sandstone and Newburg sandstone intervals (Figure 5-35). The Salina F4 Salt was determined not to have sufficient thickness in this area to warrant further evaluation, unlike the Northern and Central Prospects discussed above. However, many stacked and/or adjacent opportunities are available within a relatively small geographic area proximal to a favorable corridor.

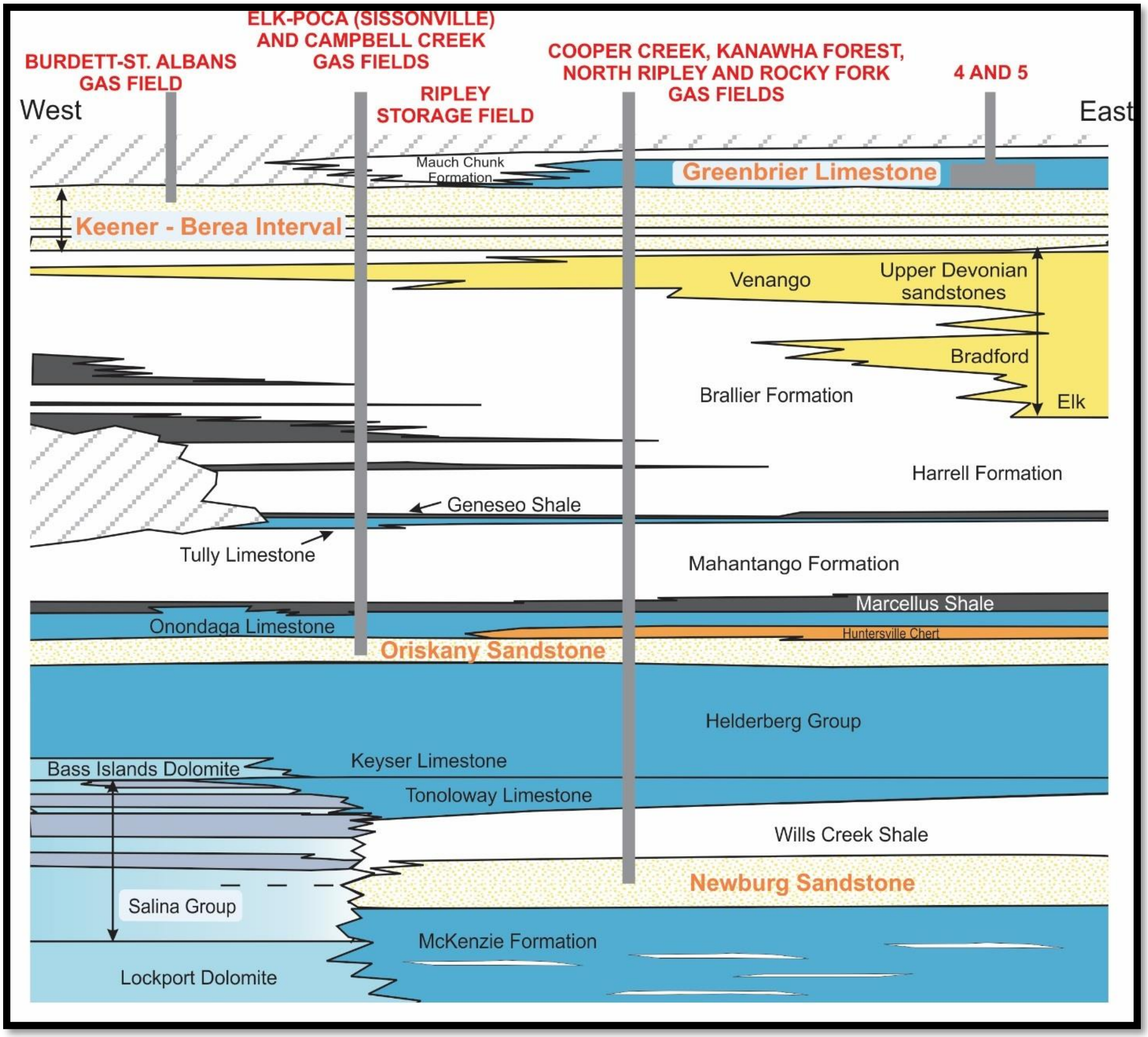



**Figure 5-35. Cartoon of the subsurface geology associated with the Southern Prospect, where 10 different storage opportunities have been identified (generalized and not to scale).**

#### *5.3.3.1 Greenbrier Limestone: Mined-Rock Caverns*

The lime mudstone facies of the Greenbrier Limestone, identified as the preferred hard-rock interval to mine for underground NGL storage (Section 4.1), has been mapped throughout the West Virginia portion of the Southern Prospect in thicknesses of 40 ft or more within the depth interval of 1,800 – 2,000 ft (Figure 5-36). Because the Greenbrier does not exist at this preferred depth and thickness in northwestern Kanawha County, the interval was ranked as two distinct areas – Area 4 in northern Putnam and Roane counties and Area 5 in southeastern Kanawha and northern Boone counties. The lime mudstone thicknesses in Areas 4 and 5 range from 40 to 180 ft and 40 to 80 ft, respectively.

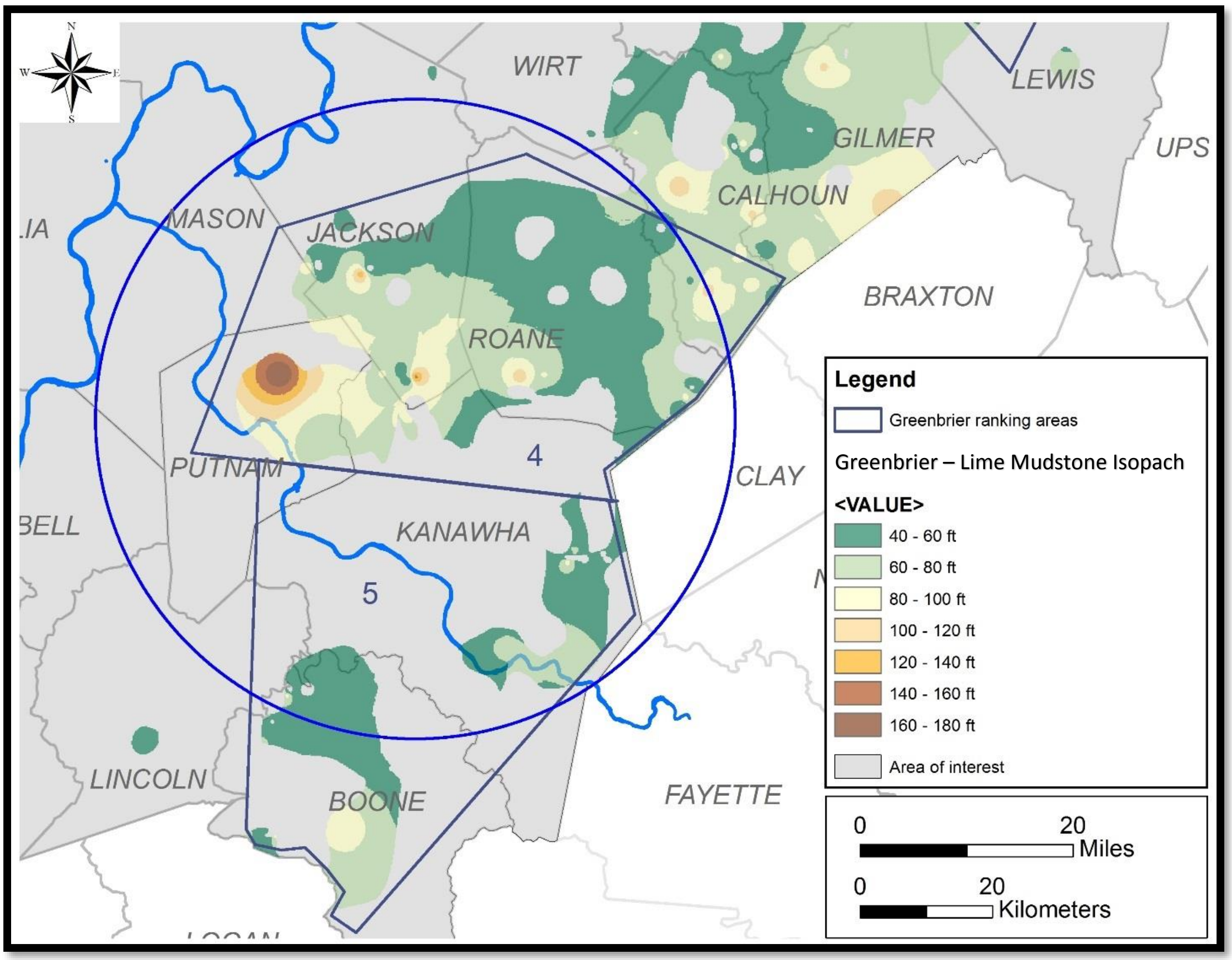



**Figure 5-36. Net isopach of the Greenbrier's lime mudstone facies in the Southern Prospect.**

Areas 4 and 5 were rated highly for their footprints and proximity to infrastructure. The lime mudstone facies exists within five mi of the Kanawha River and proposed/existing infrastructure. In Area 4, the footprint covers more than 530,000 ac and Area 5 covers more than 170,000 ac. In addition, both these areas received favorable ratings for stacked opportunities because two or three other geologic intervals occupy the same general area as the Greenbrier.

In Area 4, the Greenbrier overlies the Lower Devonian Oriskany Elk-Poca (Sissonville) Field and the Upper Silurian Newburg Rocky Fork Field.  In Area 5, the Greenbrier overlies the Lower Devonian Oriskany Campbell Creek Field and the Newburg in the Kanawha Forest Field.

These two areas have different ratings for trap integrity. Trap integrity was determined by looking for the presence of grainstone facies above and below the mudstone interval within the Greenbrier Limestone interval.  Area 4 was rated poorly because only about 11 percent of the mudstone facies was both over- and underlain by the grainstone facies. Area 5 rates much higher because about 81 percent was both over- and underlain by the grainstone facies.

Three geologic cross sections were prepared using geophysical logs and subsurface Greenbrier facies tops data to illustrate the varying thicknesses of mudstone (dark blue) and grainstone (light blue) over this prospect. Two west-to-east and one north-to-south cross sections were constructed in areas with log coverage where the limestone was in the appropriate thickness and depth interval (Figure 5-37). Log curves (GR, RHOB and Pe) were utilized to delineate the depths and thicknesses of these facies, with the Pe curves (shown in red) providing essential lithologic data control to pick these tops.  As presented in Section 4.1, the best areas for mining a cavern from the Greenbrier's lime mudstone facies will be found where the lime mudstone facies is thickest and overlain and underlain by thick grainstones, preferably with bound water and water-filled porosity.  For example, API No. 47-039-06143 on cross section A-A' has both an excellent thickness of the lime mudstone (69 ft) and thick upper and lower grainstone intervals (Figure 5-38).

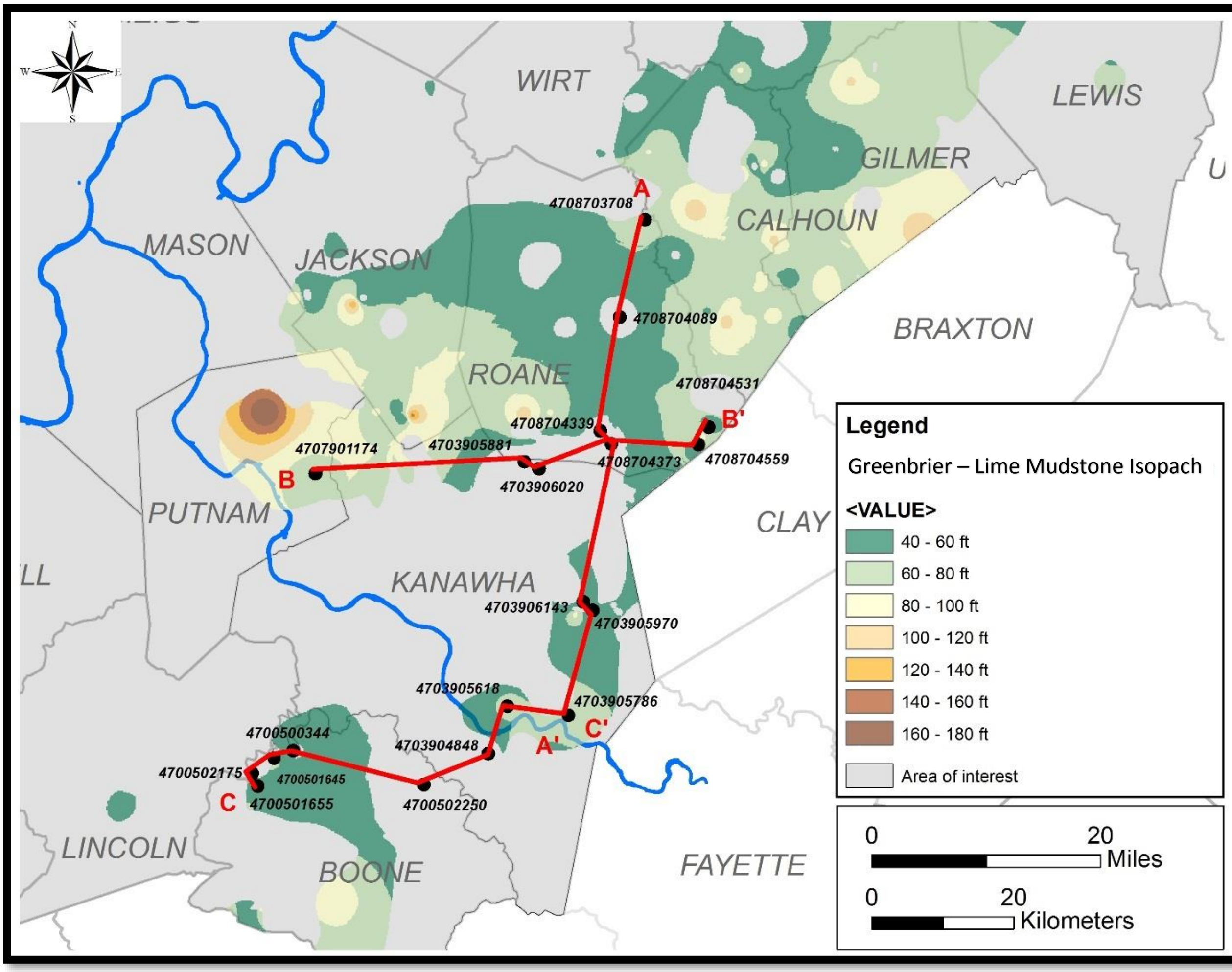



**Figure 5-37. Greenbrier cross section locations in the Southern Prospect.**

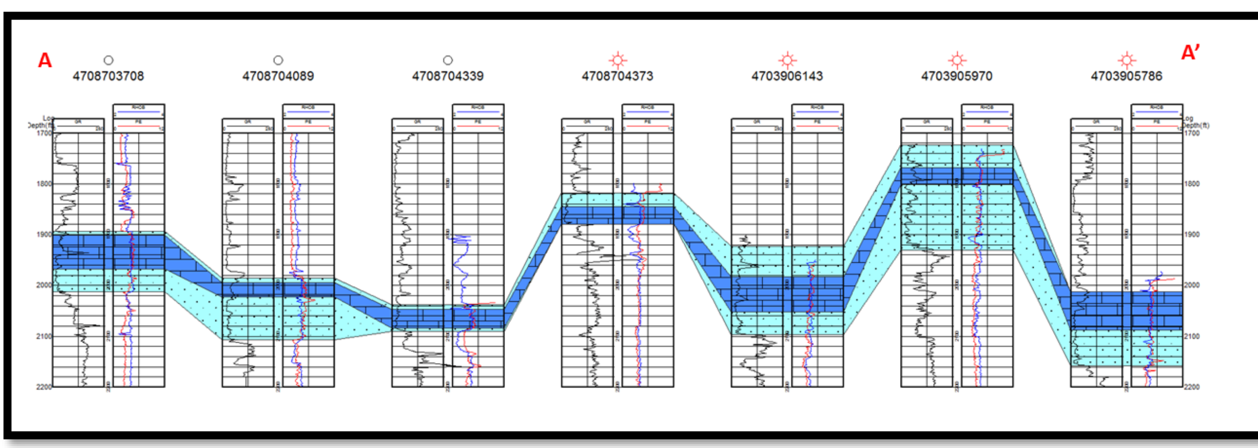



**Figure 5-38. Cross section A - A' (north-south) encompasses both Greenbrier Areas 4 and 5. The lime mudstone facies is shown in dark blue, and the grainstone facies is shown in light blue.**

Cross section B - B' illustrates the thicks and thins of the lime mudstone from west to east through the prospect area (Figure 5-39). In API No. 47-079-01174, the lime mudstone (dark blue) is 50 ft thick, with upper and lower grainstone (light blue) thicknesses of more than 40 ft, thus encapsulating the mineable unit. The depth and thickness of the upper and lower grainstones vary considerably along the section. The lime mudstone facies thins in northern Kanawha County, resulting in division of the Greenbrier Limestone Interval into Areas 4 and 5 for this prospect.

