APPALACHIAN STORAGE HUB (ASH) FOR LIQUID ETHANE

QUARTERLY REPORT

February 2017 – April 2017

Submitted By

APPALACHIAN OIL & NATURAL GAS RESEARCH CONSORTIUM

National Research Center for Coal & Energy

Ohio Geological Survey

Pennsylvania Geological Survey

West Virginia Geological Survey

MAY 2017

Quarterly Progress Report

1.0 INTRODUCTION

The Appalachian Oil & Natural Gas Research Consortium (Consortium) has reached the final quarter in their one-year Appalachian Storage Hub (ASH) for Liquid Ethane Study (the Study) to identify potential reservoirs for the storage of liquid ethane and other products derived from the liquid-rich Marcellus and Utica shale plays. The main goal of the Study is 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. Essentially, this pipeline would follow the Ohio and Kanawha rivers.

The project is being 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).

During the initial quarter of the Study (August 1 – October 31, 2016) the efforts of the Consortium were concentrated on: defining the area of interest (AOI) (Appendix 6.1); data collection within the AOI; development of a project database and website; and correlation of subsurface units ranging from Mississippian Greenbrier Limestone to Upper Cambrian Gatesburg Formation.

Second quarter (November 1, 2016 – January 31, 2017) milestones were to: continue the stratigraphic correlation of key units; initiate the mapping program for all potential storage units; and initiate the studies of reservoir character.

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 in sandstone reservoirs in the Lower Mississippian (Keener to Berea interval); Upper Devonian (Venango, Bradford and/or Elk intervals), Lower Devonian (Oriskany Sandstone); Upper Silurian (Newburg Sandstone); Lower Silurian (Clinton/Medina and Tuscarora sandstones); Lower Ordovician (Rose Run Formation); and Upper Cambrian (Gatesburg Formation and Upper Sandy member). These intervals are depicted in the Study's regional subsurface rock correlation diagram provided in Appendix 6.2.

Milestones for the third quarter were to:

- Complete the stratigraphic correlation of key units (Strategy 2)
- Complete the mapping program for all potential storage units (Strategy 3)
- Complete the studies of reservoir character (Strategy 4)
- Develop ranking criteria for all potential storage reservoirs (Strategy 5)

All milestones were met during the third calendar quarter of the Study (see Appendix 6.3 for the project's milestone chart), although data collection and website enhancement are continuing efforts throughout the project. Details follow in the Research Section.

2.0 RESEARCH

Third quarter research efforts focused on continuing to index and organize geologic data relevant to the AOI for use by Research and Advisory Group members; compiling and correlating additional well header, raster logs, digital curves and subsurface formation tops data; finalizing cross sections and maps for geologic intervals of interest; identifying and compiling relevant reservoir characterization information; and developing criteria with which to rank all potential storage reservoirs.

2.1 Data Collection & Database Creation

2.1.1 Study Website

A new prototype for the Study website has been developed and is in the process of being populated with project information. ASH Research Group members were asked to submit final versions of maps, cross sections, and other data types by April 30, 2017, as well as any newly collected or digitized well logs. These files will now be coded according to content and then added to the website.

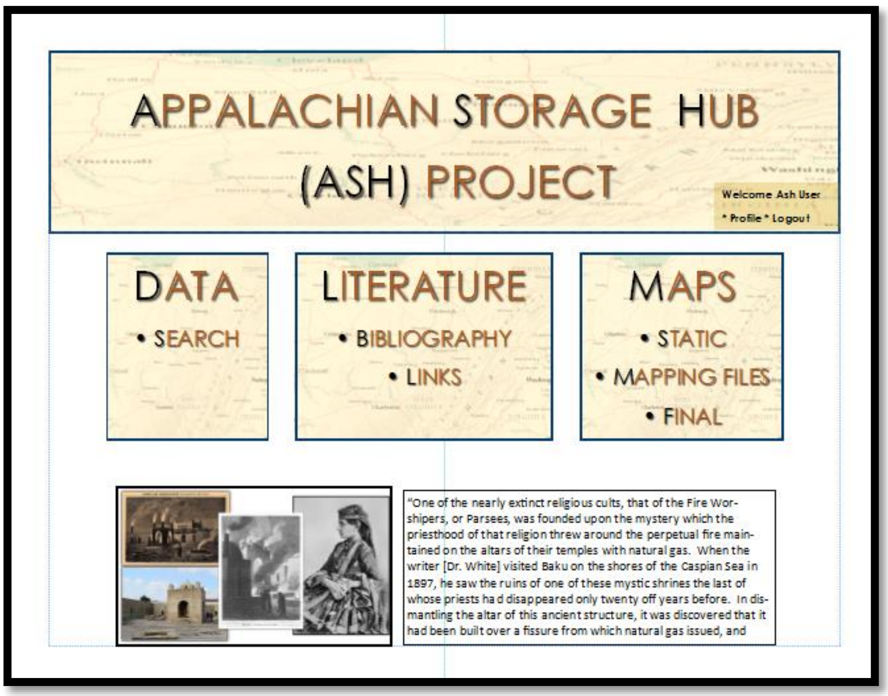


Figure 2.1.1. ASH website homepage re-design. Background data are being assembled and coded according to type.

2.2 Stratigraphic Correlations and Mapping

During the third quarter of the Study, the Research Team completed Strategies 2 and 3 – stratigraphic correlation of key units and final regional map preparation for potential storage intervals, respectively. As technical lead for the stratigraphic correlation and mapping work, OGS consumed and managed well-specific data and formation tops in the Study's Master PETRA® project database. The digital data contained in this PETRA® project are consistent with the final interval correlations for the AOI, as illustrated in the Study's stratigraphic correlation chart (Appendix 6.2).

OGS prepared final subsurface structure and isopach maps for each of the following geologic intervals: Greenbrier Limestone (GRNB), Keener to Berea sandstones (KENR-BERE), Venango sandstones (V5-V1), Bradford sandstones (B5-B1), Elk sandstones (E4-E1), Oriskany Sandstone (ORSK), Newburg Sandstone (NBRG), Salina F4 Salt (SLNF), Clinton/Medina Group (CATG), and Rose Run-Gatesburg sandstones (RSRN) (Figures 2.2.1 - 2.2.20). 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.

Subsurface structure maps utilized a 100-foot (ft) contour interval, while the isopach maps utilized contour intervals ranging from 10 to 50 ft, depending on individual formation characteristics. In addition, the Salina F4 Salt isopach map illustrates net (i.e., true) thicknesses, as this mapped interval is interpreted to be entirely comprised of salt.

To provide a visual representation of the AOI's subsurface stratigraphy, as well as to illustrate lateral and vertical relationships among potential reservoirs for ethane storage, a total of nine geologic cross sections (two dip and one strike for each of three intervals) were prepared using available subsurface data. These intervals were grouped by geologic age and include (from oldest to youngest): Cambrian to Ordovician, Early Silurian to Early Devonian, and Late Devonian to Early Mississippian. Due to the size and scale of these cross sections, these cross sections are provided as an appendix to this report (Appendix 6.5).

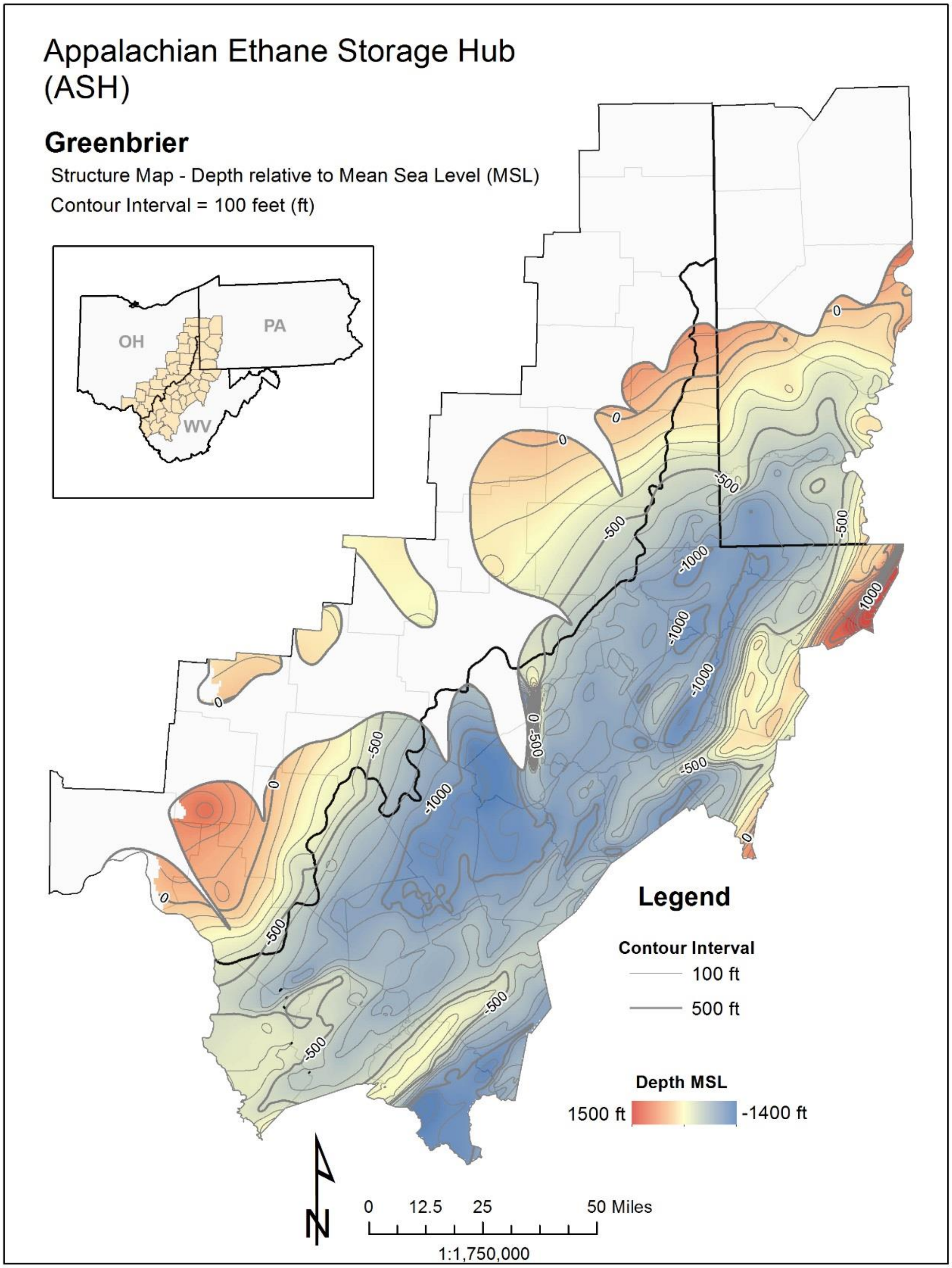


Figure 2.2.1. Structure contour map of the Greenbrier Limestone (GRNB) interval (true vertical depth subsea elevation map). Contour interval = 100 ft.

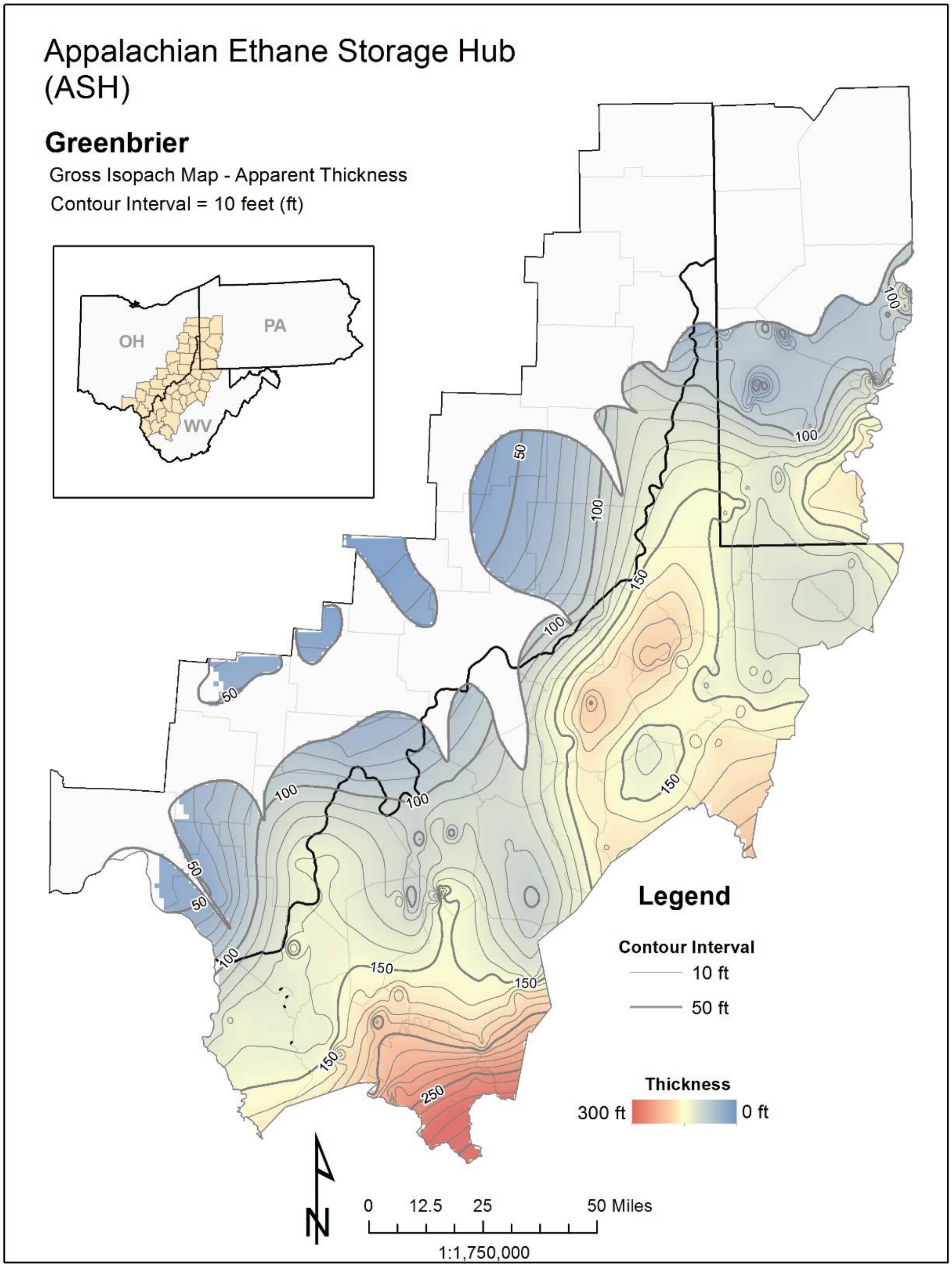


Figure 2.2.2. Gross isopach map of the Greenbrier Limestone (GRNB) interval (apparent thickness map). Contour interval = 10 ft.

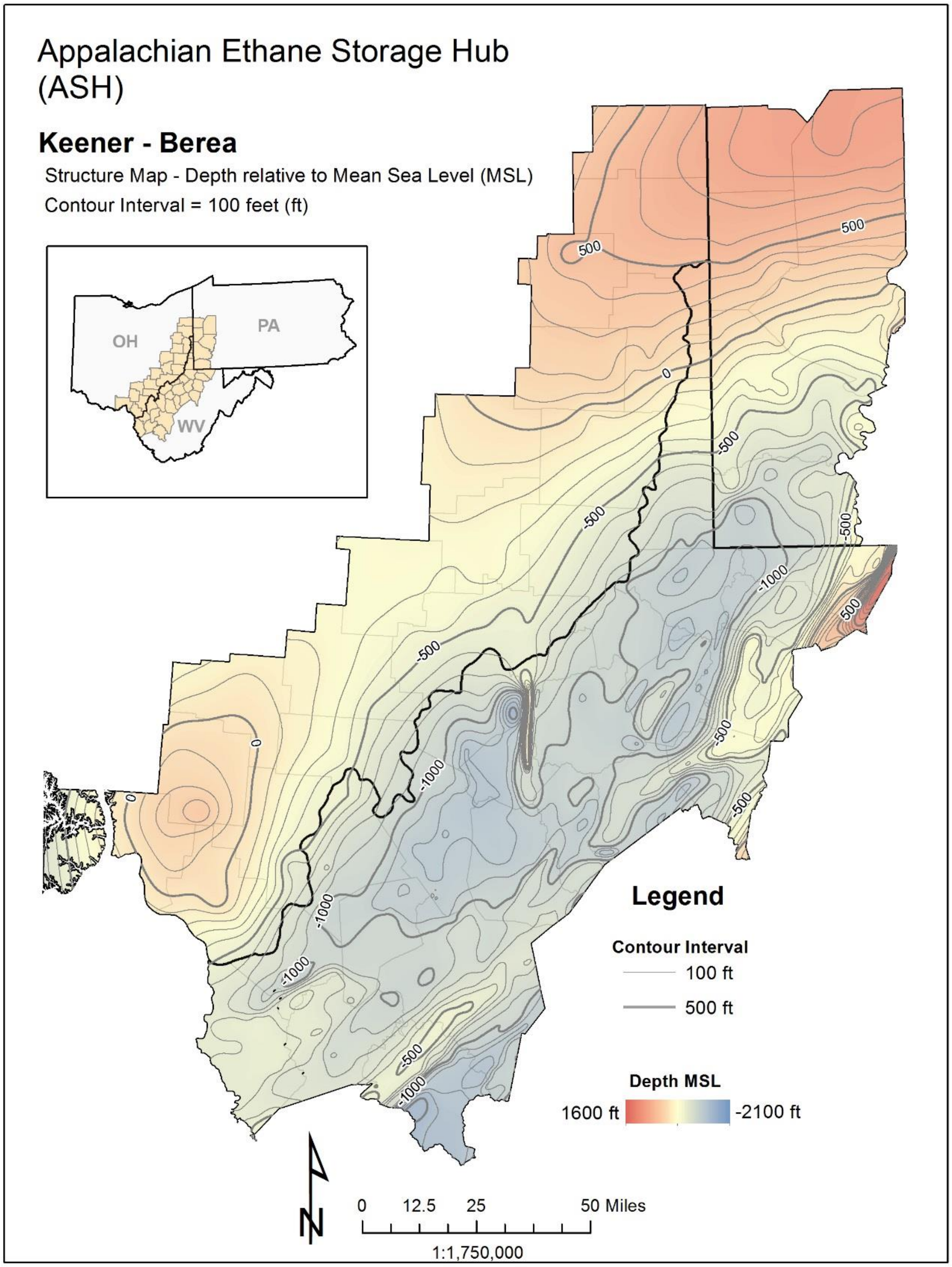


Figure 2.2.3. Structure contour map of the Keener to Berea (KENR-BERE) interval (true vertical depth subsea elevation map). Contour interval = 100 ft.

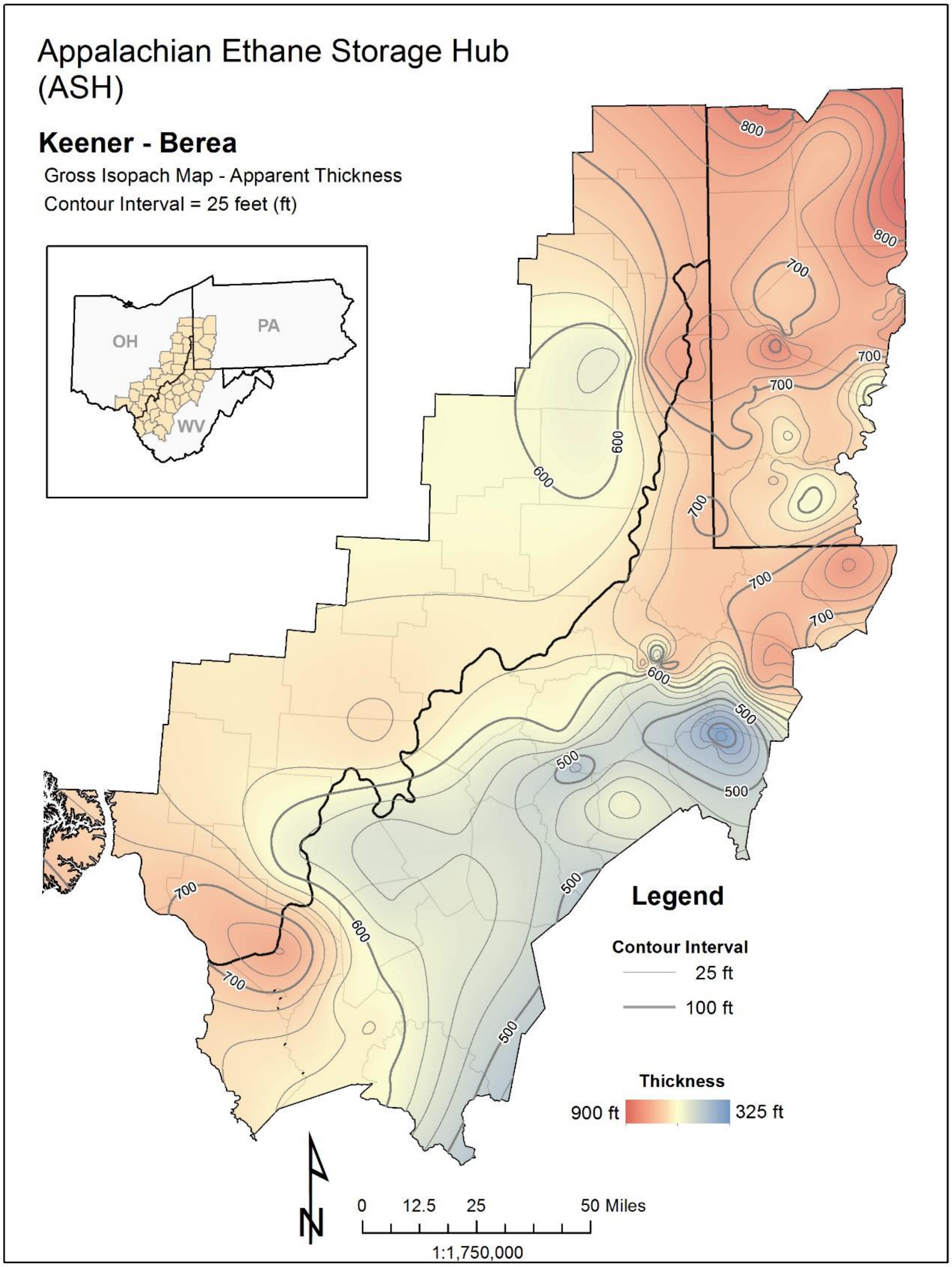


Figure 2.2.4. Gross isopach map of the Keener to Berea (KENR-BERE) interval (apparent thickness map). Contour interval = 25 ft.