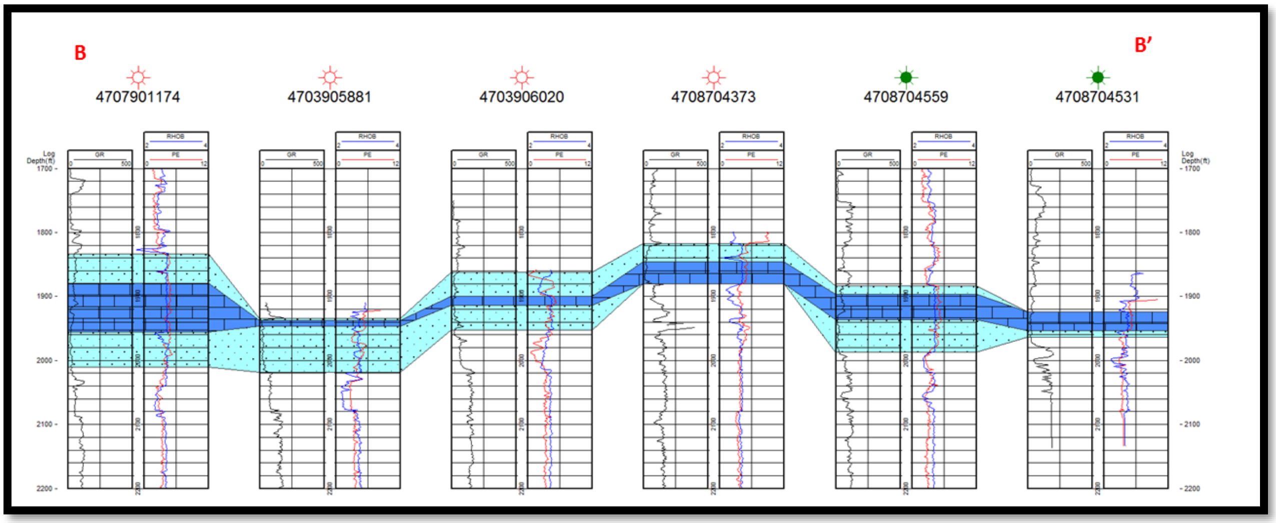



**Figure 5-39. Cross section B - B’ (west-east) in the southern section of Area 4.**

There is an adequate thickness of lime mudstone in several places along cross section C - C’ (Figure 5-40), as much as 94 ft, as well as a thick lower grainstone. The upper grainstone facies comes and goes. The lime mudstone facies thins towards the border of Boone and Kanawha counties.

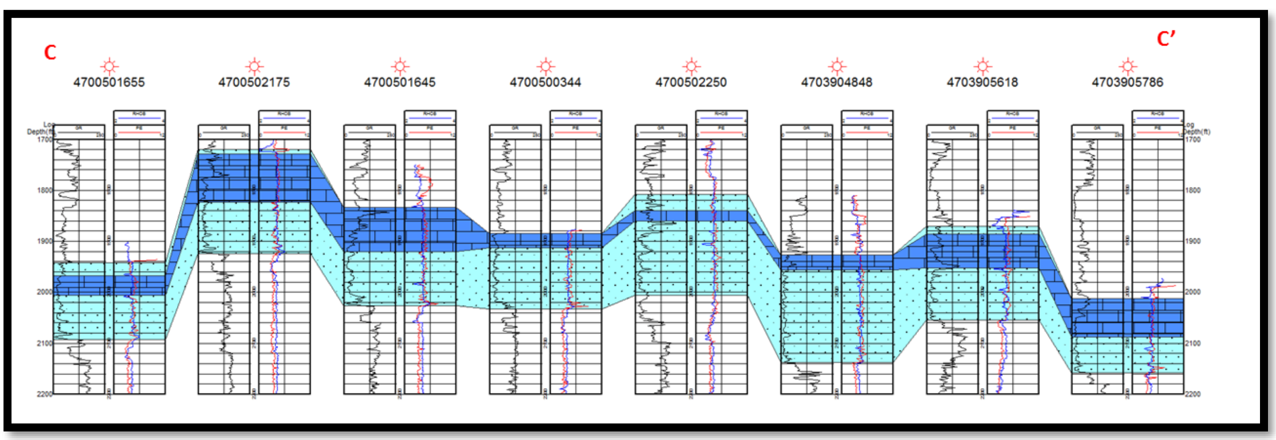



**Figure 5-40. Cross section C - C’ (west-east) in Area 5.**

Areas 4 and 5 both received favorable ratings (i.e., 2) for well penetrations. Although these areas do not have the same density of pre-existing wells that other reservoirs and prospects prepared for this Study, proper plugging of wells penetrating to or through the Greenbrier

Limestone interval will be necessary to eliminate potential hazards to miners and reduce pathways for gas migration.

### *5.3.3.2 Keener to Berea Interval: Depleted Gas Fields*

The Burdett-St. Albans Field is in the southwestern portion of the Southern Prospect, and has primarily produced gas from the Berea Sandstone. Initial production volumes do not suggest much in the way of a storage opportunity (Figure 5-41), but the field had produced nearly 9 BCF gas as of 1996 (Tomastik, 1996). Maps prepared by the Research Team indicate that the average depth of the Berea Sandstone ranges from 1,800 to 2,500 ft in this area (Figure 5-42), and that net sand thicknesses range from about 4 to 27 ft (Figure 5-43).

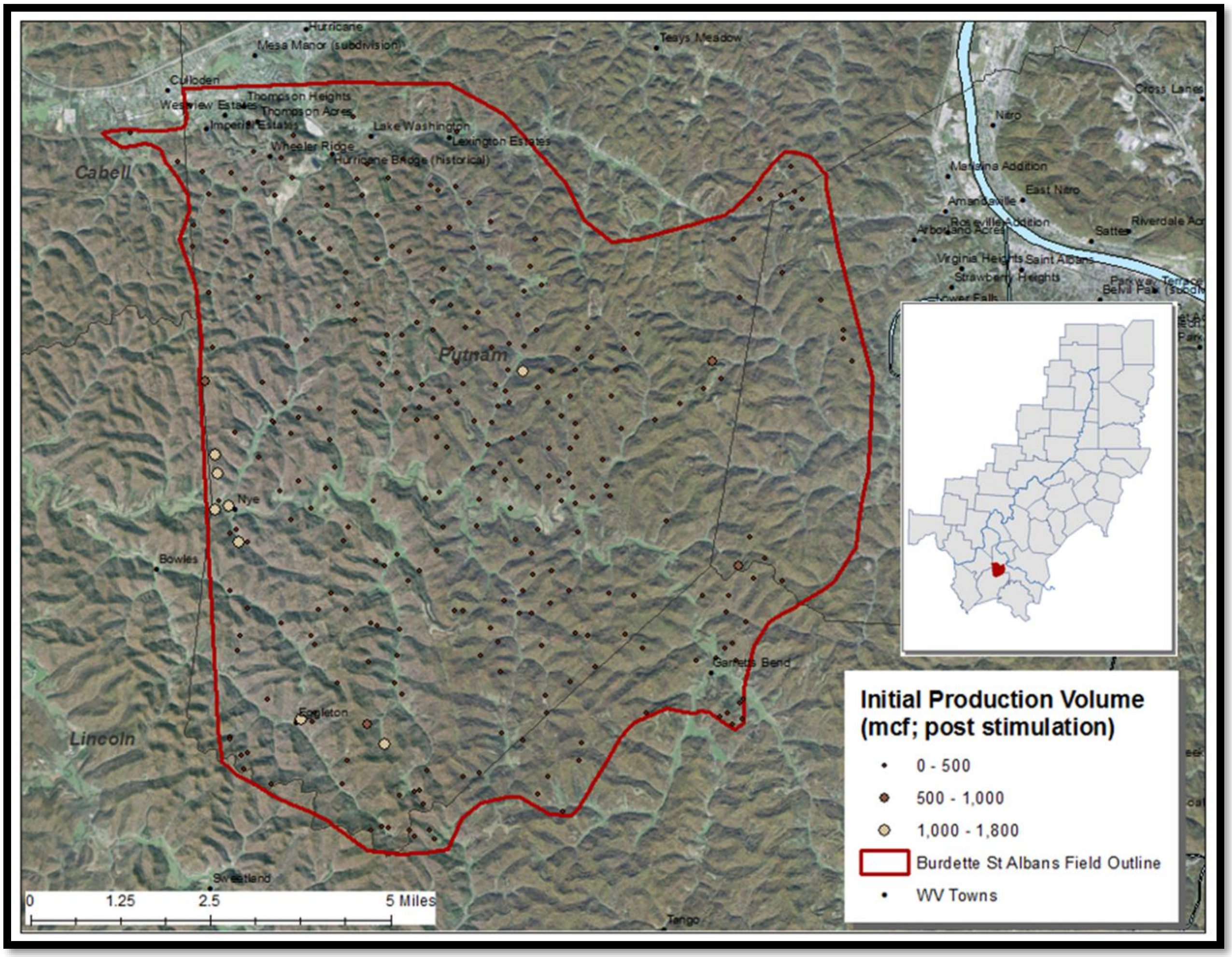



**Figure 5-41. Burdett-St. Albans Field, initial gas production (MCF) post stimulation.**

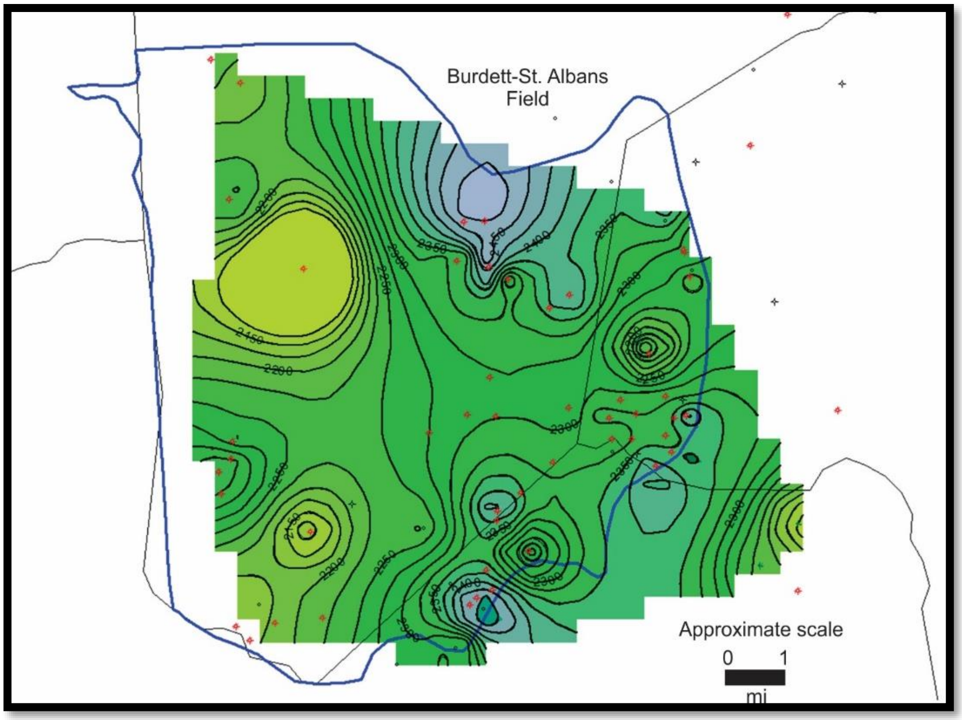



**Figure 5-42. Contour map on top of the Berea Sandstone (depth below ground surface in ft) in Burdett-St. Albans Field (blue outline). The color-ramped grid varies from green (shallow) to purple (deep), and the contour interval is 25 ft.**

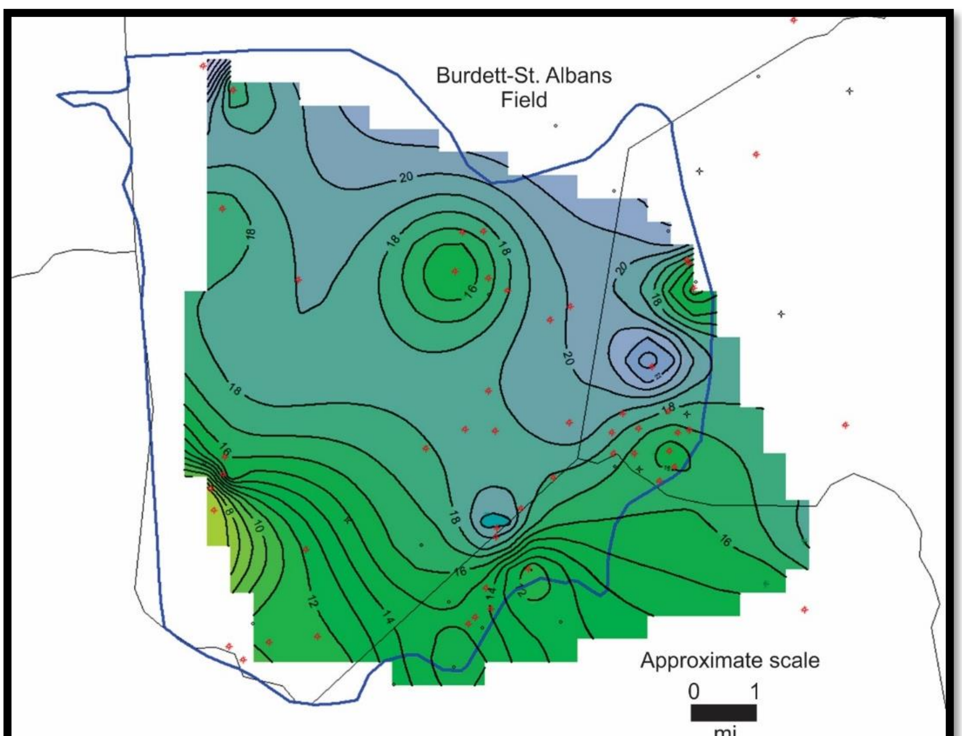



**Figure 5-43. Net thickness map of the Berea Sandstone in Burdett-St. Albans Field (blue outline). The color-ramped grid varies from green (thin areas) to purple (thick areas), and the contour interval is 1 ft.**

MRCSP GIS field-level data for the Burdett-St. Albans Field and data interpreted specifically for the interval as part of this Study are given in Tables 5-11 and 5-12, respectively.

***Table 5-11. Burdett-St. Albans Field Berea Sandstone reservoir data (MRCSP GIS database).***

| Average producing depth (ft) | Net thickness (ft) | Pressure (psi) | Porosity (%) | Initial pressure (psi) | Trap type |
|---|---|---|---|---|---|
| 2,217 | 21 | 1,000 | 10.0 | 960 | Stratigraphic |

***Table 5-12. Reservoir data prepared for the Burdett-St. Albans Field as part of the current Study.***

| | Keener to Berea | Berea Sandstone | | | |
|---|---|---|---|---|---|
| Values | Gross thickness (ft) | Depth (ft) | Gross thickness (ft) | Net thickness (ft) | Average density porosity (%) |
| Minimum | 526 | 1,824 | 11 | 4 | 6.0 |
| Maximum | 571 | 2,510 | 46 | 27 | 20.0 |
| Average | 544 | 2,289 | 26 | 17 | 12.0 |

Three cross sections were prepared using geophysical logs and subsurface tops data to illustrate the Keener to Berea interval in general, and the Berea Sandstone in particular (Figure 5-44). Well casing is generally set in the Big Injun (Price/Burgoon equivalent), which occurs beneath the Greenbrier Limestone. The Weir sandstone in this area is a sandy to silty interval above the Berea that occasionally develops reservoir porosity. The organic-rich Sunbury Shale directly overlies the Berea, thickening toward the south, where it intertongues with the Berea. In addition to the Sunbury's geochemical signature making it the likely source rock for the Berea (Tomastik, 1996), it presumably contributed a significant amount to Berea gas production as well. Good porosity exists in the Berea, although vertical seals and lateral traps may be problematic.