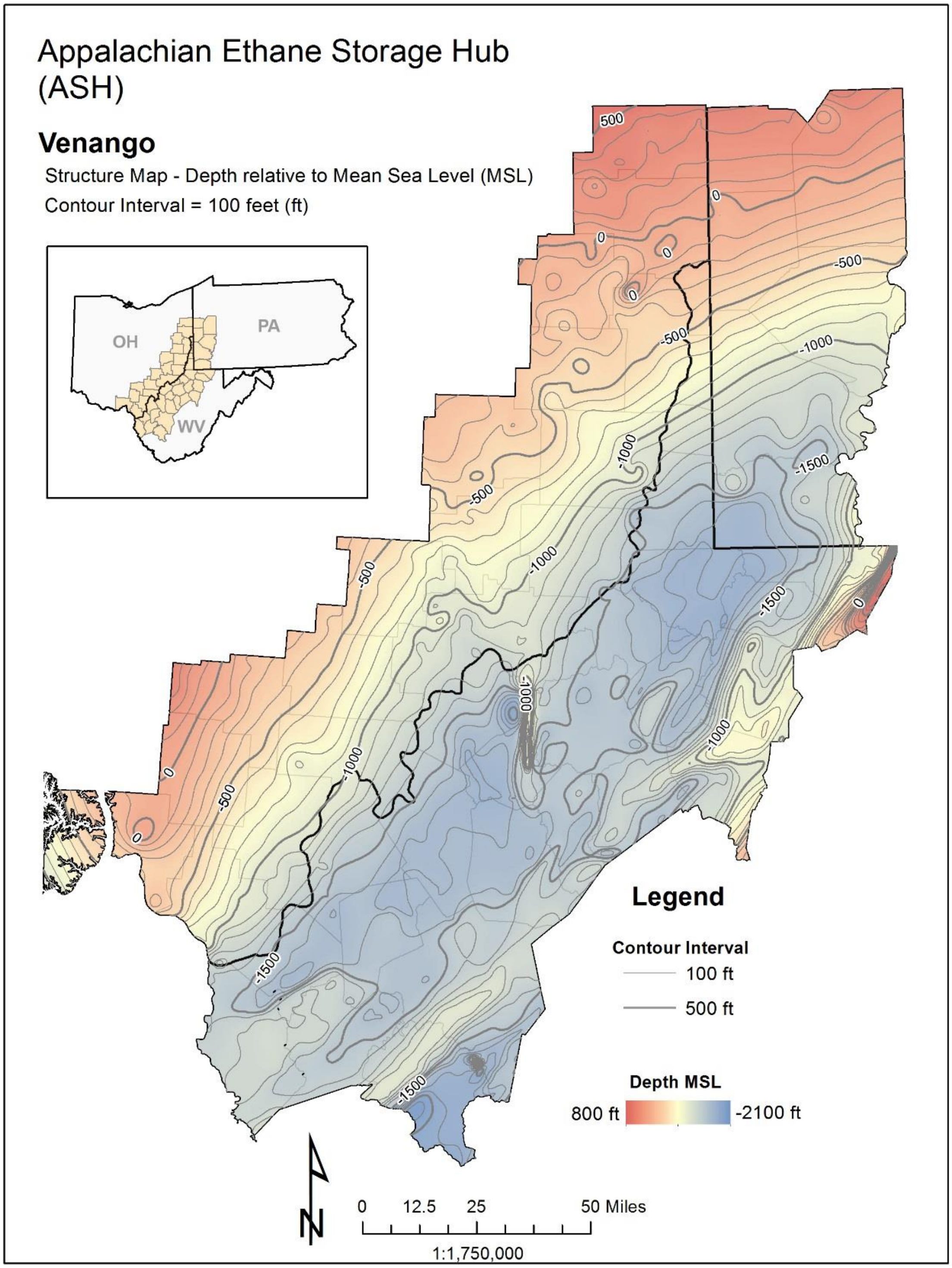


Figure 2.2.5. Structure contour map of the Venango sands (V5 – V1) interval (true vertical depth subsea elevation map). Contour interval = 100 ft.

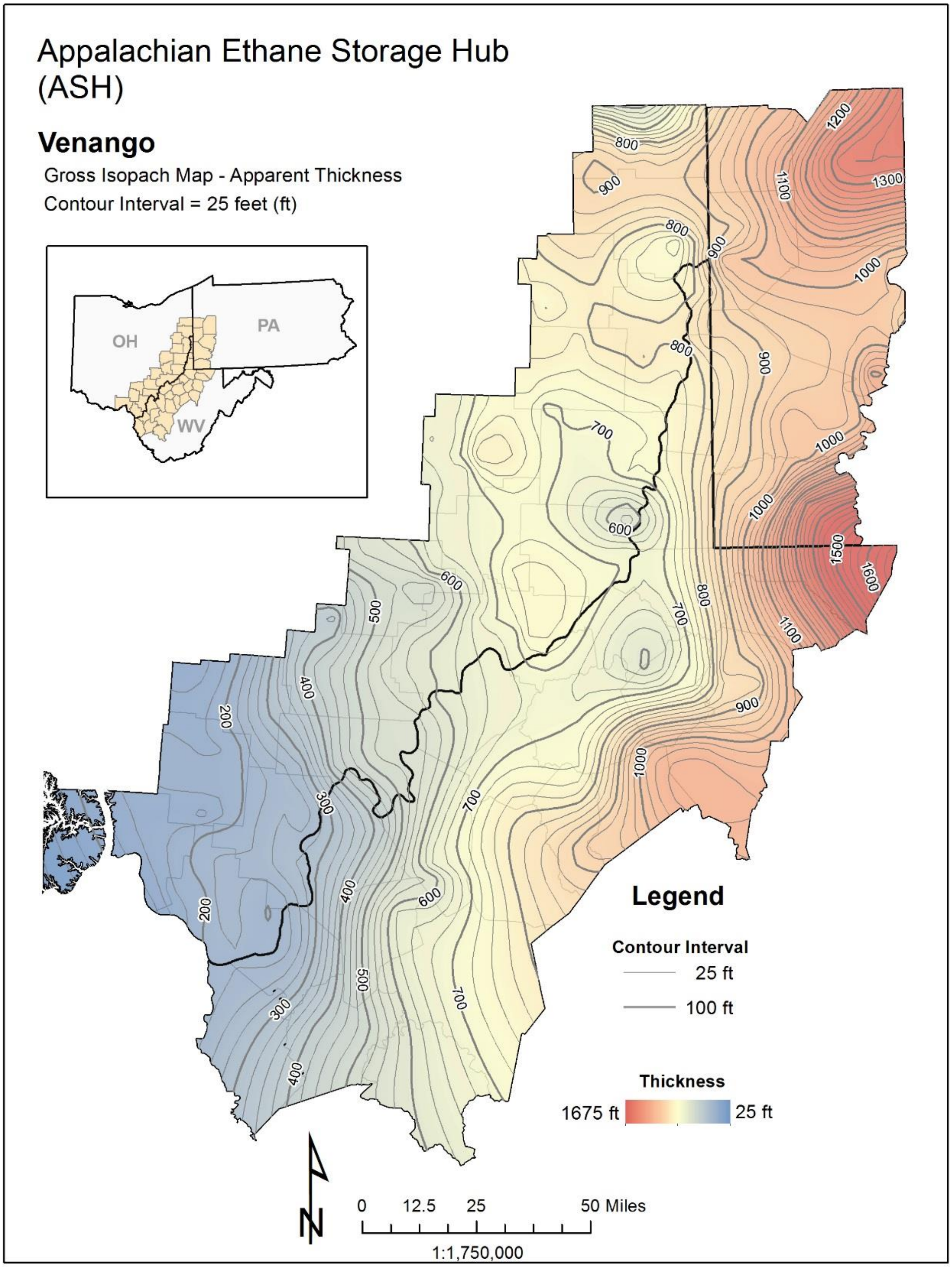


Figure 2.2.6. Gross isopach map of the Venango sands (V5 – V1) interval (apparent thickness map). Contour interval = 25 ft.

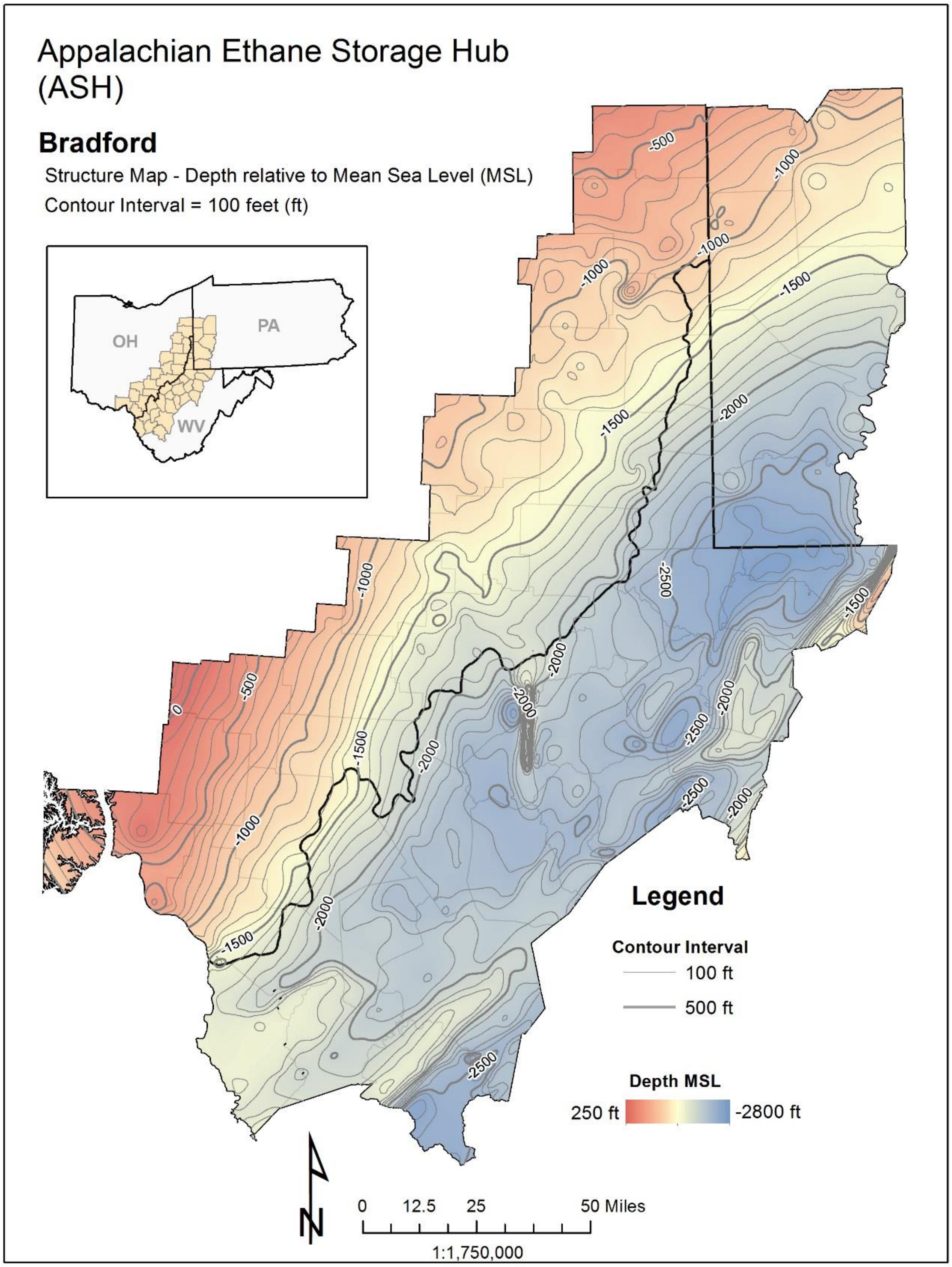


Figure 2.2.7. Structure contour map of the Bradford sands (B5 – B1) interval (true vertical depth subsea elevation map). Contour interval = 100 ft.

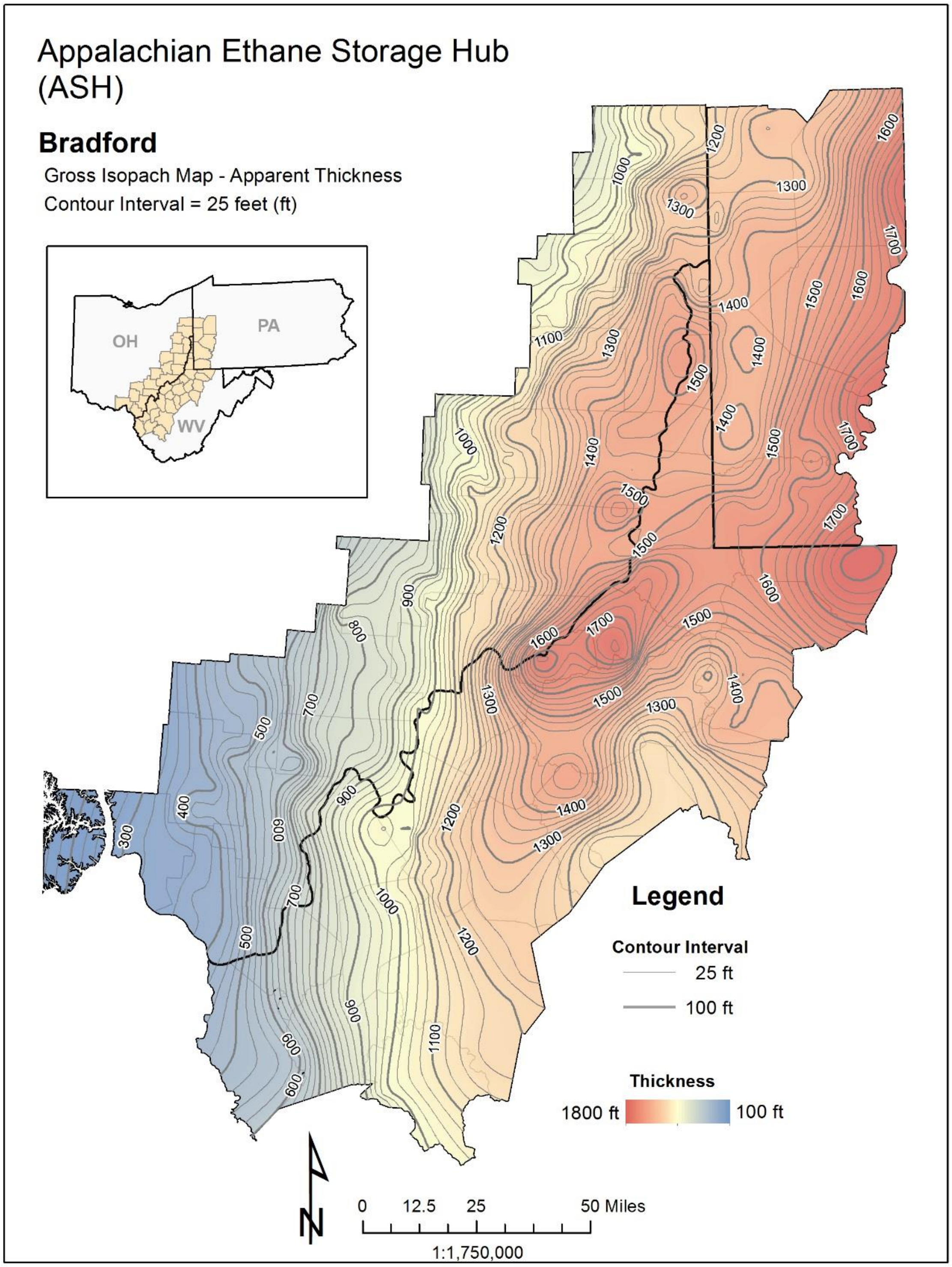


Figure 2.2.8. Gross isopach map of the Bradford sands (B5 – B1) interval (apparent thickness map). Contour interval = 25 ft.

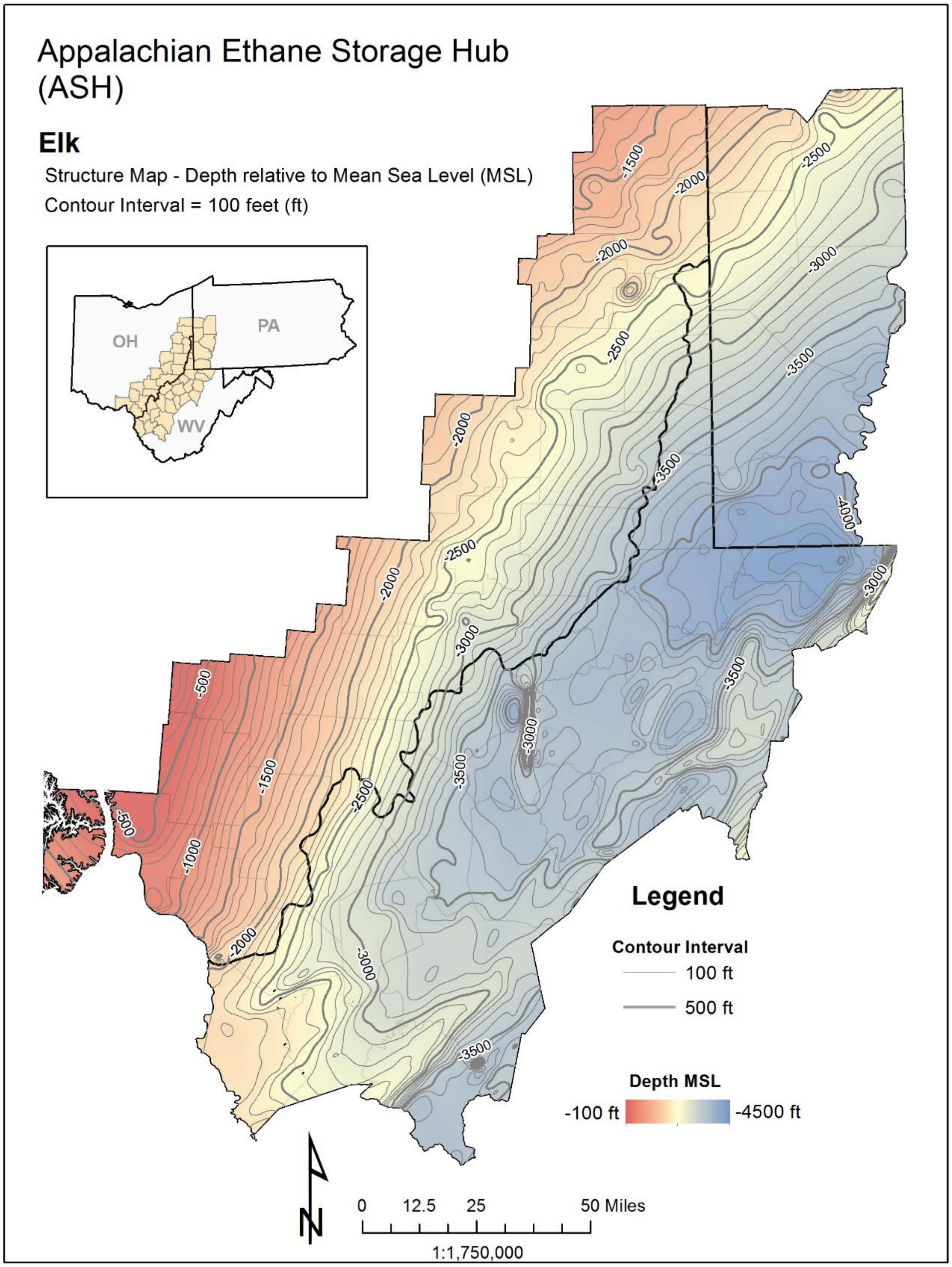


Figure 2.2.9. Structure contour map of the Elk sands (E4 – E1) interval (true vertical depth subsea elevation map). Contour interval = 100 ft.

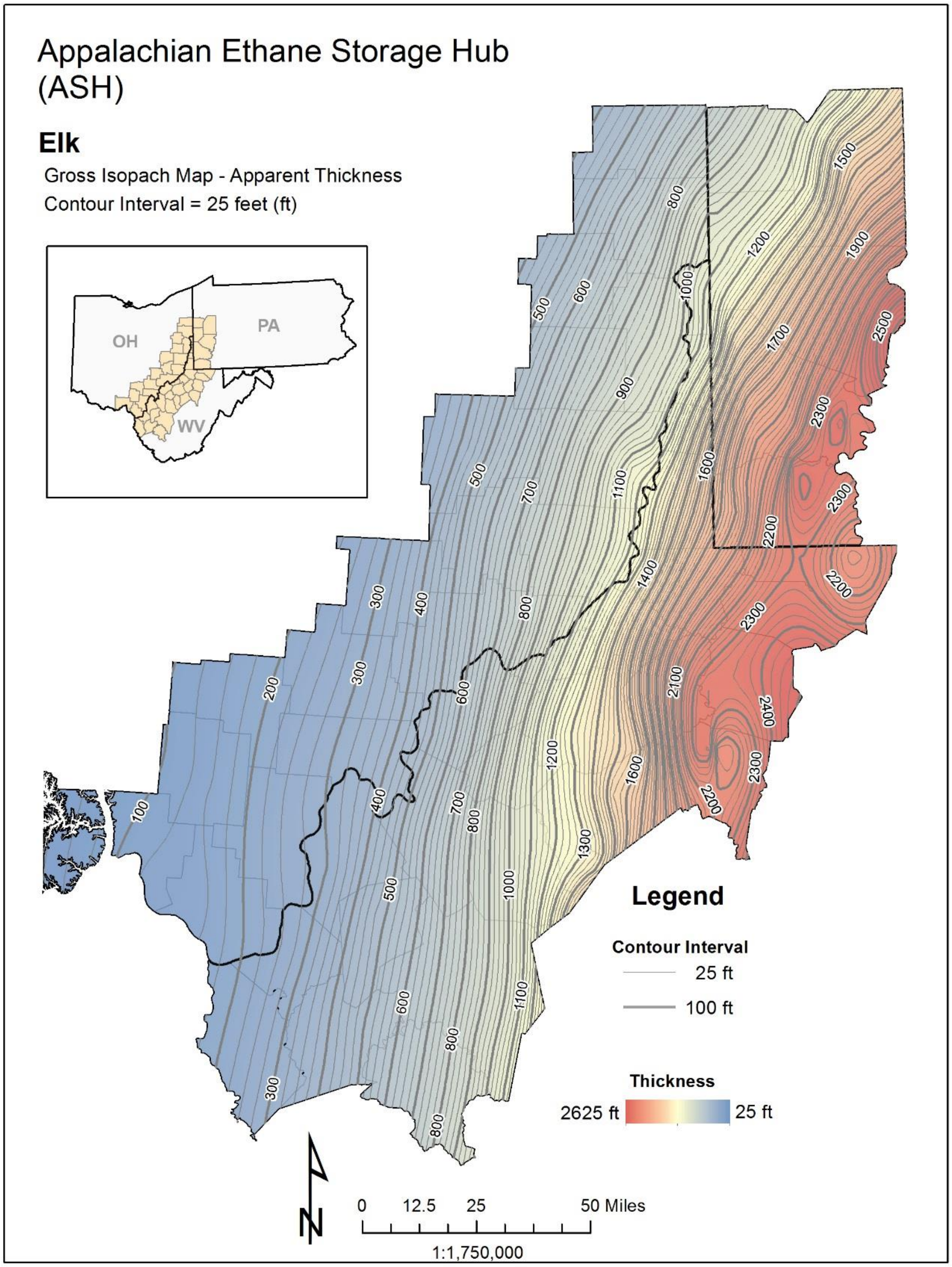


Figure 2.2.10. Gross isopach map of the Elk sands (E4 – E1) interval (apparent thickness map). Contour interval = 25 ft.

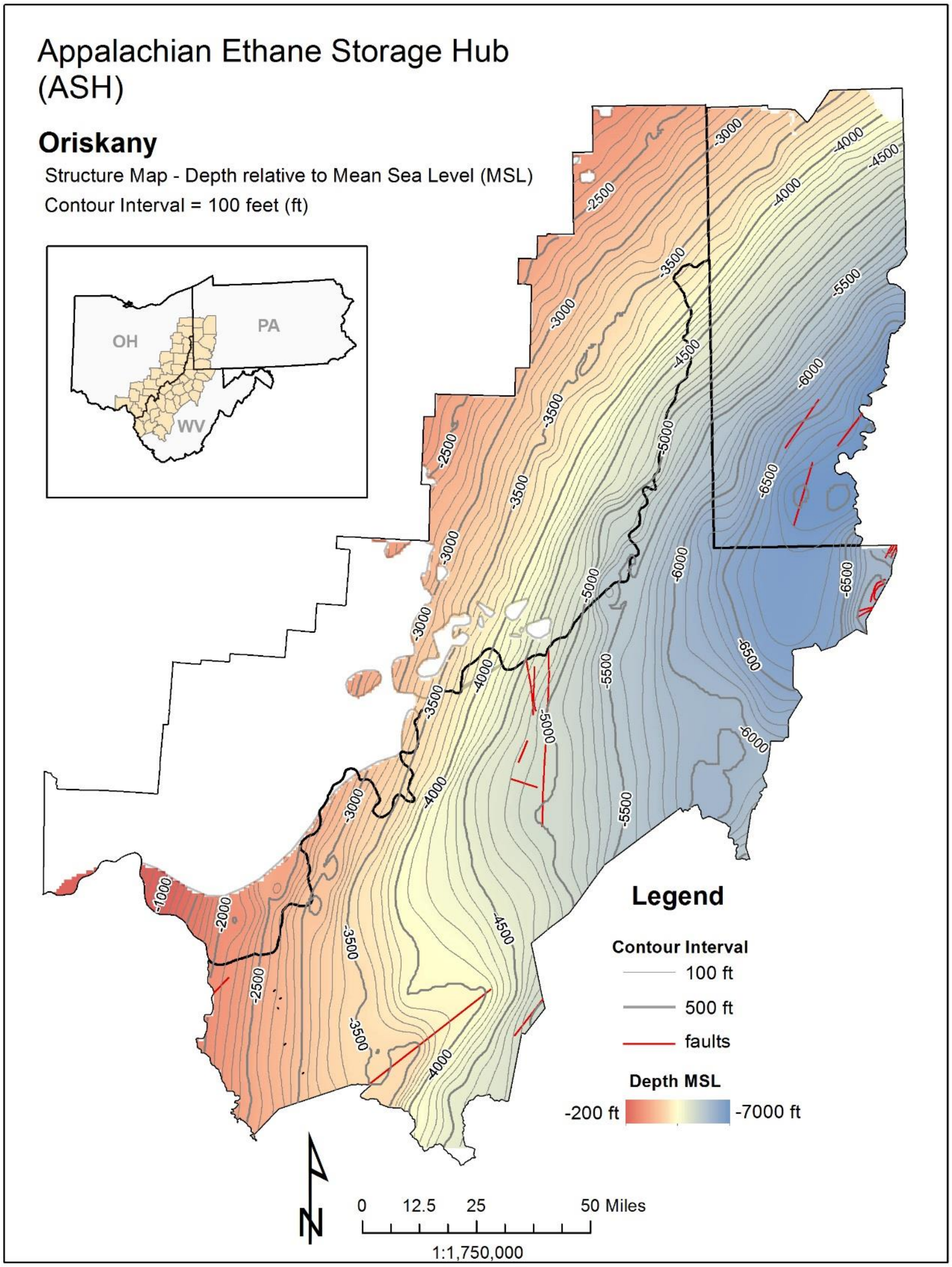


Figure 2.2.11. Structure contour map of the Oriskany Sandstone (ORSK) interval (true vertical depth subsea elevation map). Contour interval = 100 ft.