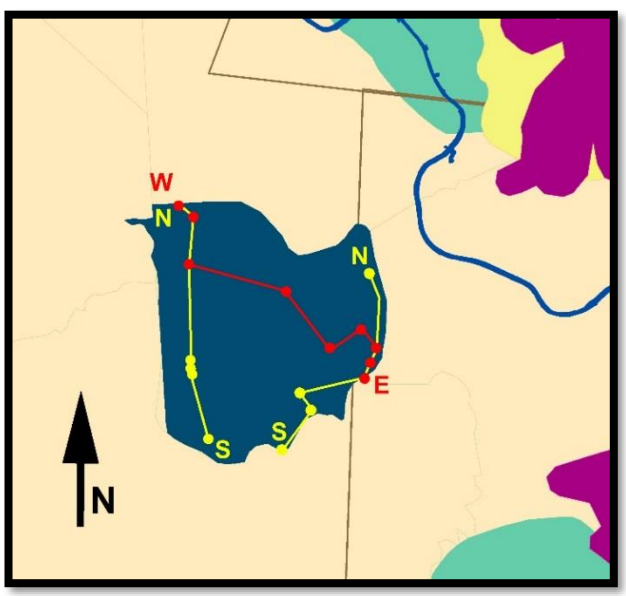



**Figure 5-44. Location of two north-south cross sections (yellow) and one west-east cross section (red) through the Keener to Berea interval in Burdett-St. Albans Field.**

Figures 5-45 and 5-46 present the north-south cross sections along the western and eastern edges of the field, respectively. The west-east cross section is provided in Figure 5-47. In Figure 5-45, the Berea Sandstone is highlighted in yellow and shown along with the overlying Sunbury Shale (gray). Bulk density (RHOB; blue) and neutron porosity (NPHI; red) logs show good cross-over in the Berea interval, which is suggestive of permeability.

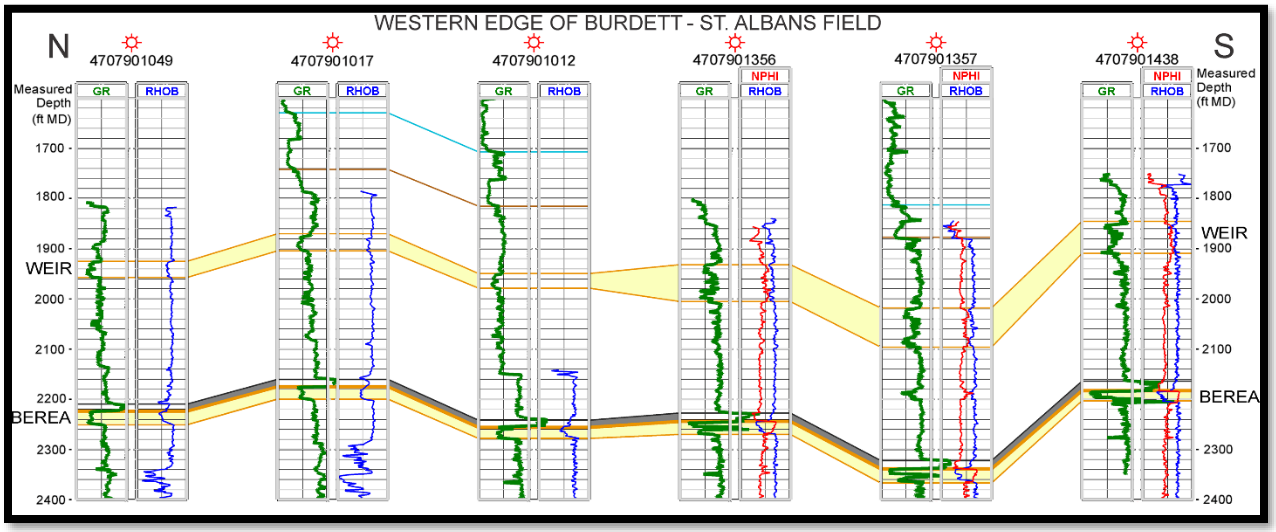



**Figure 5-45. North-south geologic cross section along the western edge of the Burdett-St. Albans Field.**

Bulk density logs (RHOB; blue) highlight porosity development in the Berea, as well as in the Big Injun (also known as Price/Burgoon) (Figure 5-46). Other Keener to Berea Interval sandstones that may produce locally in this field include the Weir (yellow) and the Big Injun (Figure 5-47).

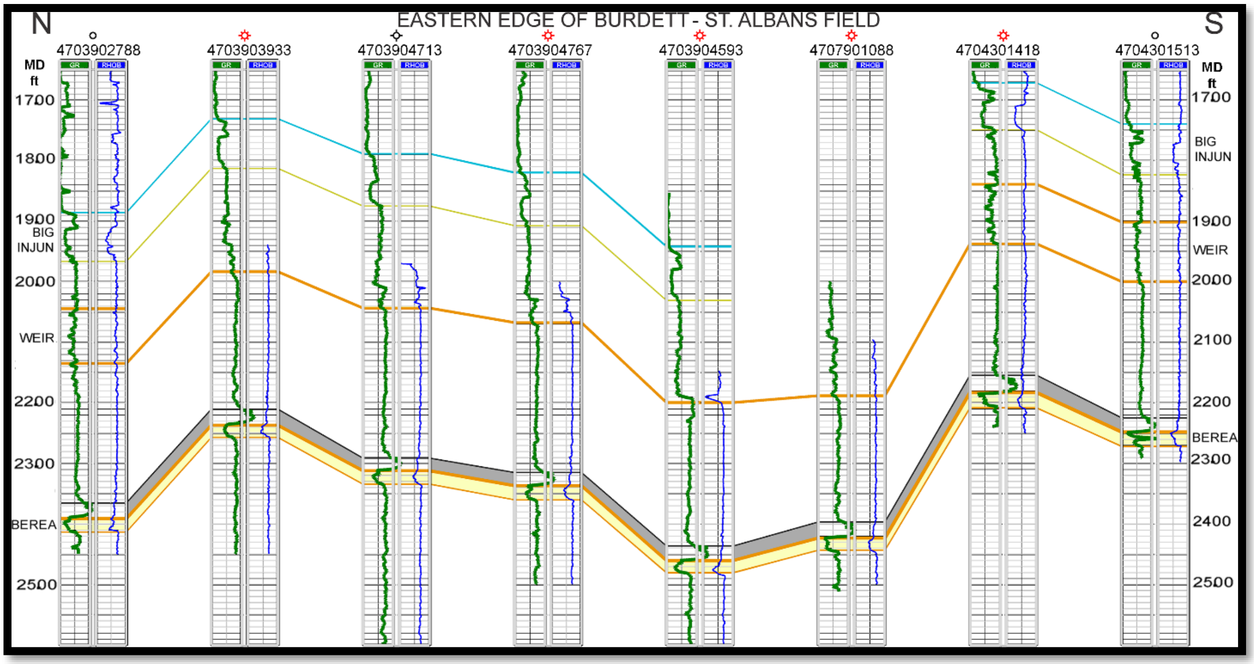



**Figure 5-46. North-south geologic cross section along the eastern edge of Burdett-St. Albans Field.**

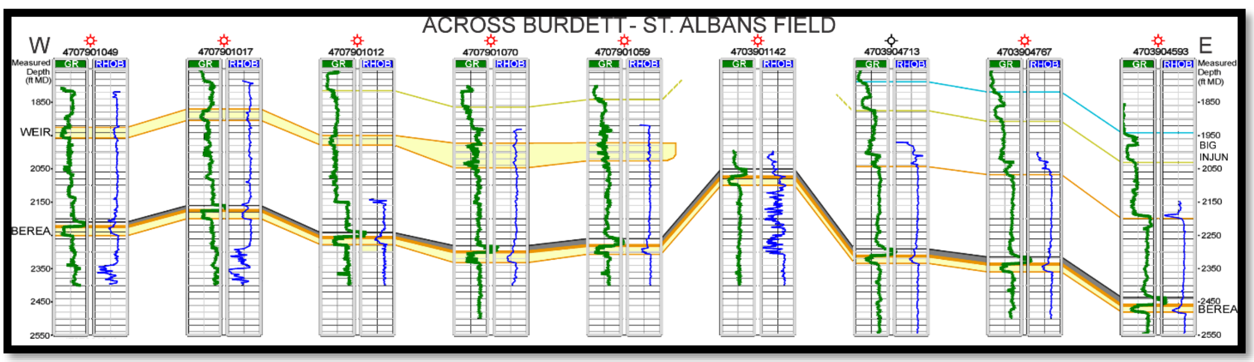



**Figure 5-47. West-east geologic cross section across the Burdett-St. Albans Field.**

The Burdett-St. Albans Field's Berea Sandstone has a relatively large footprint (nearly 50,000 ac), occurs at favorable depths (2,000 – 3,500 ft range) and is close to existing/proposed infrastructure. The average net thickness of the Berea is 26 ft, and porosity ranges from 6 to 20 percent, averaging 12 percent. The pressure of this field is between 900 and 1,500 psi, which is optimal for NGL storage.

The only criteria for which this field received low to poor ratings (i.e., 0-1) were for well penetrations, trap integrity and stacked opportunities. Legacy well completions in this and other geologic intervals in this area means that site-specific reconnaissance and detailed site preparation will be necessary. As illustrated by the cross sections above, the lateral and vertical limits of the Berea Sandstone in the field are poorly constrained, hence the reason for a poor rating. There are no other geologic intervals that coincide with Burdett-St. Albans Field to provide a stacked opportunity for storage. A final note of caution is that due to the intertonguing of the

Berea with the Sunbury Shale in this area, any NGLs stored here could possibly adsorb onto the clay minerals of the shale, hindering extraction of these products.

#### *5.3.3.3 Oriskany Sandstone: Depleted Gas Fields*

The Elk-Poca (Sissonville) and Campbell Creek fields are centrally located in the Southern Prospect, and have produced gas from the Oriskany Sandstone (Figures 5-48 and 5-49). The Elk-Poca (Sissonville) Field alone has produced nearly 1 trillion cubic feet (TCF) of gas, and portions of this area have since been converted to natural gas storage (Patchen and Harper, 1996). Each of these fields is discussed in separate subsections below.

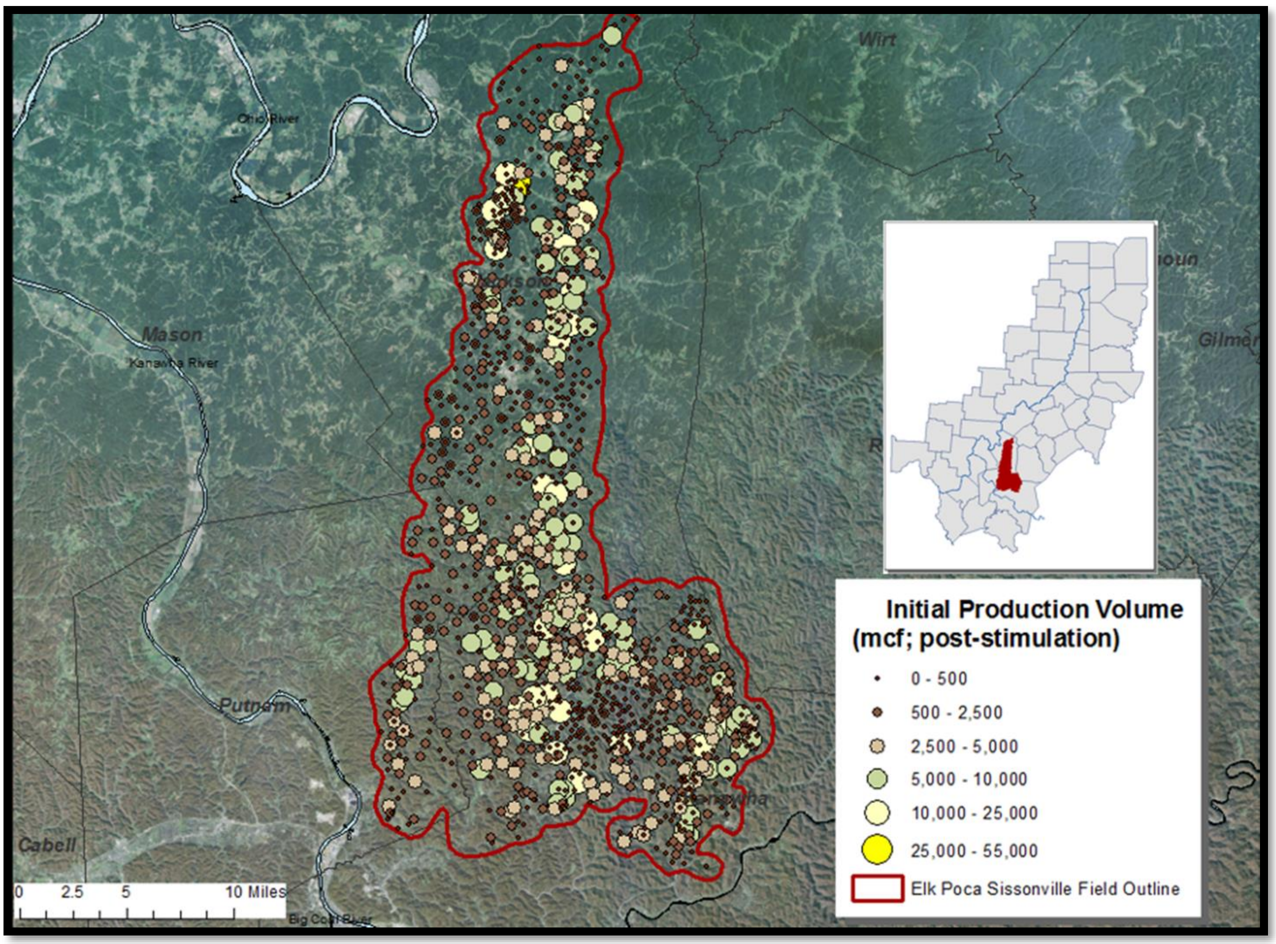



**Figure 5-48. Elk-Poca (Sissonville) Field, Initial gas production (MCF) post-stimulation.**

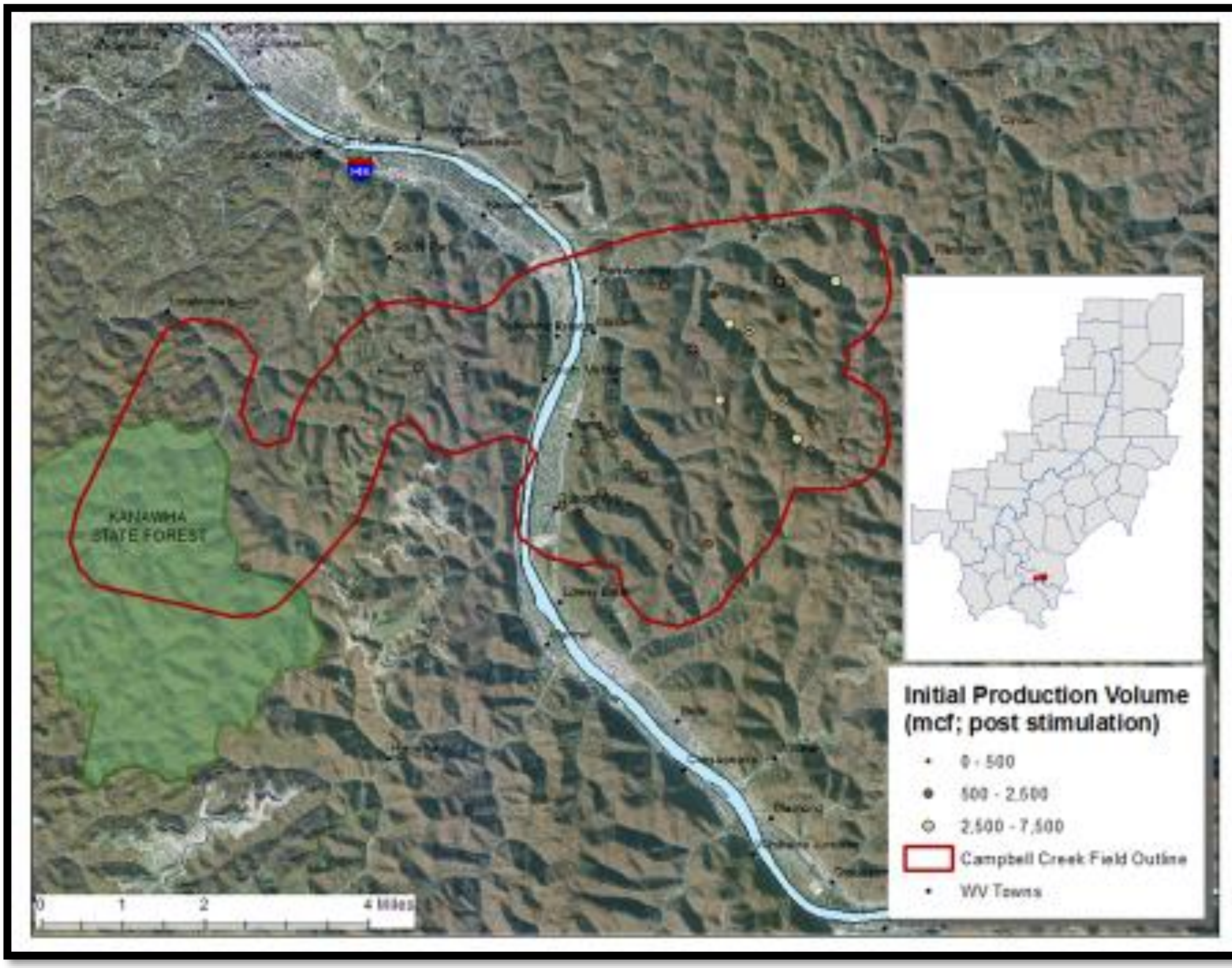



**Figure 5-49. Campbell Creek Field, Initial gas production (MCF) post-stimulation.**

## Elk-Poca (Sissonville) Field

Maps prepared by the Research Team indicate the top of the Oriskany Sandstone in Elk-Poca (Sissonville) Field occurs ≥1 mi below ground surface (Figure 5-50). It is deepest in the eastern half of the field and shallows westward. This sandstone reservoir is thickest in the eastern and central areas of the field, exceeding 60 ft in some places (Figure 5-51). The formation thins westward toward the stratigraphic pinchout.