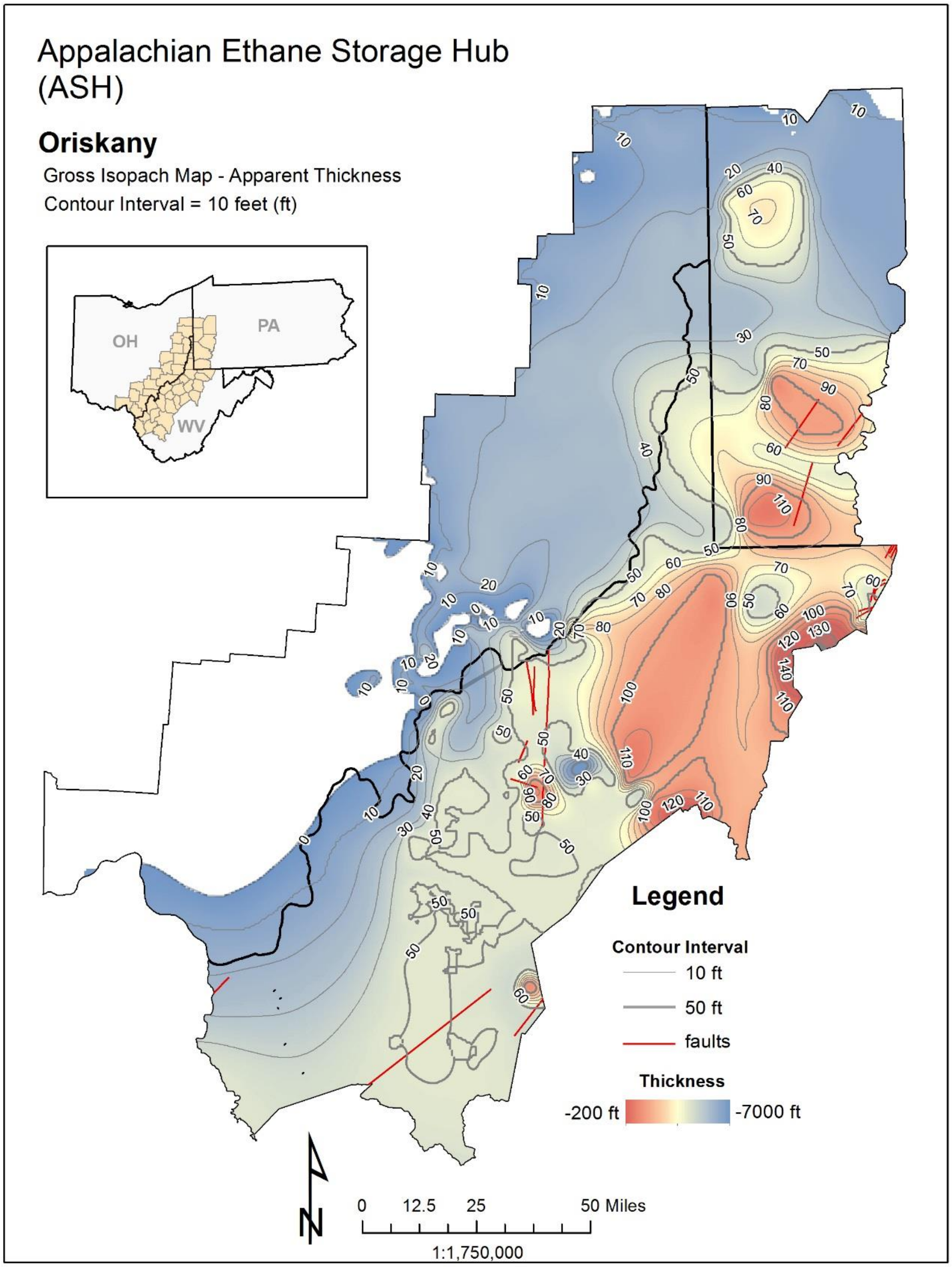


Figure 2.2.12. Gross isopach map of the Oriskany Sandstone (ORSK) interval (apparent thickness map). Contour interval = 10 ft.

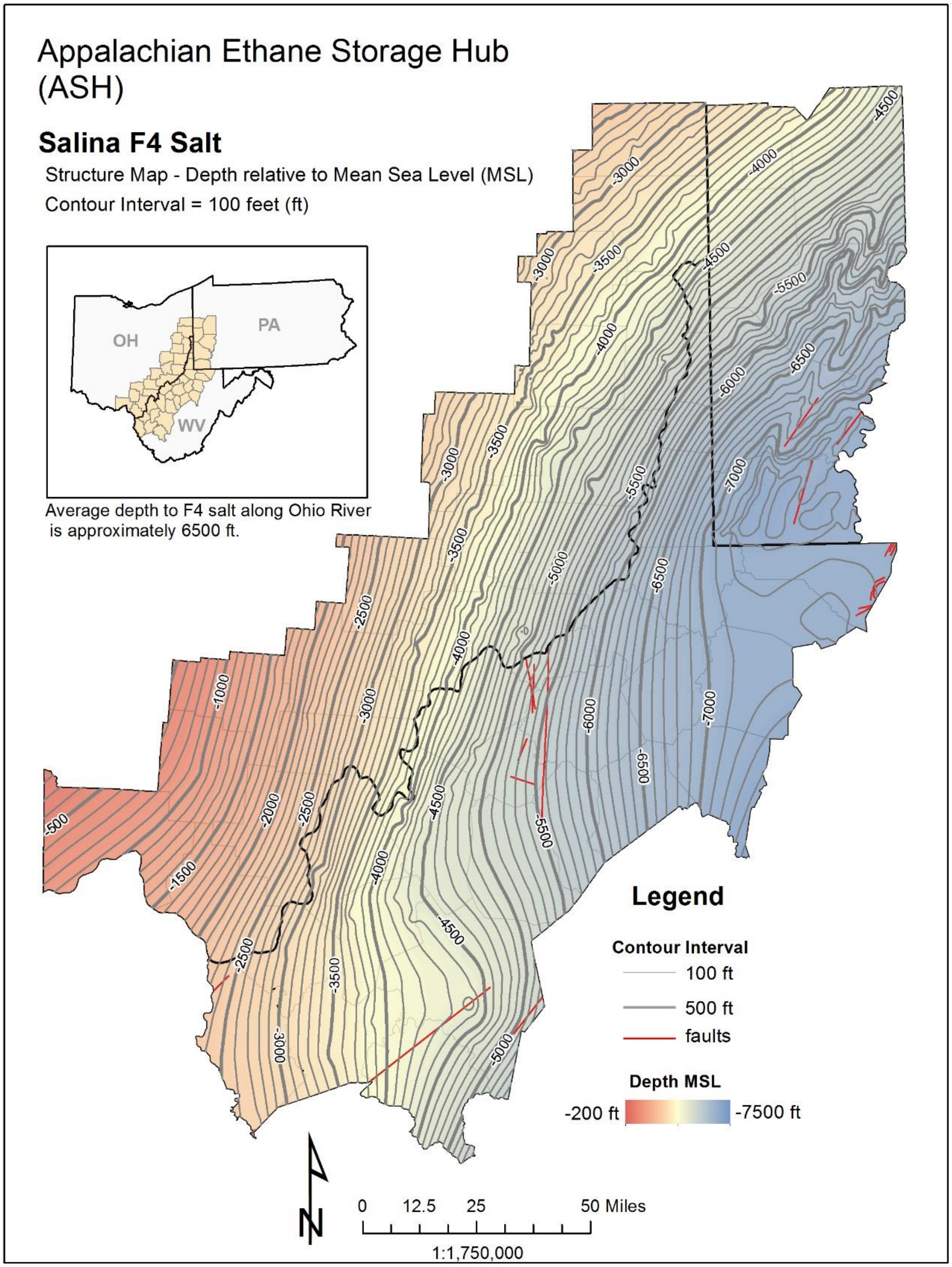


Figure 2.2.13. Structure contour map of the Salina F4 Salt (SLNF) interval (true vertical depth subsea elevation map). Contour interval = 100 ft.

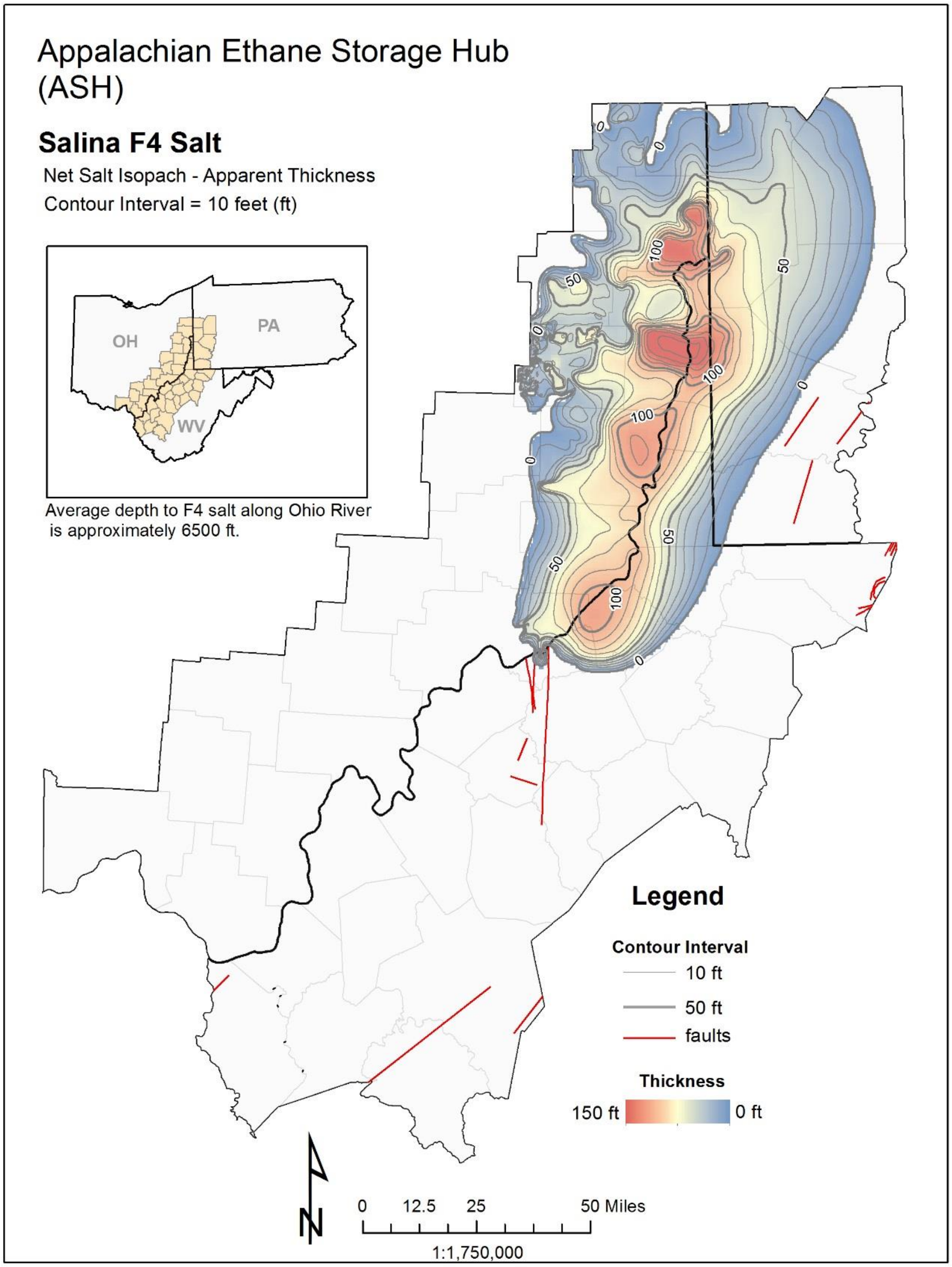


Figure 2.2.14. Net isopach map of the Salina F4 Salt (SLNF) interval (true thickness map). Contour interval = 10 ft.

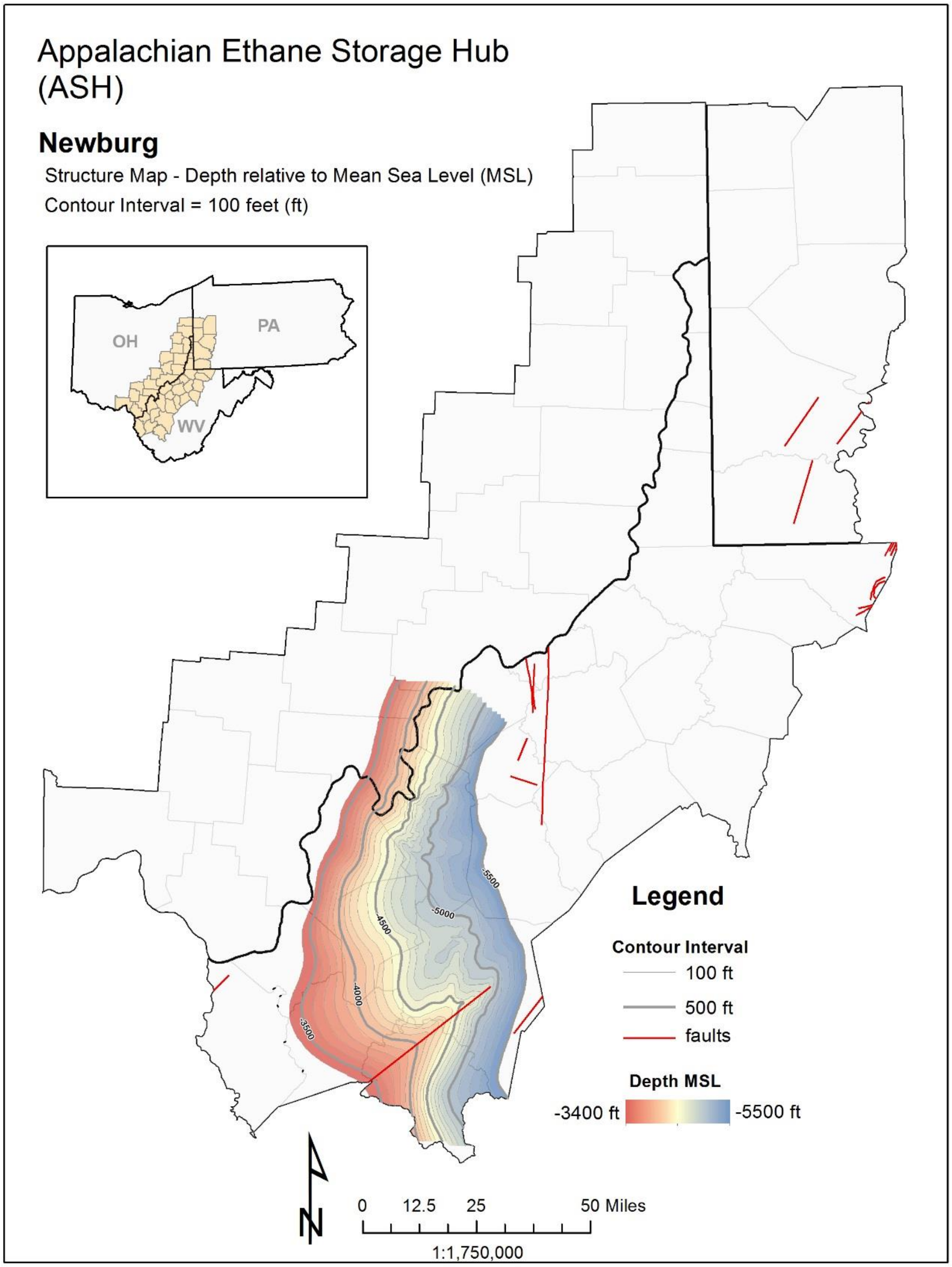


Figure 2.2.15. Structure contour map of the Newburg Sandstone (NBRG) interval (true vertical depth subsea elevation map). Contour interval = 100 ft.

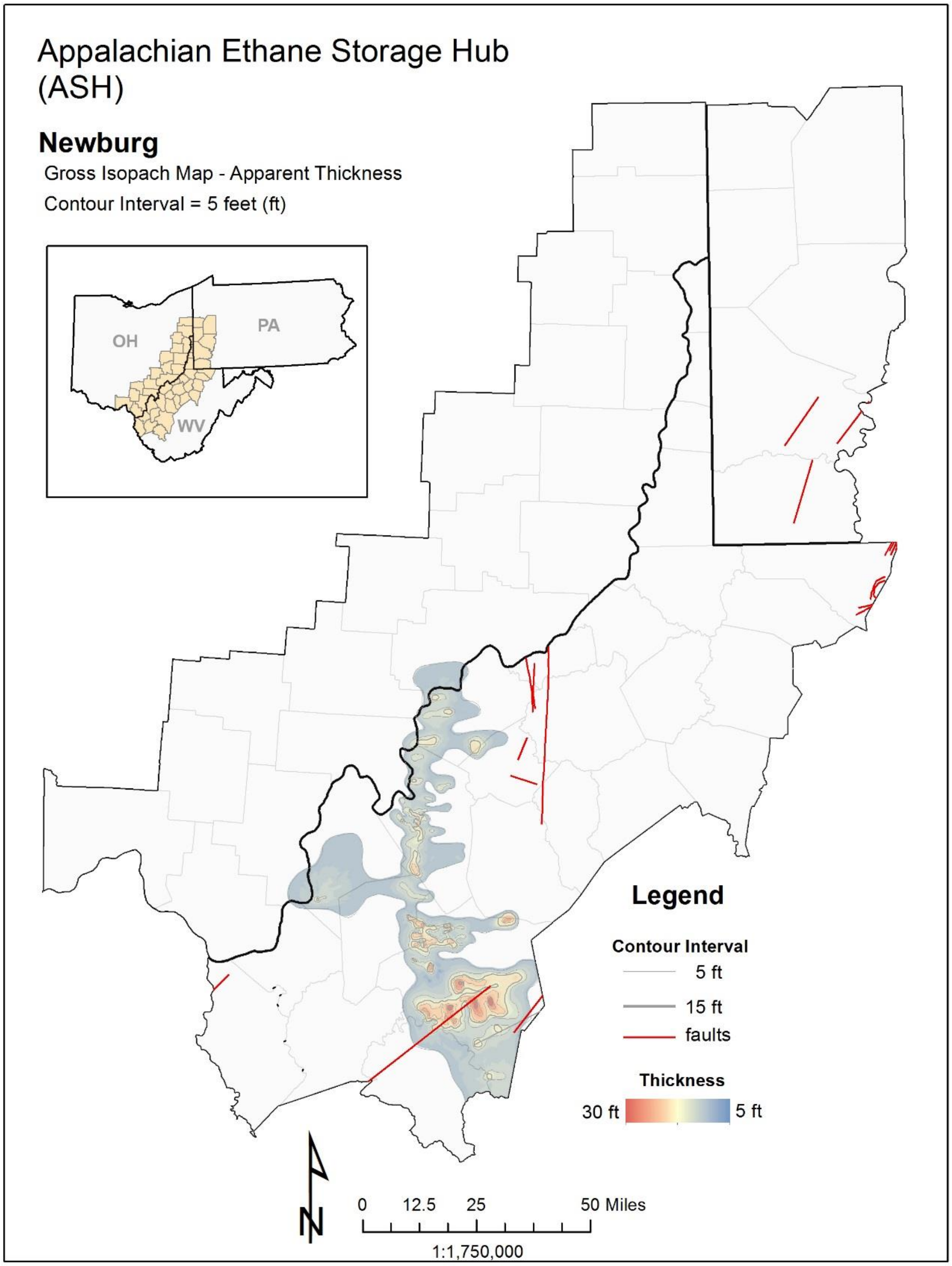


Figure 2.2.16. Gross isopach map of the Newburg Sandstone (NBRG) interval (apparent thickness map). Contour interval = 5 ft.

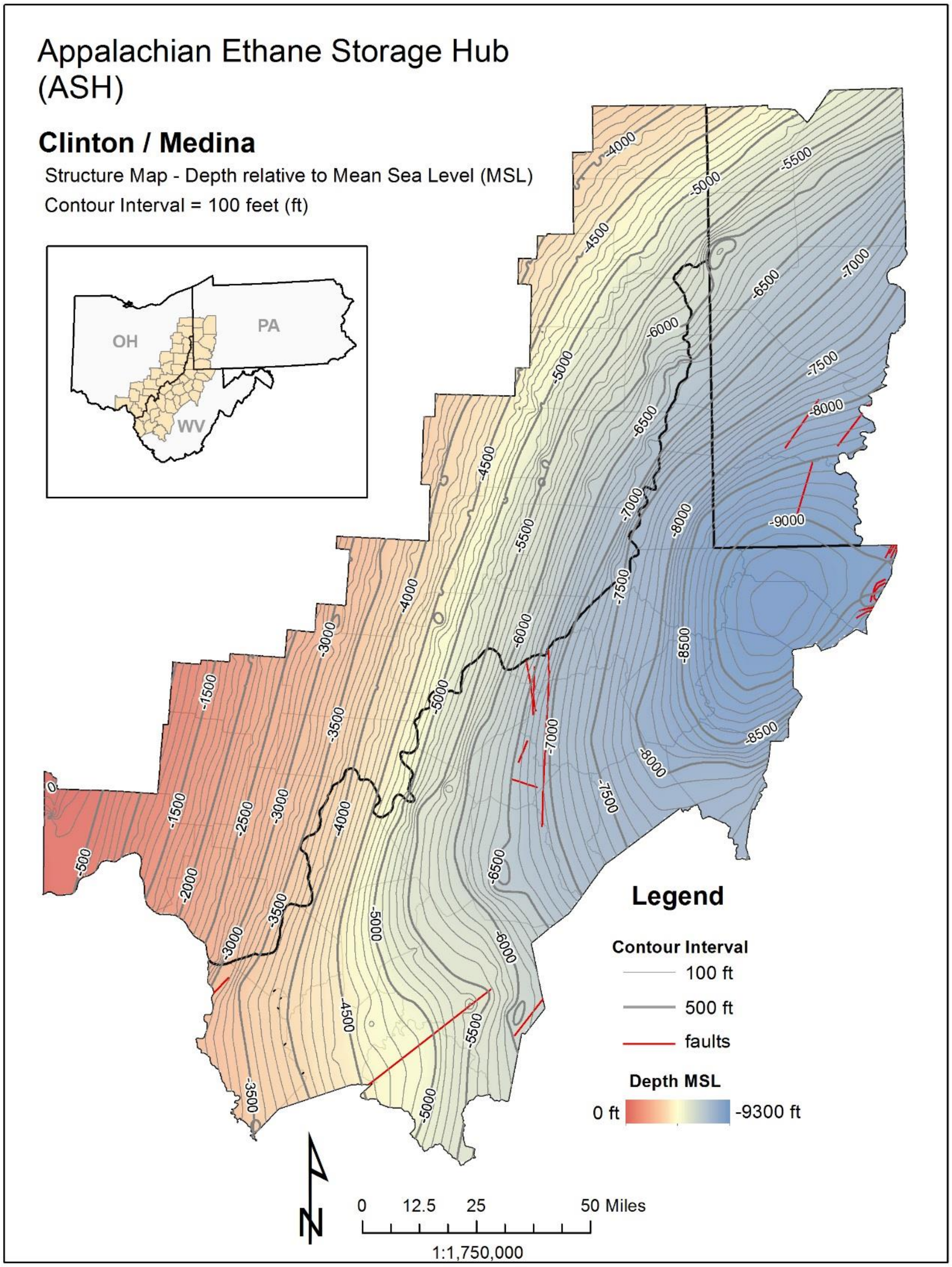


Figure 2.2.17. Structure contour map of the Clinton/Medina (CATG) interval (true vertical depth subsea elevation map). Contour interval = 100 ft.