The Sissonville high and Milliken Anticline are the two prominent structures responsible for gas accumulation within the Elk-Poca (Sissonville) Field. In fact, the thickness variations of the Oriskany in this area can be correlated closely to the crest of the Milliken Anticline and crosses the Sissonville high subparallel to the axis of the Milliken Anticline (Patchen and Harper, 1996). These structures influenced not only the deposition of the Oriskany Sandstone but also its porosity and permeability characteristics.

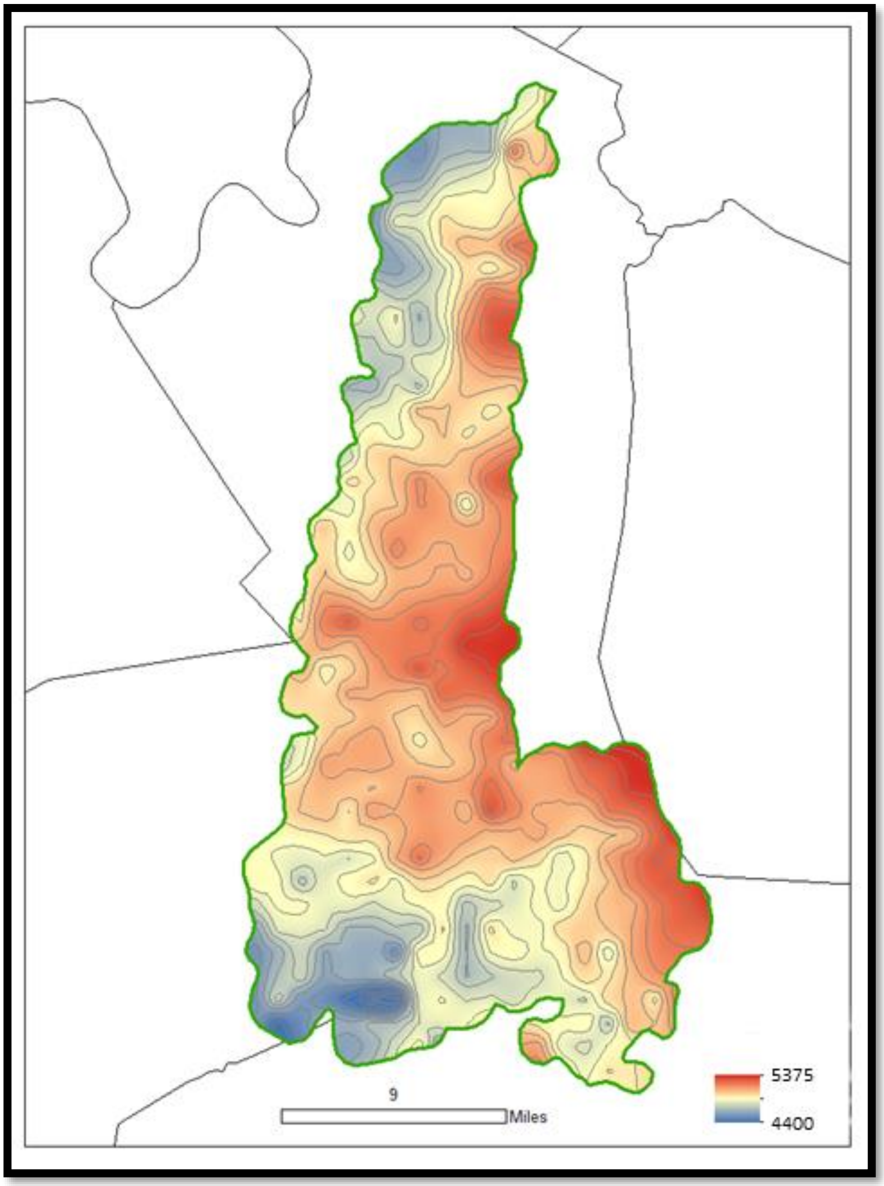



**Figure 5-50. Contour map on top of the Oriskany Sandstone (depth below ground surface in ft) in Elk-Poca (Sissonville) Field.**

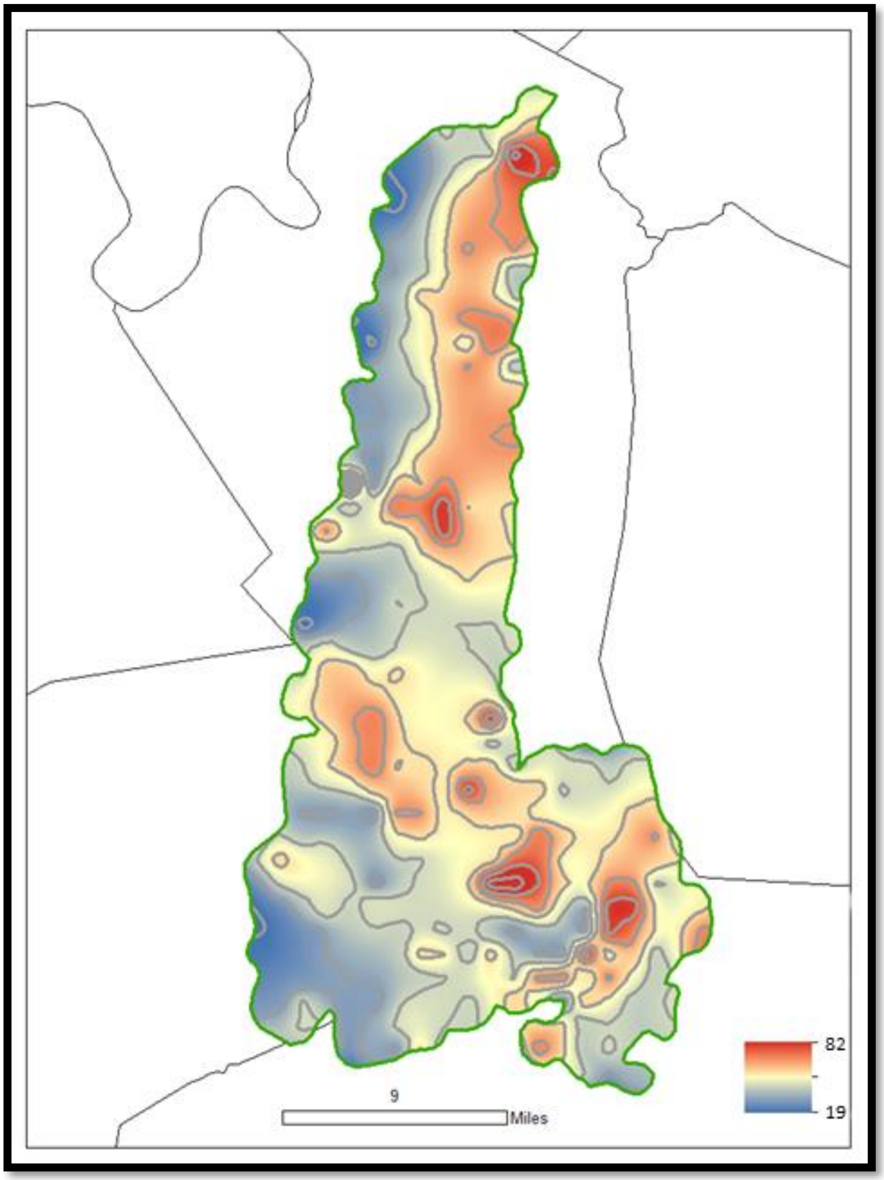



**Figure 5-51. Gross thickness (ft) map of the Oriskany Sandstone in Elk-Poca (Sissonville) Field.**

Field-specific reservoir data were prepared for these fields by compiling pre-existing MRCSP GIS field-level data for the current Study (Table 5-13). Depth and gross thickness data interpreted from geophysical logs for the current Study are provided in Table 5-14. Due to the age of the wells in this field, the Research Team did not have sufficient geophysical log coverage to compile net thickness and porosity data. Data from Patchen and Harper (1996) are provided in Table 5-14 as a surrogate.

***Table 5-13. Elk-Poca (Sissonville) field-level reservoir data (MRCSP GIS database).***

| Average producing depth (ft) | Net thickness (ft) | Pressure (psi) | Porosity (%) | Initial pressure (psi) | Trap type |
|---|---|---|---|---|---|
| 5,032 | 18 | 2,200 | 14.0 | 2,179 | Structural/ Stratigraphic |

***Table 5-14. Reservoir data prepared for the Elk-Poca (Sissonville) Field and immediate vicinity as part of the current Study.***

| Values | Depth (ft) | Gross thickness (ft) | Net thickness (ft)* | Average porosity (%)* |
|---|---|---|---|---|
| Minimum | 4,140 | 2 | Not available | 4.5 |
| Maximum | 5,497 | 102 | Not available | 15.2 |
| Average | 4,952 | 39 | 14 | 8.7 |

*from Patchen and Harper (1996)

The porosity data reported above are consistent with visual porosity estimates prepared for the Darrell Matheny #2 (API No. 47-107-02166), situated to the north of Elk-Poca (Sissonville) Field in Wood County, West Virginia. Appendix I provides photomicrographs and additional discussion relative to the Oriskany Sandstone in this portion of the AOI.

Due to its large area (nearly 245,000 ac) and proximity to the Ohio River, Elk-Poca (Sissonville) Field received high ratings for acreage and distance to infrastructure. Net thickness and porosity ratings were favorable, due to average net thickness greater than 10 ft and porosities averaging almost 9 percent. The field has reported pressures greater than 1,500 psi, which gives Elk-Poca (Sissonville) Field a favorable rating in this category as well. This field's trap integrity was rated favorable because the structural-stratigraphic pinchout play in this area has been well documented. In addition, there are multiple stacked opportunities in the Southern Prospect where this Oriskany field's footprint overlaps with the Greenbrier interval, a natural gas storage field and multiple Newburg sandstone reservoirs.

### Campbell Creek Field

The Campbell Creek Field is located in the Malden and Louden districts of Kanawha County, West Virginia. It occupies a proven acreage footprint of approximately 21,000 ac. Depth to the top of the Oriskany Sandstone ranges from 4,400 to 5,200 ft below ground surface, and the producing interval thickness averages 23 ft.

The deep discovery well in the Campbell Creek Field (Fink & Buckner #1) was drilled in 1930 with an initial production volume of 164 MCF. Initial production volumes (post-stimulation) for wells in the field range from about 100 to 7,000 MCF, but the Oriskany fields in this area have produced a large volume of gas. Cumulative production of the Campbell Creek and adjacent Hernshaw and Big Chimney fields was measured at approximately 24.7 BCF in 1973. The trapping mechanism in this field is a combination of structural (Warfield anticline) and stratigraphic (permeability barrier) traps.

Field-specific reservoir data were prepared for these fields by compiling pre-existing MRCSP GIS data for the current Study (Table 5-15).

***Table 5-15. Campbell Creek field-level reservoir data (MRCSP GIS database).***

| Average producing depth (ft) | Net thickness (ft) | Pressure (psi) | Porosity (%) | Initial pressure (psi) | Trap type |
|---|---|---|---|---|---|
| 4,825 | 15 | 2,100 | 9.0 | 2,089 | Structural/ Stratigraphic |

Campbell Creek is another viable Oriskany field in the Southern Prospect for NGL storage due its proximity to storage infrastructure, the Kanawha River and chemical and industrial processing facilities. The Oriskany Sandstone occurs at optimal depths (3,500 – 5,000 ft), exceeds 10 ft in thickness and has relatively high porosity. The only criteria for which this field received low (i.e., 1) ratings were for well penetrations and stacked opportunities.

#### *5.3.3.4 Oriskany Sandstone: Natural Gas Storage Field*

The Ripley Field is located near the northern edge of the Southern Prospect in Jackson County, West Virginia (Figure 5-2), and is an existing facility storing natural gas in the Lower Devonian Oriskany Sandstone (Figure 5-52). Located within the larger footprint of the Elk-Poca (Sissonville) Field, development of oil and gas began in 1938, and the area was actively drilled for about a decade (Overbey, 1961). The depleted field was converted to gas storage around 1954. Today, total dry gas capacity for the field is 25,050 MMCF (14,497 MMCF base gas/10,553 MMCF working gas). Total injection capacity is 64 MMCF/day, with a maximum deliverability of 83.2 MMCF/day.