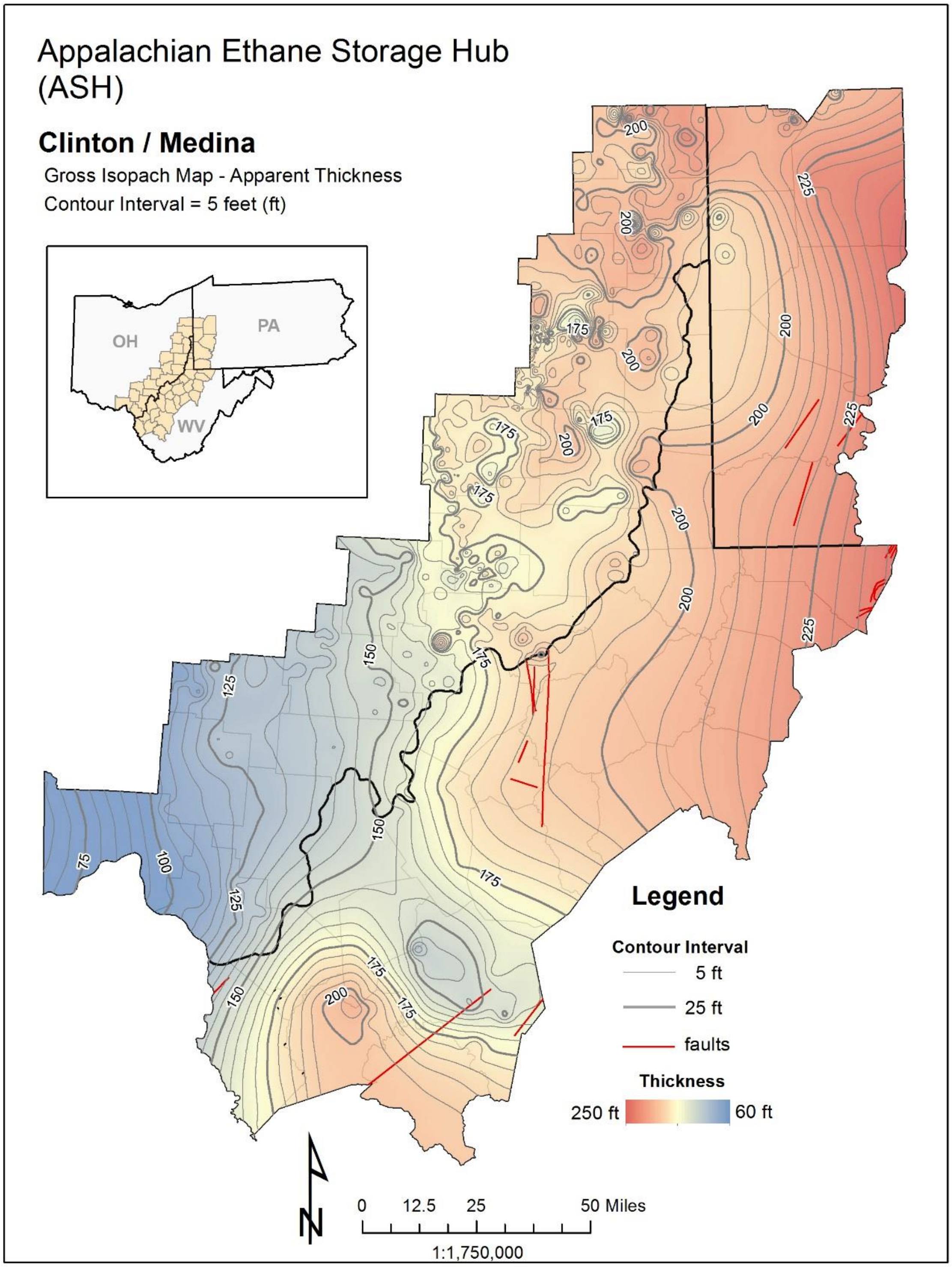


Figure 2.2.18. Gross isopach map of the Clinton/Medina (CATG) interval (apparent thickness map). Contour interval = 5 ft.

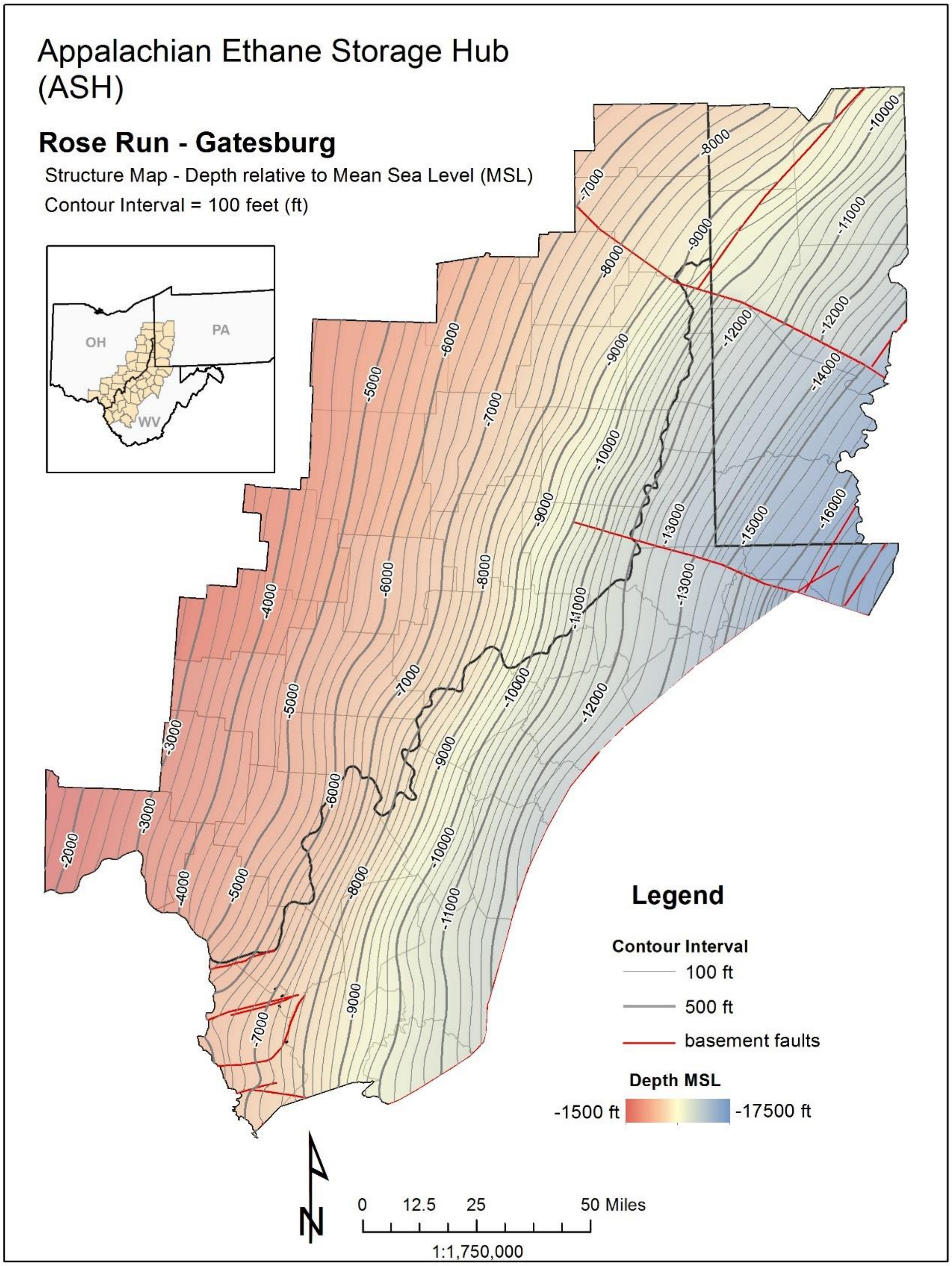


Figure 2.2.19. Structure contour map of the Rose Run – Gatesburg (RSRN) interval (true vertical depth subsea elevation map). Contour interval = 100 ft.

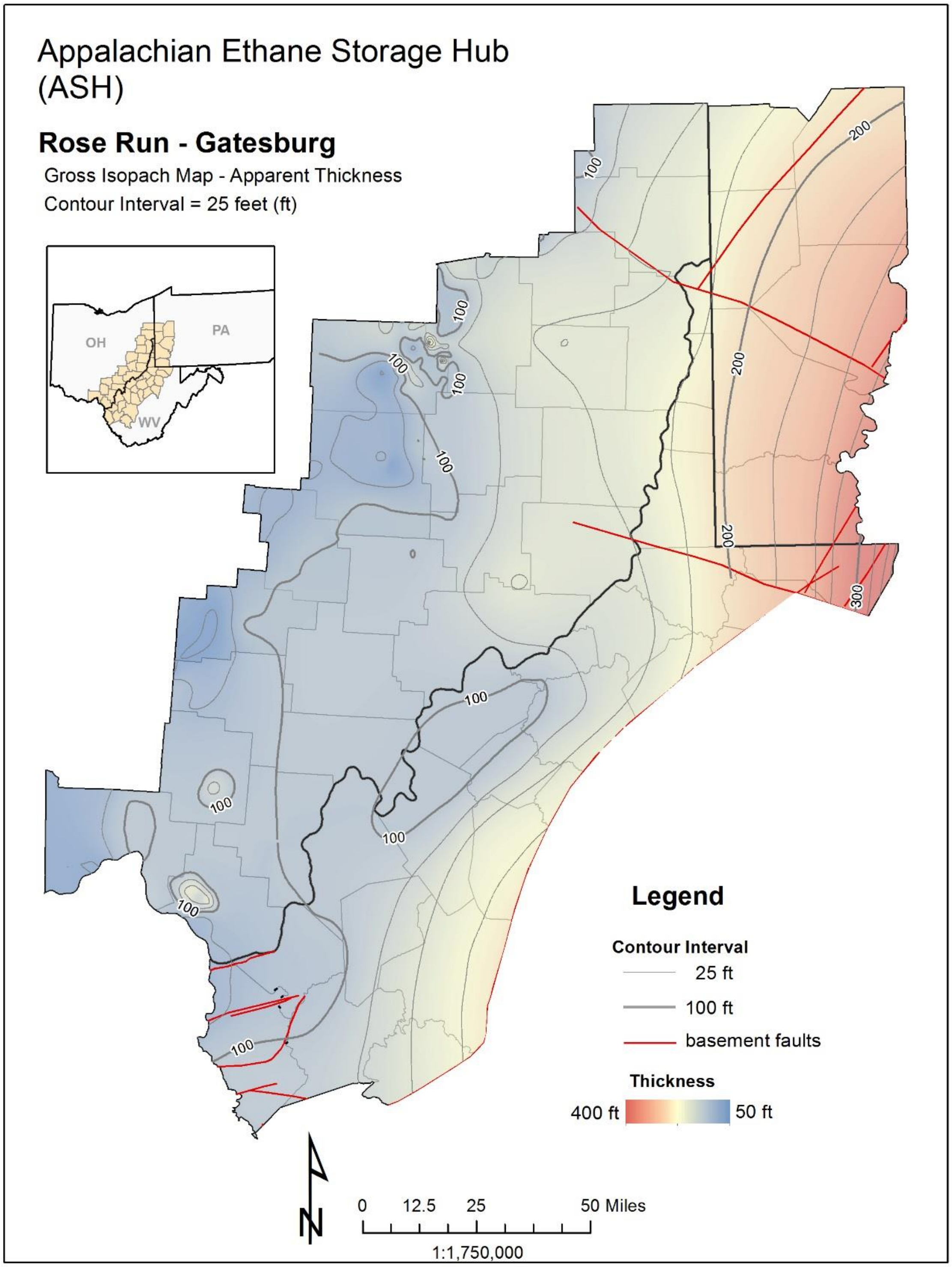


Figure 2.2.20. Gross isopach map of the Rose Run – Gatesburg (RSRN) interval (apparent thickness map). Contour interval = 25 ft.