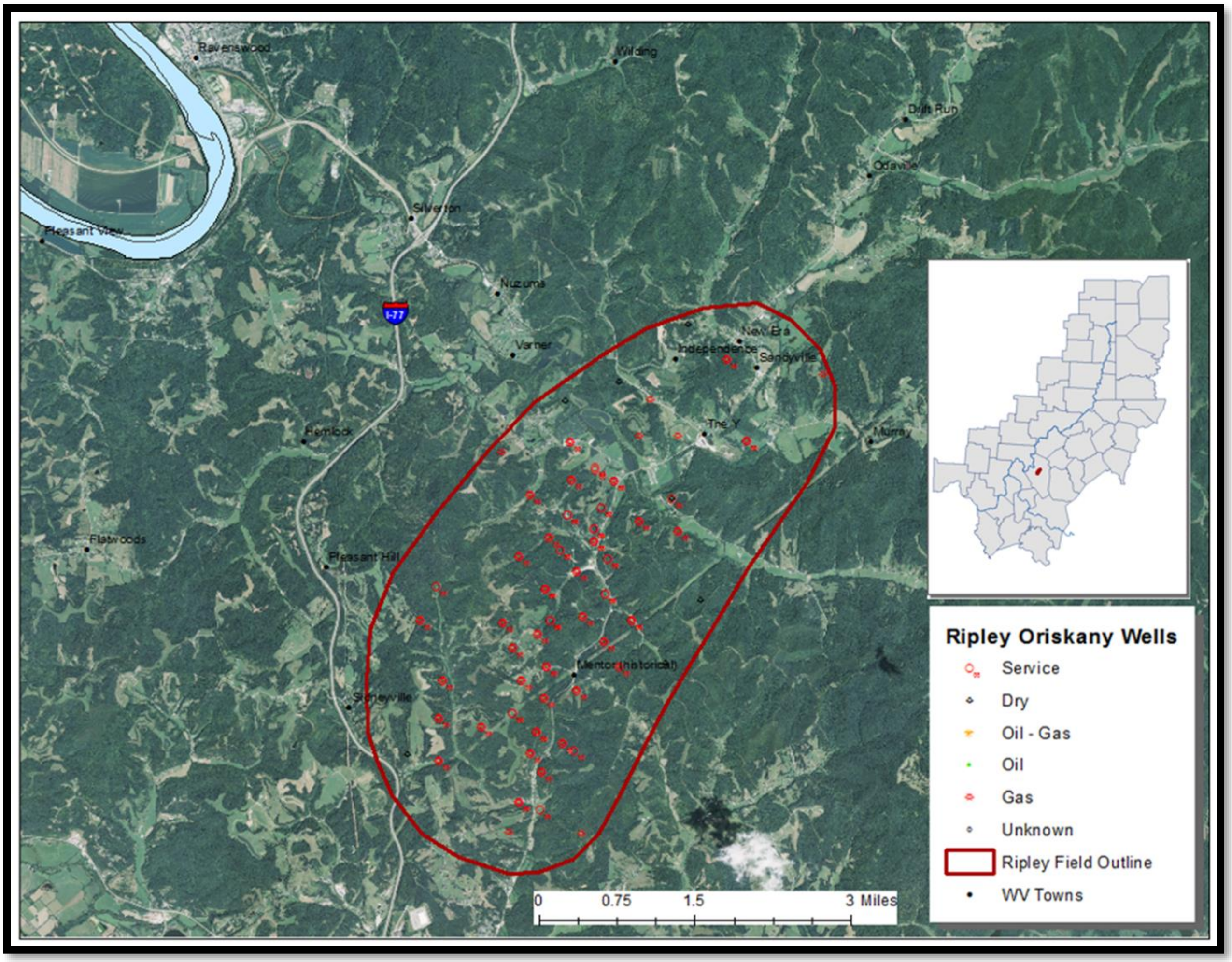



**Figure 5-52. Ripley Field (existing natural gas storage), with well locations.**

In the Ripley Field, Oriskany porosity is primary; to the east (and largely outside the AOI) many Oriskany storage fields utilize fracture porosity. The trap mechanism for the field is stratigraphic, with a permeability barrier on the western (updip) side of the field created by the pinchout of the uppermost permeable beds as the formation thins.

Pre-existing MRCSP GIS field-level data for the Ripley Field and data interpreted from geophysical logs as part of the current Study are provided in Tables 5-16 and 5-17, respectively. In this area of West Virginia, the Oriskany Sandstone generally is tightly cemented, with intermittent pay beds of more friable, porous and permeable sandstone. This may be partially responsible for the wide variation in porosity reported for the Oriskany in these summary tables (2 to ~9 percent).

***Table 5-16. Ripley field-level reservoir data (MRCSP GIS database).***

| Average producing depth (ft) | Net thickness (ft) | Pressure (psi) | Porosity (%) | Initial pressure (psi) | Trap type |
|---|---|---|---|---|---|
| 4,980 | 20 | 1,835 | 9.1 | not available | Structural/ Stratigraphic |

***Table 5-17. Reservoir data prepared for the Ripley Field as part of the current Study.***

| Values | Depth (ft) | Gross thickness (ft) | Net thickness (ft) | Average neutron porosity (%) |
|---|---|---|---|---|
| Minimum | 4,660 | 15 | 15 | 2.0 |
| Maximum | 5,012 | 56 | 56 | 2.0 |
| Average | 4,923 | 40 | 40 | 2.0 |

A major strength of the Ripley Field as a location for NGL storage is the presence of storage infrastructure and proximity to the Ohio River (about 3.5 mi away). In November 2016, Columbia Gas Transmission (now TransCanada) filed a request with the Federal Energy Regulatory Commission (FERC) to construct and operate three new storage wells in the Ripley field. The proposed wells (API Nos. 47-035-03026, 47-035-03027and 47-035-03028) are permitted as slant-hole drills (see Figure 5-53) and would add, according to the FERC filings, a combined total of 15 MMCF/day of deliverability. Proposed target depths for the wells range from 4,868 to 5,015 ft true vertical depth (5,163 to 5,357 ft measured depth), with pay thickness ranging from 35 to 38 ft.

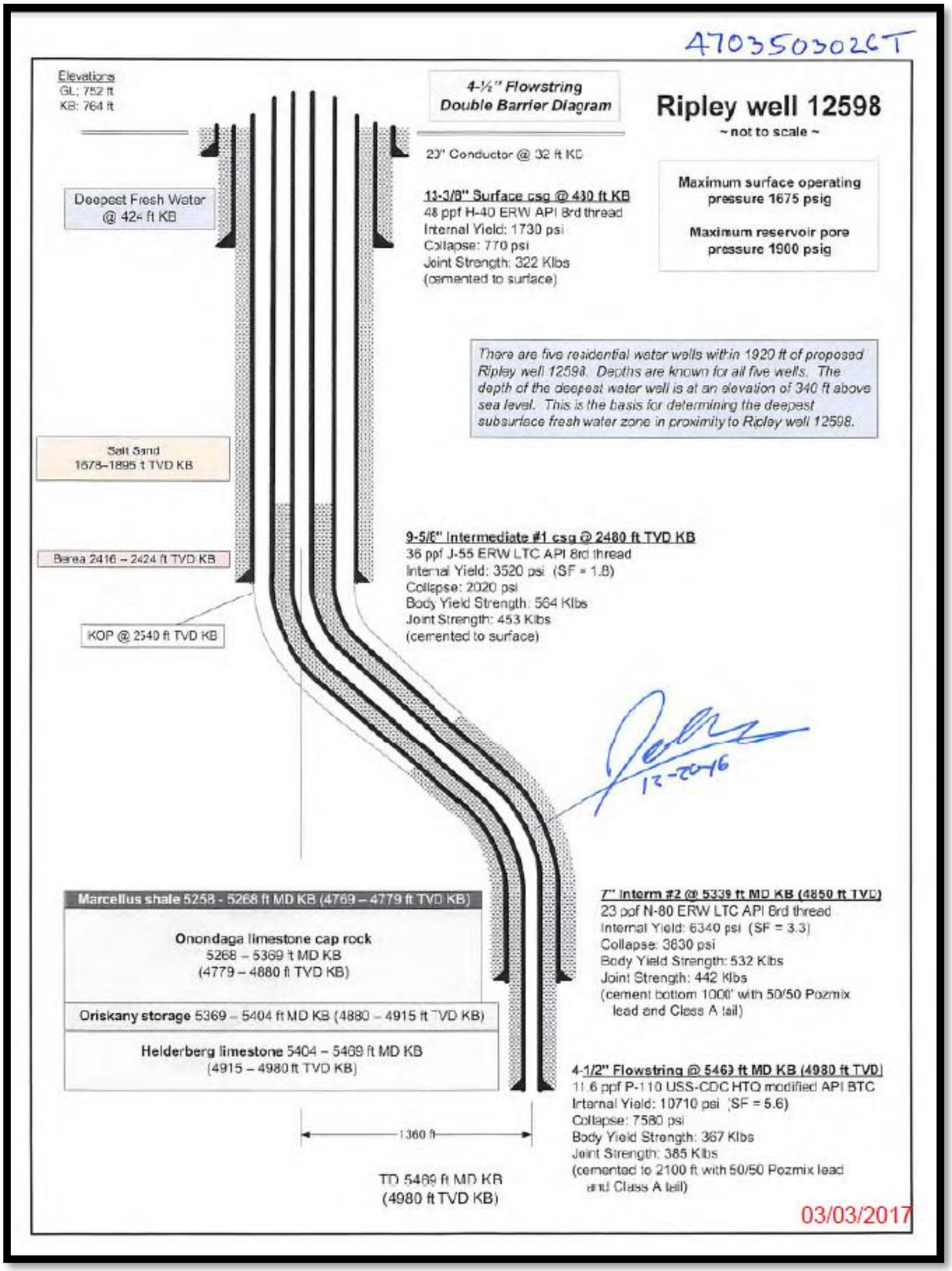



**Figure 5-53. Wellbore design for one of the three new storage wells Columbia Gas/TransCanada is currently drilling in the Ripley Field.**

The Ripley Field received high ratings not only for its location but also for its size (more than 9,000 ac), its average depth (4,923 ft, which is well within in the 3,500 – 5,000 ft range) and capacity to store gas (a working capacity of more than 10,000,000 MCF). The field received favorable ratings for net thickness (greater than 20 ft), porosity (in the 5 – 10 percent range), and reservoir pressure (greater than 1,500 psi). Stacked and adjacent opportunities exist in this area of the Southern Prospect, as Ripley Field overlies the North Ripley Field and is within the footprint of Elk-Poca (Sissonville) Field. The only poor (i.e., 0) rating the field received was for well penetrations, one criterion commonly associated with sandstone reservoirs throughout this portion of the Appalachian basin.

#### *5.3.3.5 Newburg Sandstone: Depleted Gas Fields*

The Research Team identified four Newburg gas fields that offer NGL storage potential (Figure 5-54). North Ripley Field is situated along the Ohio River in Jackson County. The other three straddle the Kanawha River. Less than five mi to the north of the Kanawha River, in Putnam and Kanawha counties, the Rocky Fork Field is separated by a narrow structural low from the adjacent Cooper Creek Field. The Kanawha Forest Field, located in Kanawha and Boone counties, abuts the river to the south.

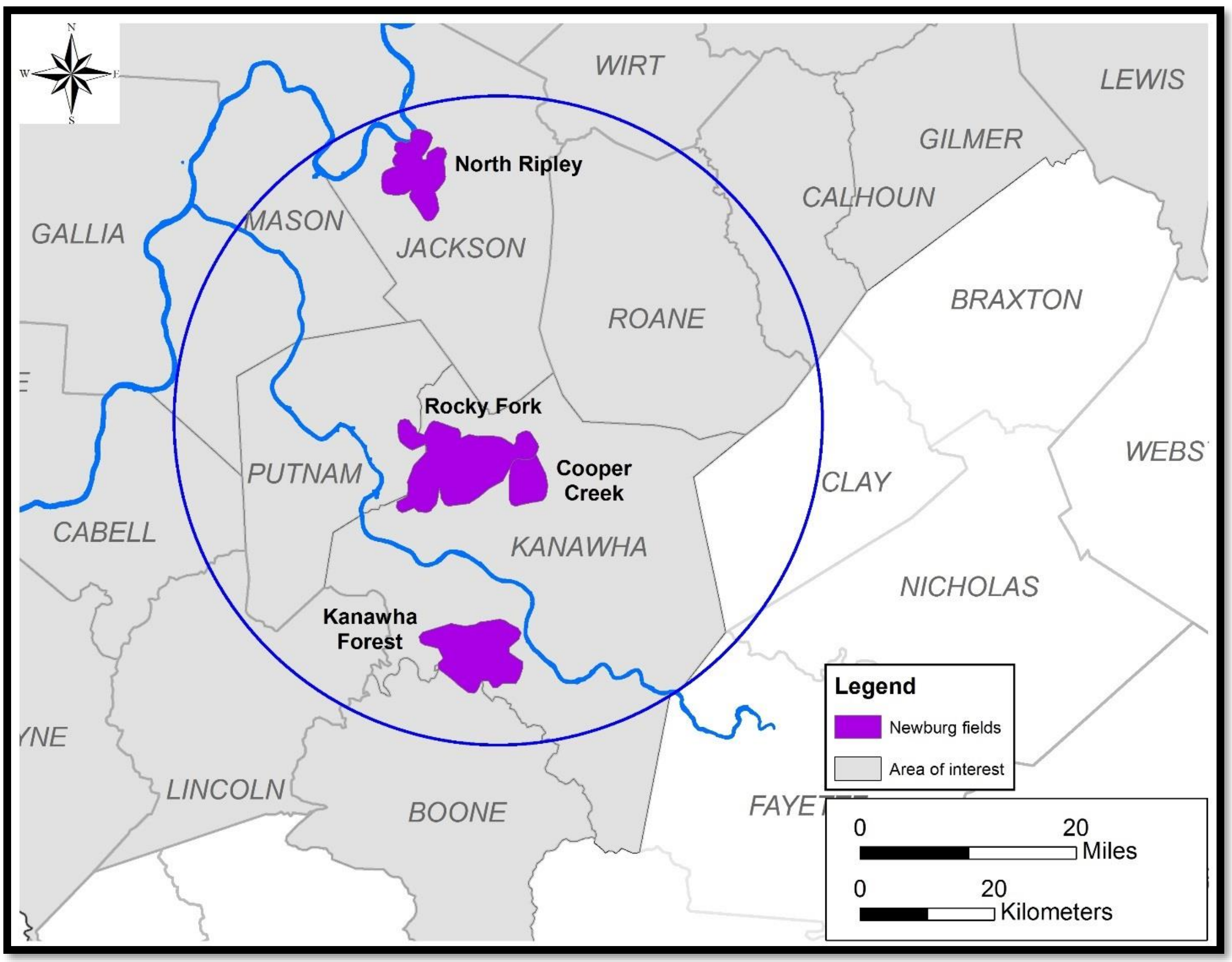



**Figure 5-54. Four Newburg sandstone fields in the Southern Prospect.**

These fields are separated geographically and geologically by saltwater contacts and dry holes (Lewis, 2013), with field sizes ranging from about 8,600 ac (Cooper Creek Field) to more than 42,000 ac (Rocky Fork Field). North Ripley Field is roughly 19,000 ac in size, and the Kanawha Forest Field is about 28,000 ac in size.

All four of these Newburg sandstone depleted gas fields received similar ratings. They all rated highly for their large footprints, good porosities (which range from 11 to 14 percent, see Figure 5-55) and proximity to proposed/existing infrastructure. In addition, the Newburg sandstone is a combination stratigraphic/structural play, and these fields have well documented trap integrity. They are located relative to structural highs with good closure and downdip salt water contacts, and stratigraphically to updip pinchouts.

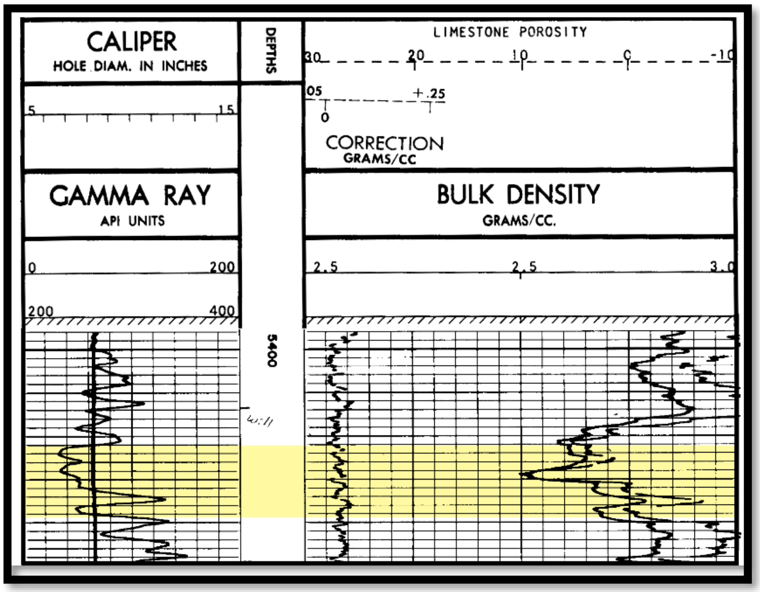



**Figure 5-55. Typical geophysical log for the Newburg sandstone, with high porosity highlighted in yellow (modified from Lewis, 2013).**

The fields are rated moderately well for their high pressures (>1,500 psi) and stacked opportunities (described individually in the subsections below). High initial pressures indicate that the overlying Salina Group, with its interbedded anhydrite, salt and dolomite, provides a competent vertical seal for storage. All four fields are rated poorly for their deep depths (>5,000 ft) and, as is the norm for the Appalachian basin, the number of legacy wells in each field is large.

Developed in the 1960s and 1970s, these Newburg fields produced natural gas from reservoir rock with well-developed porosity and permeability (Lewis, 2013) and high initial open flows, followed by steep decline curves (Patchen, 1996), with a 90 percent recovery factor. Based on this information, the Newburg sandstone could be suitable for small-scale injection operations (Lewis, 2013), likely for optimal use as peak-load storage.

Field-specific reservoir data were prepared for these fields by compiling pre-existing MRCSP GIS field-level data with average pay thickness and permeability data from Patchen (1996). Table 5-18 provides this information.

*Table 5-18. North Ripley, Rocky Fork, Cooper Creek and Kanawha Forest field-level reservoir data.*

| Field | Average producing depth (ft) | Net thickness (ft) | Average pay thickness (ft)* | Pressure (psi) | Porosity (%) | Permeability (mD)* | Initial pressure (psi) | Trap type |
|---|---|---|---|---|---|---|---|---|
| North Ripley | 5,379 | 77 | 7 | 2,300 | 14.0 | | 2,329 | Stratigraphic /Structural |
| Rocky Fork | 5,623 | 140 | 5 | 2,400 | 18.0 | 46 | 2,435 | Stratigraphic /Structural |
| Cooper Creek | 5,754 | 30 | 6 | 2,500 | 15.0 | | 2,491 | Stratigraphic /Structural |
| Kanawha Forest | 5,378 | 48 | 8 | 2,300 | 11.0 | 14 | 2,329 | Structural |

*from Patchen (1996)

## North Ripley Field

Discovered in the late 1960s, North and South Ripley fields produced a combined 86.7 BCF gas from 1970 to 1973, at depths ranging from 5,010 to 5,780 ft, with wells in North Ripley averaging 7 ft of pay. Initial pressures averaged 2,329 psi, with initial production averaging 12 MMCF/day/well (Patchen, 1996). The Newburg sandstone is noted for the number of wells exhibiting high initial production volumes, as illustrated in Figure 5-56.

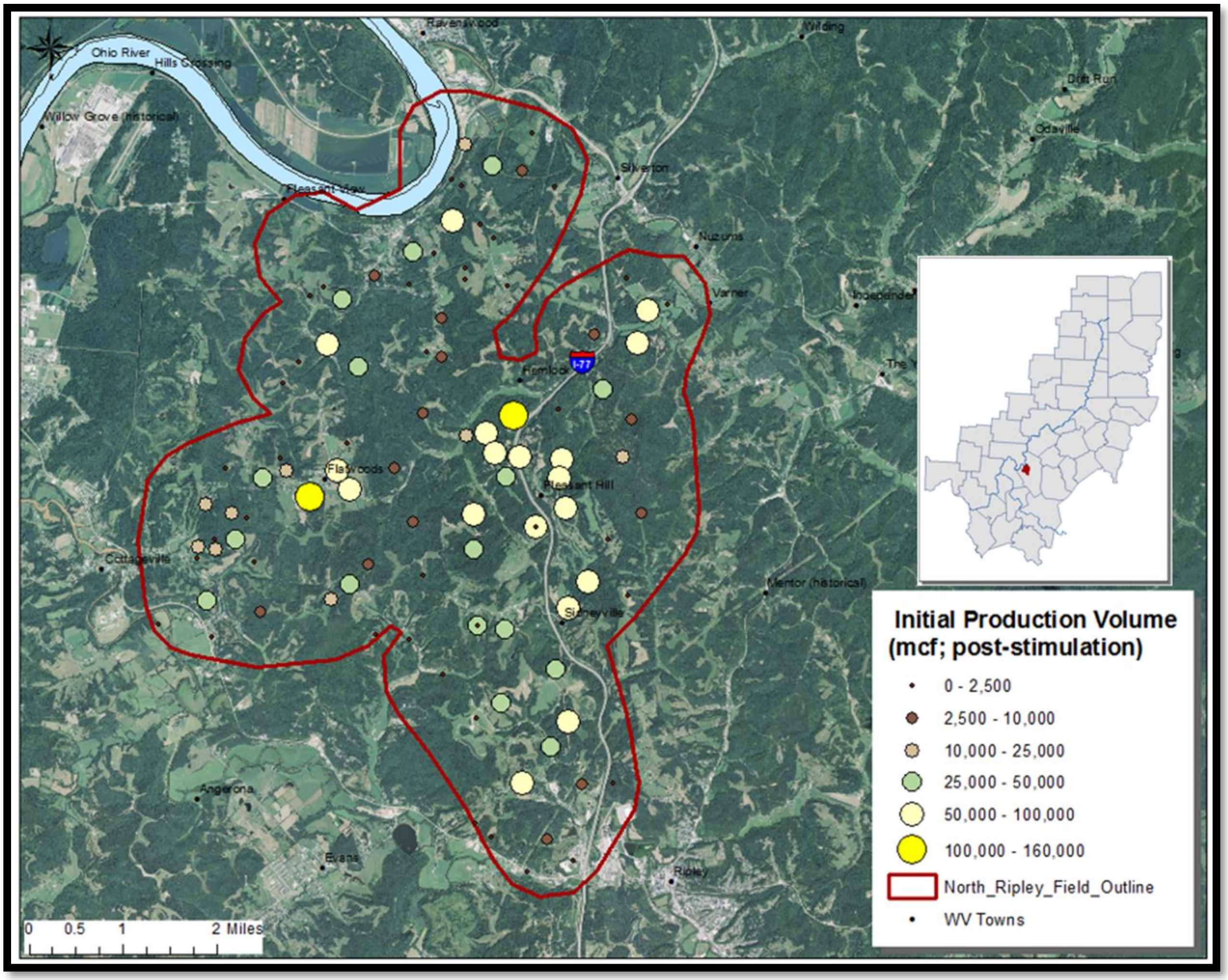



**Figure 5-56. North Ripley Field, Initial gas production (MCF) post-stimulation. Overall production volume (>86 BCF) was combined with the nearby South Ripley Field.**

The North Ripley Field was developed along the edge of the updip stratigraphic pinchout, where the higher elevations to the west generally had less than 10 ft of sandstone. The measured depth map and cross section provided in Figures 5-57 and 5-58, respectively, illustrate this relationship. Higher open flows were associated with thicker sandstone (yellow to orange on the net thickness map, Figure 5-57) that follows subtle structural nosings (highs as shown in paler orange to yellow on the measured depth map, Figure 5-57). These relationships are also illustrated by the larger cross section given in Figure 5-59.

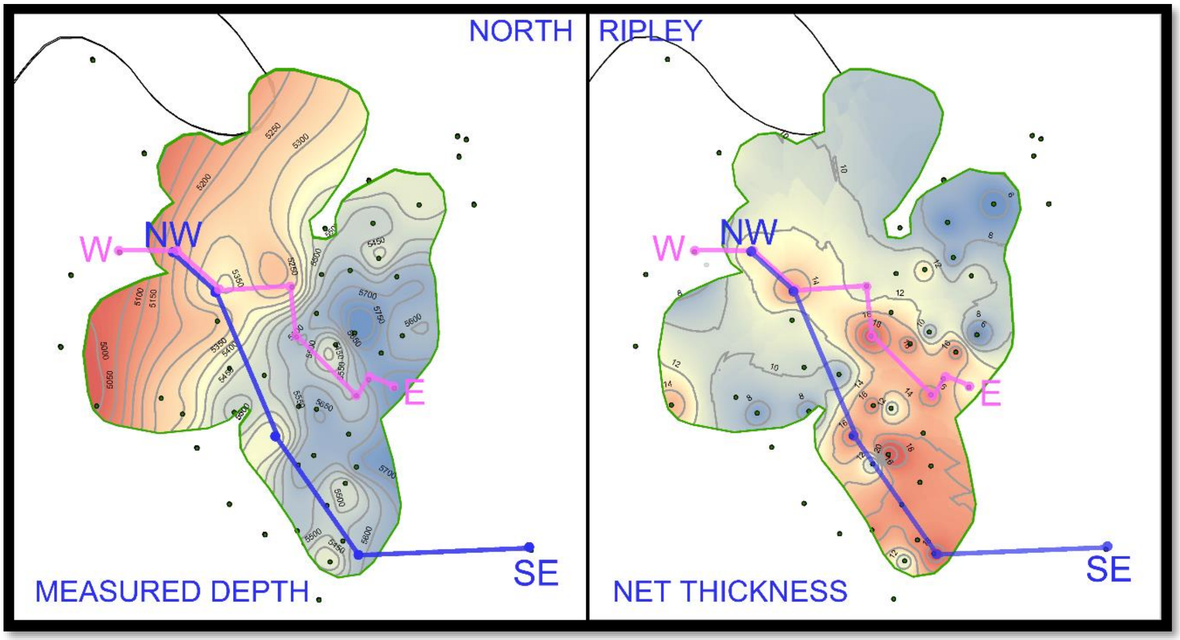



**Figure 5-57. Measured depth (ft) to the Newburg sandstone (left) and net thickness (ft) (right) in North Ripley Field, superimposed with cross section locations.   Green dots represent well control.**

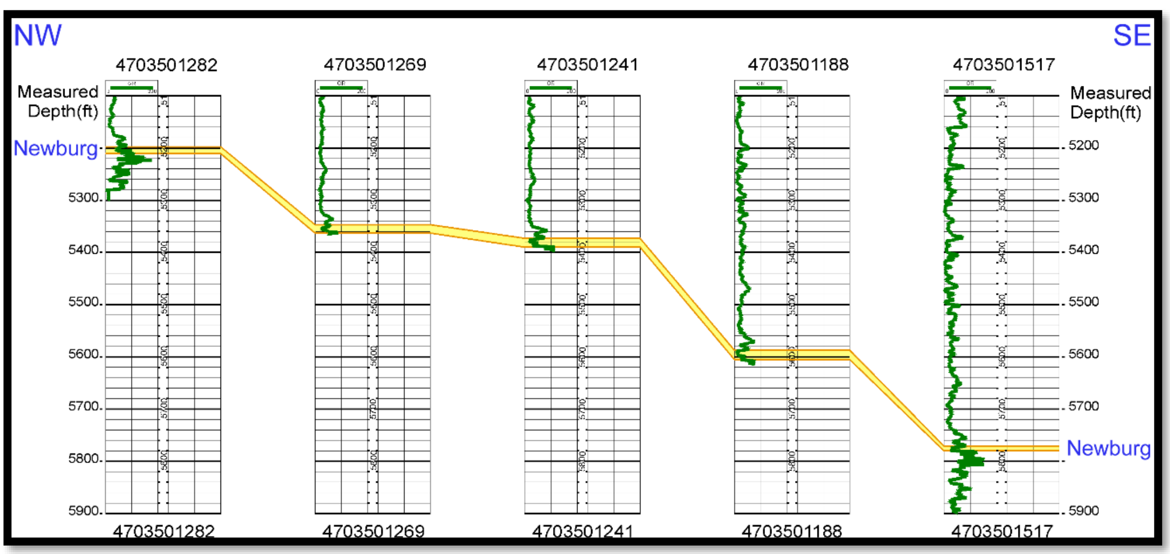



**Figure 5-58. Northwest-southeast cross section across North Ripley Field, illustrating sandstone development between the updip pinchout (left) and lower salt-water contact (right).**

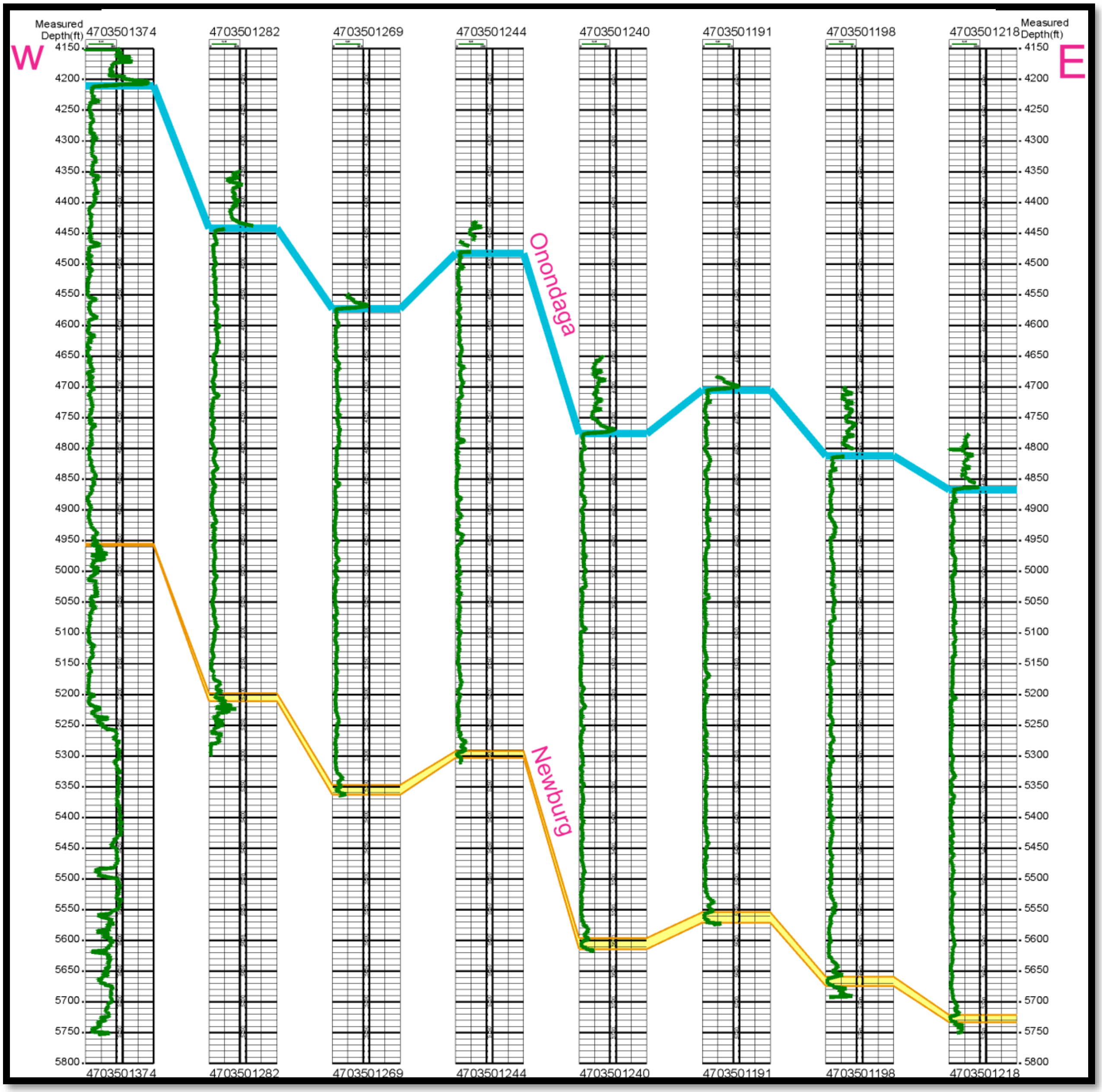



**Figure 5-59. West-east cross section across North Ripley Field that encompasses the sweet spot containing high open-flow wells and thick net sandstone, positioned structurally on highs between the updip pinchout (left 2 wells) and lower salt-water contact (not shown).**

## Rocky Fork – Cooper Creek Fields

Discovered in 1966 and 1969 respectively, Rocky Fork and Cooper Creek fields produced a combined 154 BCF gas from 1970 to 1973, at depths ranging from 5,220 to 6,150 ft, from an average 5 ft of pay. Initial pressures averaged 2,250 psi, with average initial production of 13 MMCF/day/well (Patchen, 1996). Initial production volumes for these Newburg sandstone fields are shown in Figure 5-60.

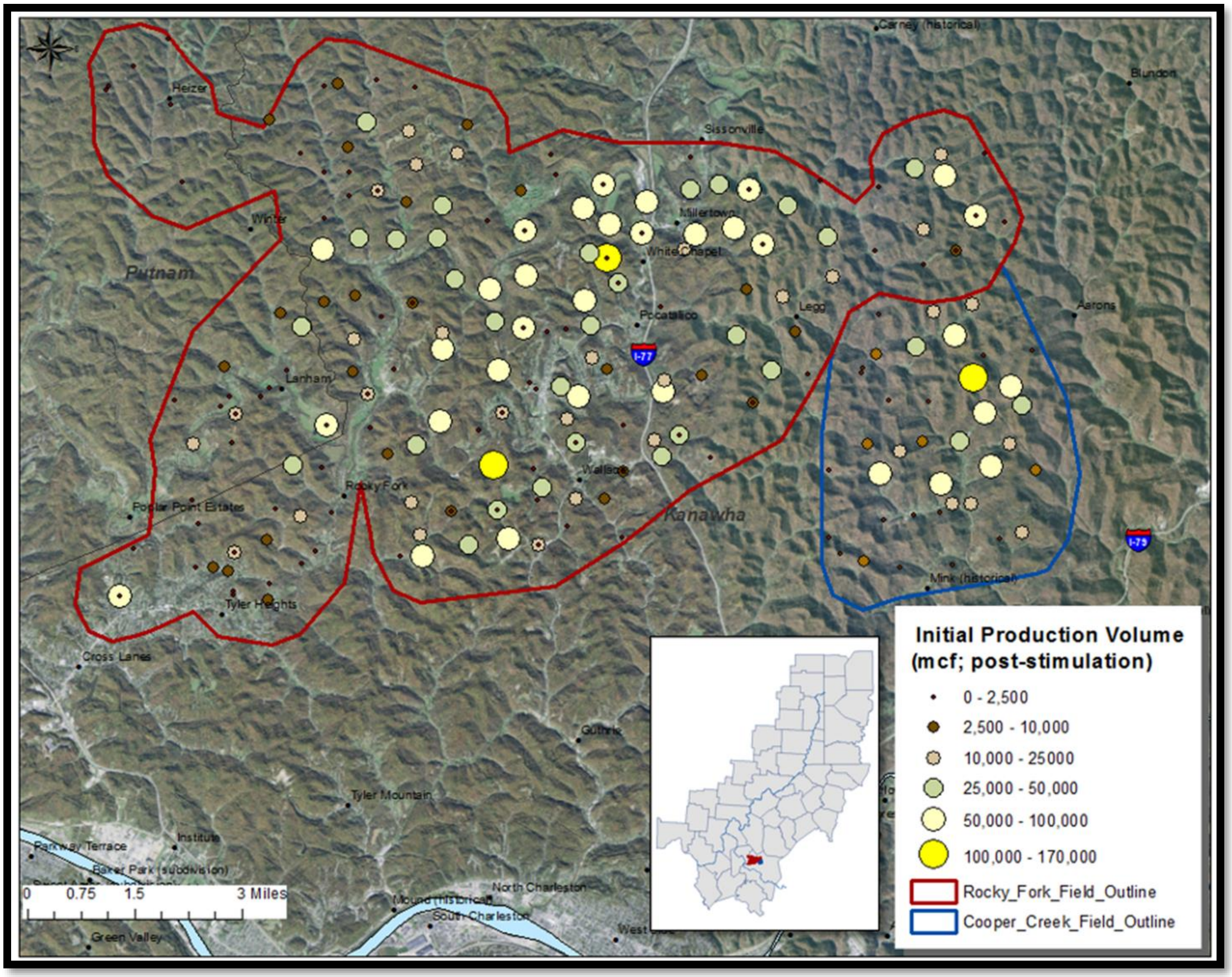



**Figure 5-60. Rocky Fork and Cooper Creek fields, Initial gas production (MCF) post-stimulation.**

Stacked storage opportunities are available in the area of Rocky Fork – Cooper Creek fields, as they are both overlain by the Elk-Poca (Sissonville) Field. In the case of Rocky Fork Field, the mudstone facies of the Greenbrier Limestone presents an additional stacked opportunity.

Figure 5-61 illustrates the measured depth and net thickness characteristics of these fields. Newburg sandstone reservoir thickness and porosity development follow subtle structural highs along the western edge of Rocky Fork Field, as shown in the cross section, with measured depths relative to MSL (Figure 5-62).

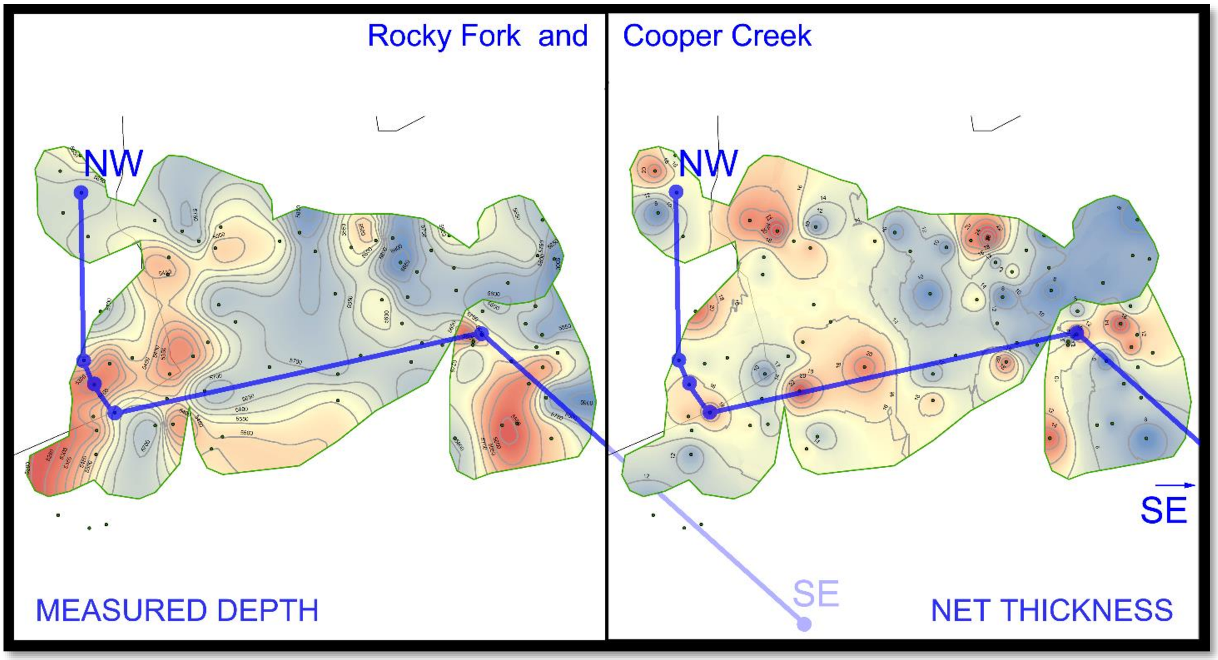



**Figure 5-61. Measured depth (ft) to the Newburg sandstone (left) and net thickness (ft) (right) in the Rocky Fork-Cooper Creek area. Cross section location shown in blue; green dots represent well control.**

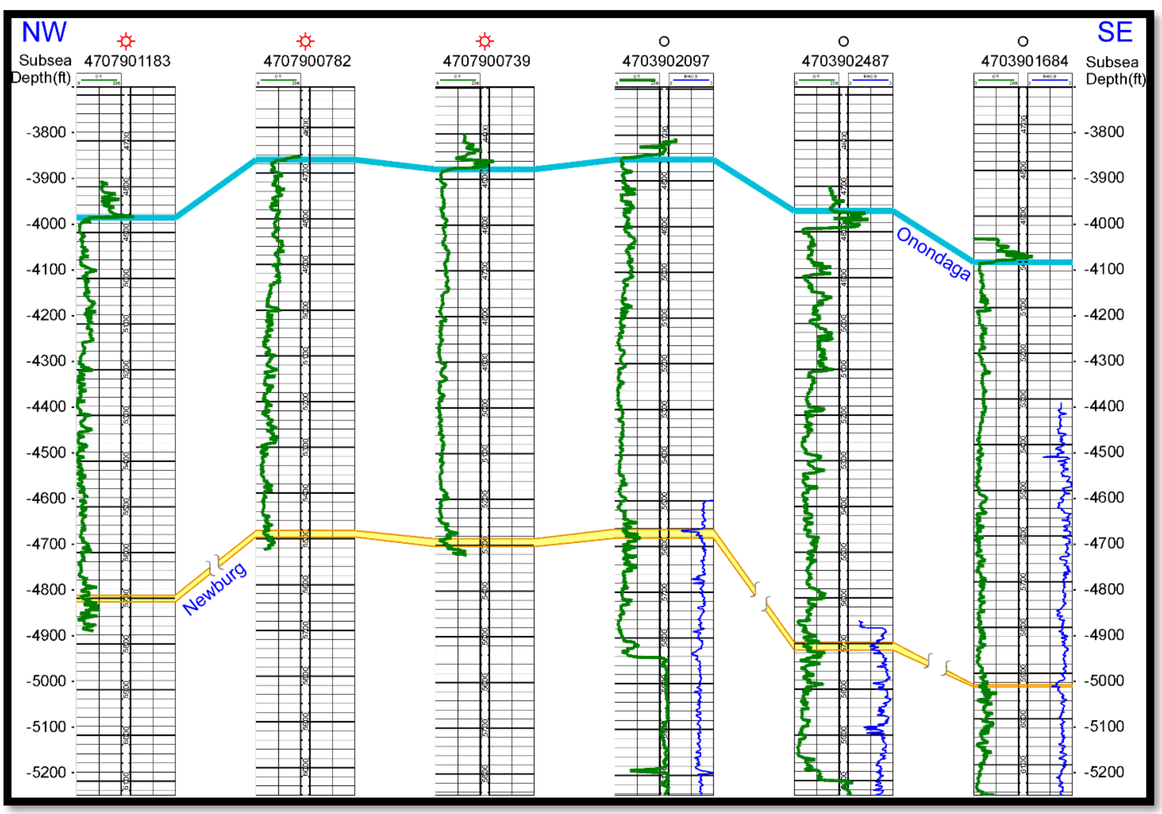



**Figure 5-62. Northwest-southeast structural cross section across Rocky Fork-Cooper Creek fields area, illustrating sandstone and porosity development over structural highs, the deeper field level of Cooper Creek relative to Rocky Fork (47-039-02487), and change in character outside the fields (47-039-01684).**

## Kanawha Forest Field

Discovered in 1964, Kanawha Forest Field produced 49 BCF gas from 1970 to 1973, at depths ranging from 4,940 to 5,940 ft, from an average 8 ft of pay. Initial pressures averaged 2,300 psi, and the average initial production was 1.2 MMCF/day/well (Patchen, 1996). Average initial volumes for this field are lower than the other Newburg fields evaluated by the Study, although high volumes do occur on the northern edge of the field, as shown in Figure 5-63.

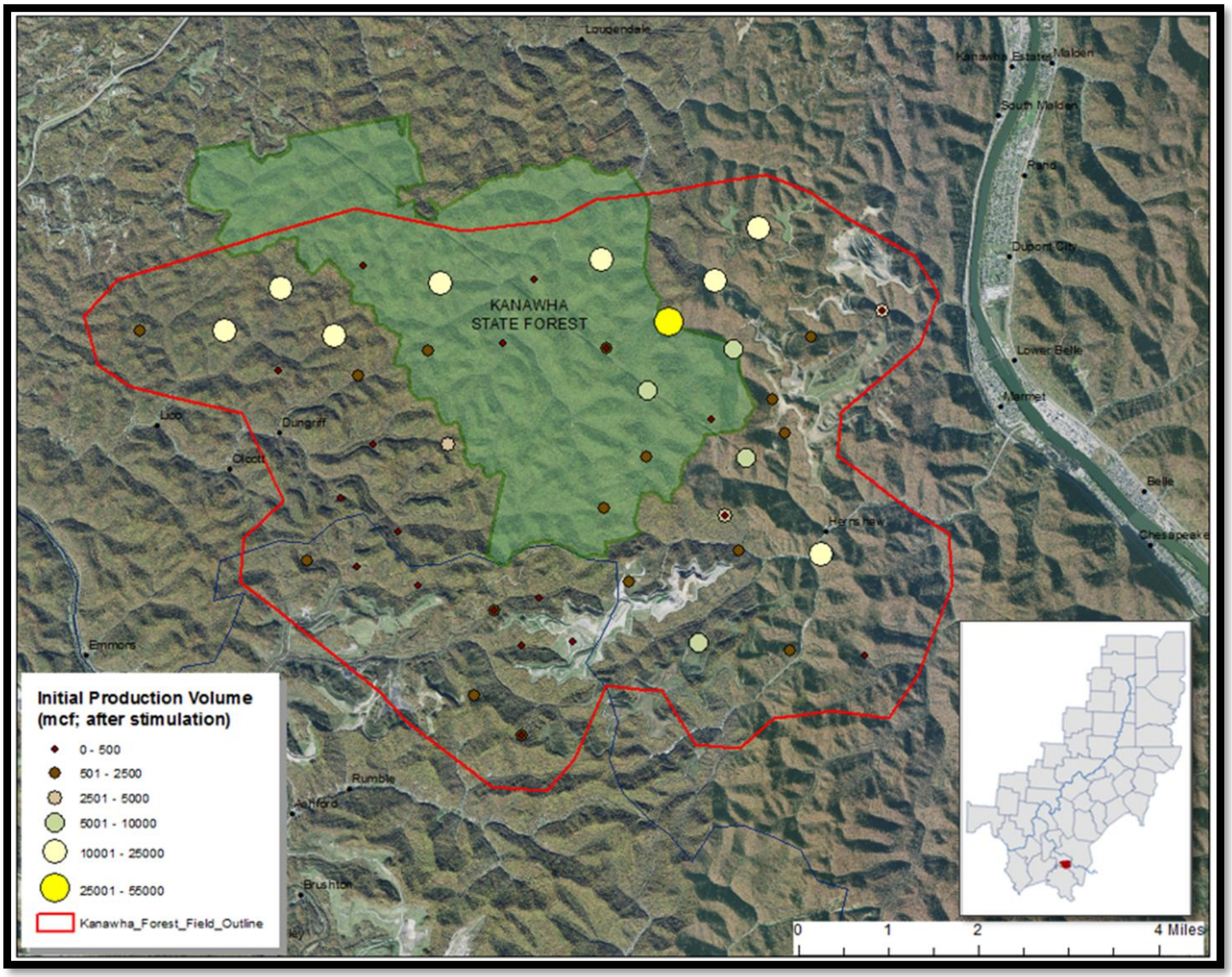



**Figure 5-63. Kanawha Field, Initial gas production (MCF) post-stimulation.**

Stacked storage opportunities are present where the Kanawha Forest Field is overlain by two Oriskany Sandstone fields (Kanawha Forest and Campbell Creek) and by lime mudstones of the Greenbrier Limestone.

Figure 5-64 maps the measured depth and net thickness of the Newburg sandstone in this field. Figure 5-65 is a cross section highlighting the net thickness of clean sandstone and porosity development in this interval.

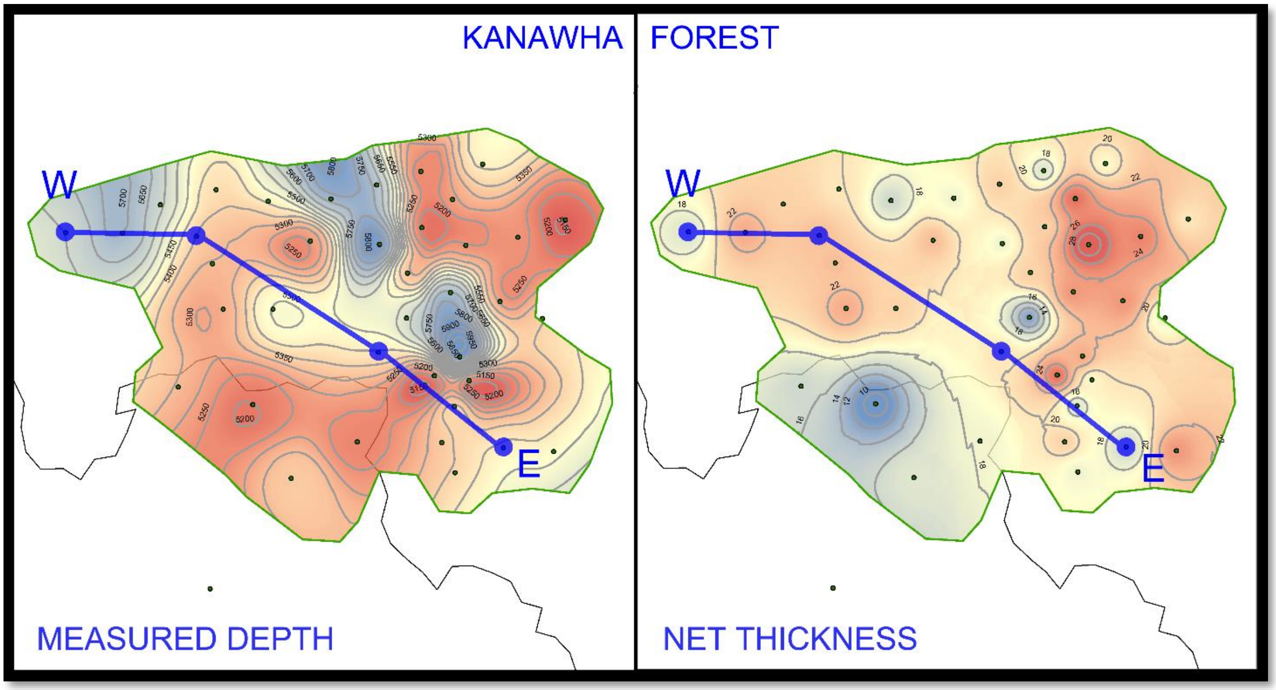



**Figure 5-64. Measured depth (ft) to the Newburg sandstone (left) and net thickness (ft) (right) in Kanawha Forest Field. Cross section location shown in blue; green dots represent well control.**

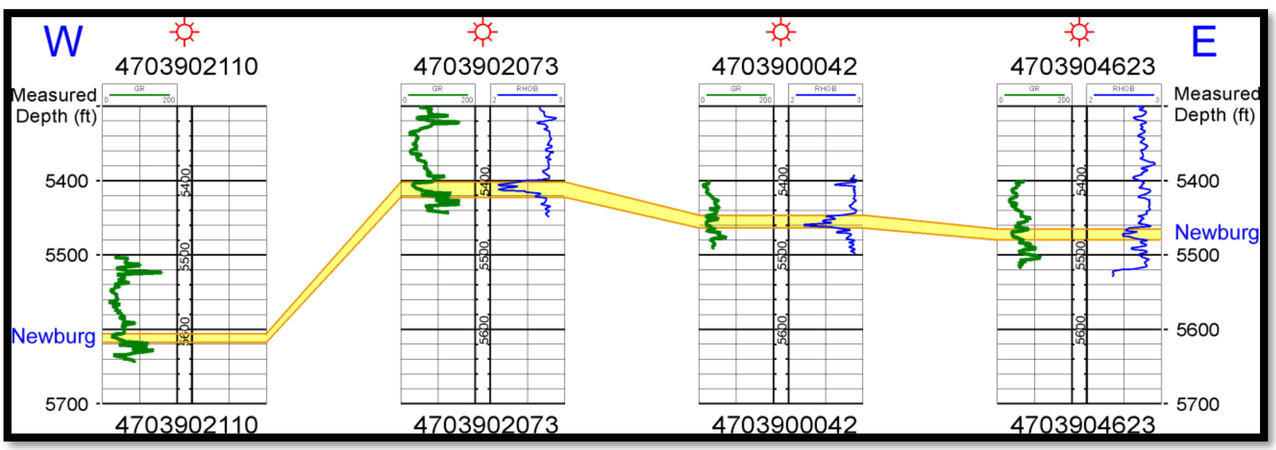



**Figure 5-65. West-east cross section across Kanawha Forest Field.**

## 6.0 RECOMMENDATIONS AND SUGGESTIONS FOR ENGINEERING FOLLOW-UP STUDY

The goal of the Research Team was to complete a geologic study of all potential options for subsurface storage of NGLs from areas of shale production in eastern Ohio, southwestern Pennsylvania and northern West Virginia to end users in southern West Virginia and northeastern Kentucky. The Study area, or AOI, comprised 50 counties in these three states. The work involved the mapping and identification of areas where the Salina F Salt is at least 100 ft thick and suitable for solution mining; mapping and identification of areas of the Greenbrier Limestone that are at least 40 ft thick and suitable for hard-rock mining; and mapping the thickness and extent of sandstone reservoirs in depleted gas fields and natural gas storage fields.

The Research Team investigated the subsurface geology in the AOI in an attempt to determine which formations and depleted gas reservoirs have the required characteristics to provide adequate, secure, long-term storage of ethane and other NGLs. The Study did not incorporate many other factors when compiling rankings of the top storage opportunities. For example, the Research Team did not consider who owns and operates a gas field that was one of the top-ranked fields, or if this operator would be interested in converting a portion of the field to NGL storage. The Research Team also did not consider who owns the rights to the Greenbrier Limestone or Salina Salt in a given area or if these owners might be interested in cooperating in an NGL storage project. And, the Research Team did not take into consideration that one of the better locations for a storage facility might be in an area in which Marcellus or Utica shale wells might be drilled in the future.

In addition, this Study did not take into account surficial activities above our highest-rated storage opportunities, other than to exclude geologic units beneath towns and cities from consideration. Nor did the Research Team consider the cost implications of developing storage and the necessary pipelines between the storage facility and the main pipelines along the Ohio River. The focus was entirely on the subsurface geology in the AOI.

However, the Research Team understands that geology is not the only consideration in NGL storage site selection. Various factors must be taken into account, and more work needs to be conducted, beginning with an on-site engineering study of a potential storage facility. Appendix J includes examples of some of these considerations for designing and computing the storage capacity of mined-rock caverns, salt caverns and depleted gas fields. The Research Team recommends that a detailed site-specific geologic study be performed in conjunction with the engineering study. These on-site studies should include additional coring and logging of research wells drilled through the formation (limestone or salt) or depleted reservoir that is under consideration. Core tests should be performed to determine porosity and permeability in gas reservoirs, and mechanical strength in limestone. Core and thin section descriptions by a qualified geologist can identify the amount and type of porosity in a gas reservoir; the amount and type of impurities in salt; and the thickness and homogeneity of the desired limestone facies within which to develop the storage container. These analyses can also be used to evaluate the reservoir character of the adjacent rock units above, below and adjacent to the intended storage container to establish seal integrity.

This combined engineering-geologic study will result in a detailed feasibility and economic evaluation of one or more site-specific storage candidates, taking into account many surface factors as well as additional subsurface criteria. These criteria should include all key engineering parameters that may eventually be required to obtain a permit to develop a storage facility in any of the three states in the AOI. Such a study is a necessary next step to move the entire initiative – the actual construction of a pipeline and Appalachian Storage Hub – forward in the near future.

## 7.0 CONCLUSIONS

This twelve-month Study comprised multiple strategies intended to identify, characterize, evaluate and rank the subsurface geologic resources of the tri-state area of Ohio, Pennsylvania and West Virginia as potential options for the storage of NGLs. The important outcome of the Study is that multiple options are present along both the Ohio and Kanawha rivers where a storage facility could be constructed in as many as three different types of storage containers.

The Research Team identified an AOI on both sides of the Ohio River that extends from southwestern Pennsylvania in the north as far as the Kanawha River Valley in southern West Virginia. Individual geologic formations and intervals of interest in this region included the Mississippian Greenbrier Limestone for the creation of mined-rock caverns; the Silurian Salina salt for the creation of cavities through brine extraction; and depleted gas fields in siliciclastic reservoirs of the Lower Mississippian-Devonian Keener to Berea interval; Upper Devonian Venango, Bradford and Elk intervals; Lower Devonian Oriskany Sandstone; Silurian Newburg sandstone and Clinton/Medina Group; and Lower Ordovician - Upper Cambrian Rose Run-Gatesburg sandstones.

The Study evolved into three main areas of focus, including: (1) a regional subsurface study of all geologic units of interest, including formation descriptions, inter-state correlations and mapping; (2) developing criteria with which to rate and eventually rank the candidate formations and reservoirs as safe and secure storage containers; and (3) a project database and website in which all of the data and research findings are located and can be accessed by the public and all companies who are interested in developing the Appalachian Storage Hub.

The Research Team prepared geologic cross sections throughout the AOI to provide a visual representation of the AOI's subsurface stratigraphy, illustrate lateral and vertical relationships among potential reservoirs for ethane storage, and most importantly, to correlate the subsurface lithostratigraphy for the region. Using this lithostratigraphic framework, regional structure and gross thickness (isopach) maps were prepared for each of the 10 geologic intervals of interest. These maps incorporated the Research Team's collective knowledge of Appalachian basin geology, starting with existing datasets and maps prepared by the Research Team for other regional geologic studies and adding current publicly available data available for each of the geologic intervals to illustrate and convey the best available subsurface geologic information specific to the AOI.

Due to the varied nature of geologic intervals being evaluated as storage prospects, characterization efforts for each type of storage container (i.e., mined-rock cavern, salt cavern and depleted gas reservoir) were unique. Regional depth, structure and net thickness maps were used to identify those geographic areas with the best mined-rock and salt cavern opportunities.

For the Greenbrier interval, net thickness maps were prepared for three discrete facies packages (upper grainstone, lime mudstone and lower grainstone). The best areas for mining a cavern from the Greenbrier's lime mudstone facies will be found where the lime mudstone facies is relatively thick and juxtaposed between upper and lower grainstone facies with bound water and water-filled porosity, which will assure hydraulic containment of stored NGLs.

For the Salina salt interval, regional mapping efforts identified four areas where the net thickness of Salina F4 Salt is greater than 100 ft, all located along the Ohio River Valley corridor. Thickness is important because operators must leave intervals of salt above the cavern and below the cap rock, as well as below the base of the cavern, to ensure vertical confinement. The interbedded nature of the salt with anhydrite and dolomite increases rapidly outside of these >100-ft footprints, so it is also important to leave a buffer zone between the cavern and the edge of the salt to ensure lateral confinement.

Due to the multitude (>2,700) of depleted gas fields in the AOI, the Research Team performed a preliminary assessment to focus characterization work for siliciclastic reservoirs within the AOI. Of these, approximately 1,500 fields occur at a depth of 2,000 ft or more. This smaller digital dataset was chosen for the preliminary reservoir characterization and rating work, as it represented the large majority of fields with reservoir data for the Study's sandstone intervals of interest (Early Mississippian through Late Cambrian age). Preliminary rating work resulted in the selection of 12 natural gas storage fields and 113 depleted gas fields for further evaluation.

Based on the results of preliminary reservoir characterization work, the Research Team took a closer look at the top opportunities using a series of detailed rating criteria tailored to each category of storage container. These efforts identified a short list of 30 locations with the greatest potential to facilitate underground storage (Figure 7-1).

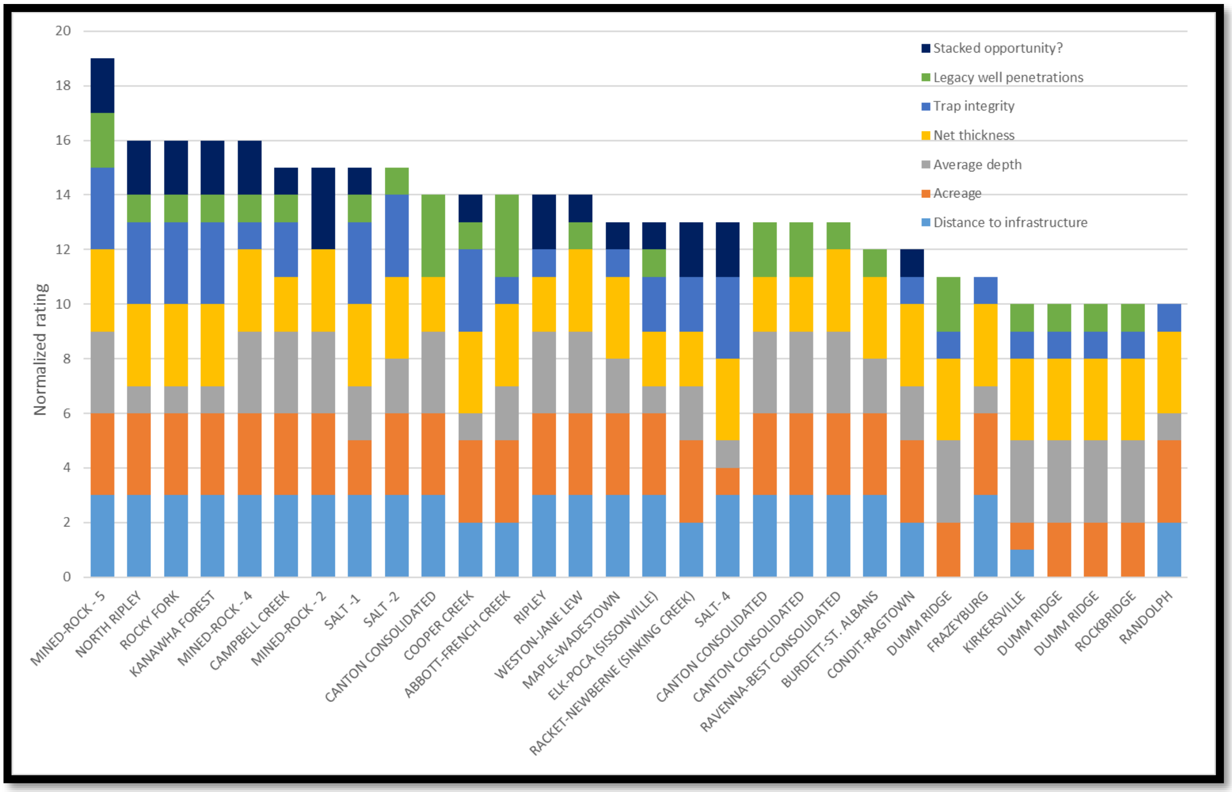



**Figure 7-1. Comparison of normalized ratings for seven criteria among 30 top-rated storage opportunities in the Study area.**

Three areas of thick Salina F4 salt are situated in the northern and central areas of the AOI along the Ohio River. The top-rated areas where the Greenbrier's lime mudstone facies was at least 40 ft thick and has a substantial acreage were identified in West Virginia. In addition, the top two natural gas storage fields and highest ranked depleted gas reservoirs are located in West Virginia.

The Study's ranking efforts were intended to identify the "best of the best" NGL storage opportunities irrespective of storage container type. To facilitate this work, ratings for the top 30 storage opportunities were normalized by using only those criteria common to each container type – distance to infrastructure, acreage, average depth, net thickness, trap integrity, legacy well penetrations and stacked opportunities. Figure 7-1 provides a visual comparison of these normalized ratings. A majority of the fields/locations have comparable rating values for distance to infrastructure, acreage, net thickness and number of well penetrations. What sets the highest ranked opportunities apart are the following: average depth, favorable trap integrity and presence of stacked opportunities. Those with a normalized rating of 15 or higher represents the AOI's best opportunities, and include a combination of all four types of storage containers (mined-rock cavern, salt cavern, natural gas storage field and depleted gas field).

The Research Team identified three storage prospects that contain top-rated geologic intervals/reservoirs and exhibit varying degrees of stacked potential. These prospects have been identified by general geographic area – northern, central and southern –and serve as examples of how end users may apply the subsurface geologic and reservoir data prepared for the current Study to their own underground storage considerations.

The Northern Prospect encompasses the northern panhandle of West Virginia and adjacent portions of eastern Ohio and western Pennsylvania, presenting storage opportunities in the Clinton/Medina sandstones in Ohio's Ravenna-Best Consolidated Field and two Salina F4 Salt cavern opportunities straddling the Ohio River. In addition, Oriskany Sandstone core data from Beaver County, Pennsylvania, can be extrapolated to, and used to aid in the evaluation of, Oriskany fields or pools of specific interest to the operator.

The Central Prospect includes portions of southeastern Ohio, southwestern Pennsylvania and north-central West Virginia and contains multiple storage opportunities, five of which were evaluated by the Research Team: Greenbrier Limestone mined-rock cavern options throughout the area; depleted gas reservoirs in the Keener to Berea interval in and between the Maple-Wadestown and Condit-Ragtown fields; a depleted gas reservoir in the Upper Devonian Venango Group in the Racket-Newberne (Sinking Creek) gas storage field; a depleted gas reservoir in Upper Devonian sandstones in the Weston-Jane Lew Field; and a Salina F4 Salt opportunity near Ben's Run.

The Southern Prospect is situated in the Kanawha River Valley of West Virginia and includes several storage opportunities, from mined-rock caverns in the Greenbrier interval to various depleted gas fields in the Keener to Berea, Oriskany Sandstone and Newburg sandstone intervals. The Salina F4 Salt was determined not to have sufficient thickness in this area to warrant further evaluation, but nonetheless, many adjacent and/or stacked opportunities are available here within a relatively small geographic area proximal to a favorable corridor. In particular, Oriskany and Newburg sandstone reservoirs, including those of the Elk-Poca (Sissonville), North Ripley, Rocky Fork, Cooper Creek and Kanawha Forest fields, have very attractive porosity and pressure characteristics; well documented trap integrity; and present stacked opportunities.

The Research Team recommends a combined engineering-geologic study as the next step in moving the initiative of constructing a pipeline and moving the Appalachian Storage Hub forward. Such a study will result in a detailed feasibility and economic evaluation of one or more site-specific storage candidates, taking into account many surface factors as well as additional subsurface criteria. These criteria should include all key engineering parameters that may eventually be required to obtain a permit to develop a storage facility in any of the three states in the AOI.

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