2.3 Reservoir Characterization

Due to the varied nature of geologic intervals being evaluated as storage prospects for the Study, characterization efforts for each interval type (i.e., mined-rock cavern, salt cavern and depleted gas reservoir) were necessarily unique. Over the past three months, all three states collaborated to compile, interpret and map data specific to the intervals of interest. WVGES identified geographic areas within the AOI that met optimal extraction depths within the Greenbrier Limestone and began to evaluate the storage benefits/drawbacks of individual facies within this unit. OGS completed the identification and mapping of optimum Salina F4 Salt areas. PAGS compiled and screened reservoir characterization data at the field level for depleted siliciclastic gas reservoirs throughout the AOI. More information regarding these three categories of effort is provided below.

During the final quarter of the Study, PAGS will use the reservoir characterization data presented below and the results of ranking work to be performed as part of Strategy 5 (Section 2.4) to prepare as many as three field-level prospect areas with detailed maps, data tables and recommendations for stacked ethane storage opportunities.

2.3.1 Greenbrier Limestone (Mined-Rock Caverns)

Depth

During the third quarter, the Research Team prepared detailed maps of the depth to top of the Greenbrier Limestone. In Pennsylvania, the Greenbrier Limestone is represented by the Wymps Gap and Loyalhanna members, with the Loyalhanna being the more regionally persistent of the two. In West Virginia, the Greenbrier is commonly known by the drillers' term "Big Lime." The extensive carbonate is conformably underlain in places by a siliciclastic unit, which is often confused with the older, unconformity-bound sandstones of the Price Formation. These stratigraphic relationships are illustrated in Figure 2.3.1.

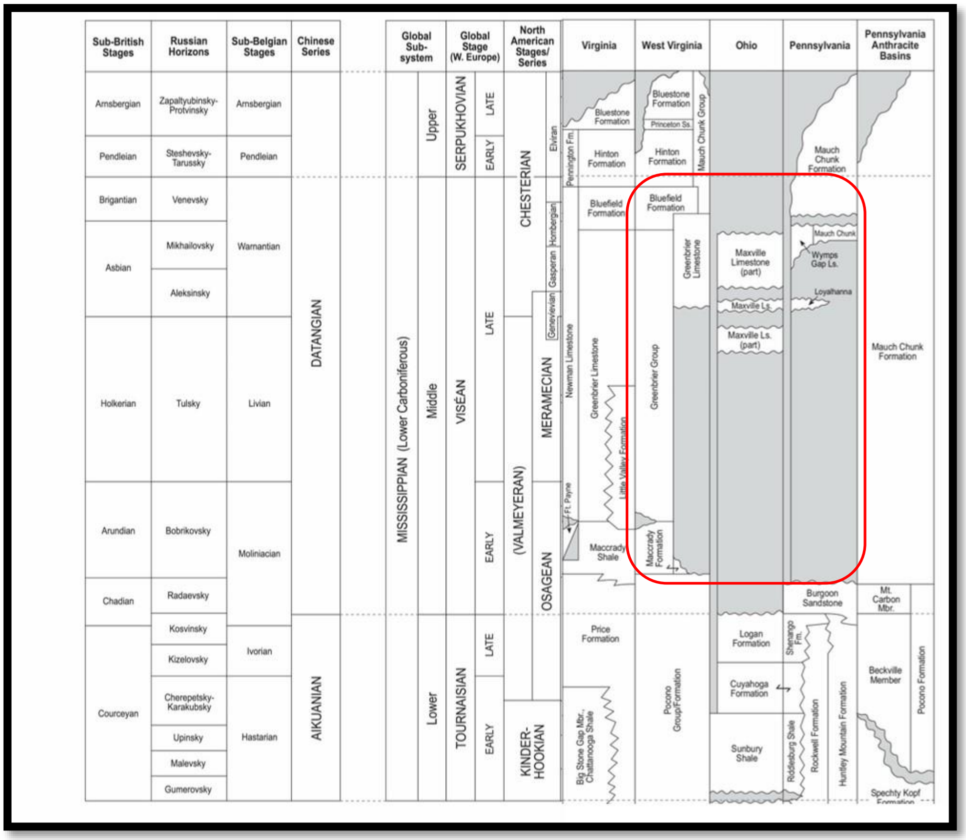


Figure 2.3.1. Mississippian stratigraphy of the Study area (Ettensohn, 2009).

Whereas the Greenbrier and its equivalents are present throughout much of the AOI, a subsurface target depth between 1,800 and 2,000 ft was recommended as a cutoff value for further screening in a pre-feasibility report commissioned by the West Virginia Development Office (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 one 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.

A collection of 428 geophysical logs were used to constrain the area where the top of the Greenbrier Limestone is located between 1,800 and 2,000 ft below ground surface. Figure 2.3.2 displays the locations of wells used to constrain the depths, and Figure 2.3.3 illustrates the trend of the Greenbrier Limestone with top depths ranging from 1,800 to 2,000 ft.

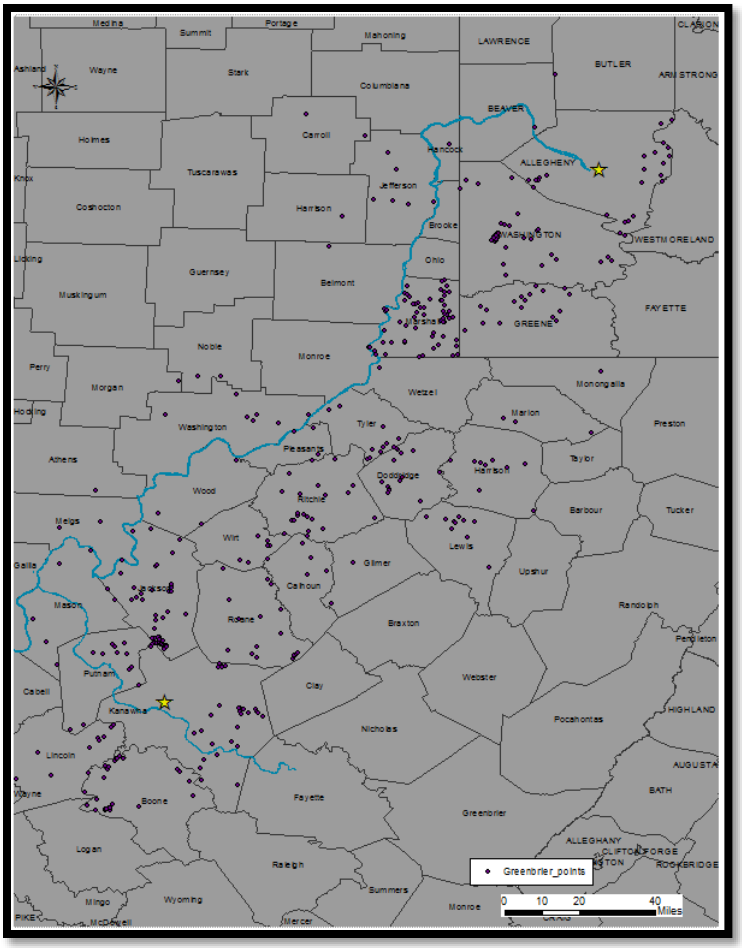


Figure 2.3.2. Wells with geophysical logs used to constrain the depth to top of the Greenbrier interval.

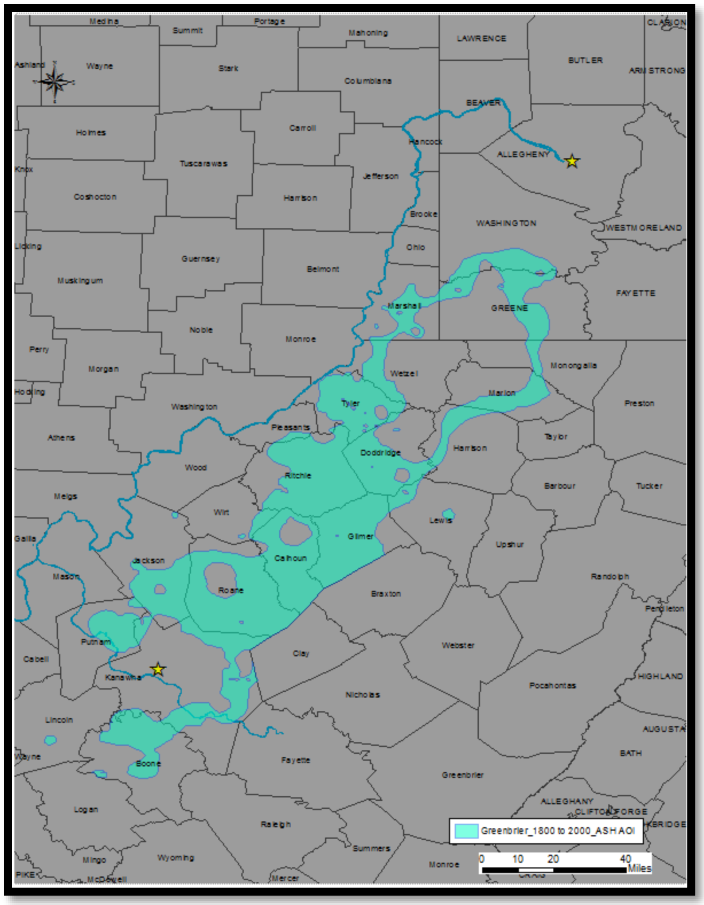


Figure 2.3.3. Areas within the AOI where the top of the Greenbrier Limestone is encountered at depths ranging from 1,800 to 2,000 ft below ground surface.

Thickness

In addition to the depth and pressure conditions discussed above, potential mined-rock cavern locations must be evaluated for several other criteria to ensure optimal placement. 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 provided by a member of the ASH Industry Group. Figure 2.3.4 summarizes the major geologic criteria necessary to construct a mined-rock cavern.

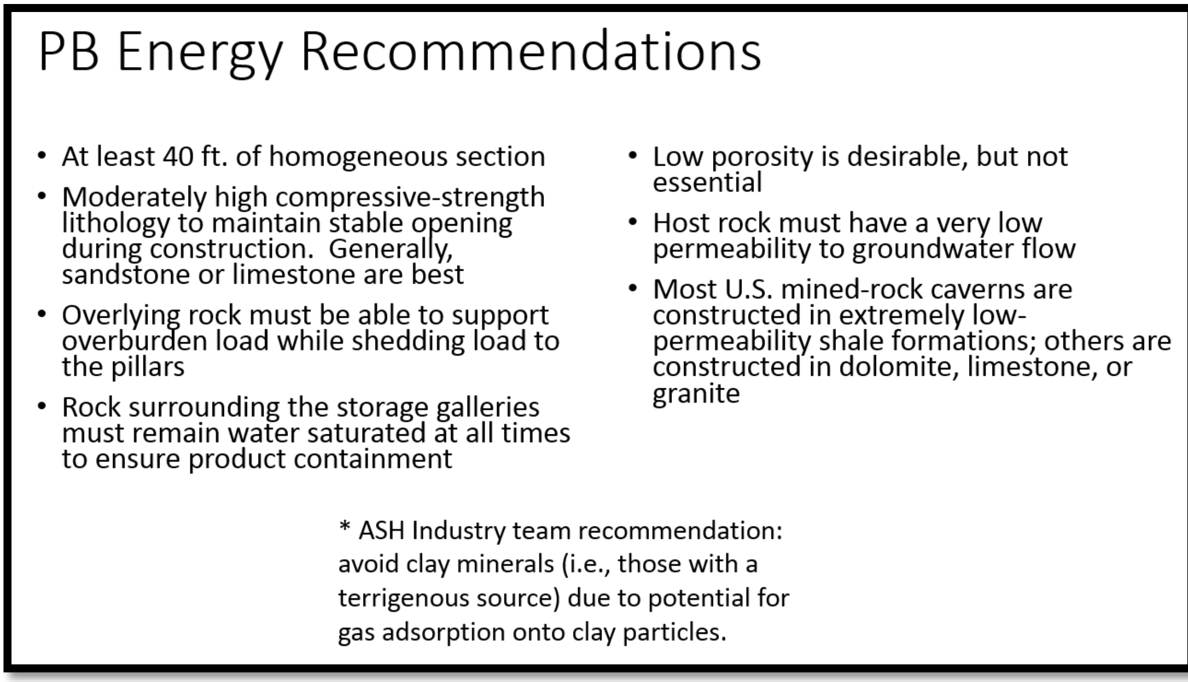


Figure 2.3.4. Major geologic criteria for construction of a mined-rock storage cavern (modified from Nelson and others, 2011).

Facies Distribution (Extent)

Improved characterization of facies distribution within the Greenbrier interval was undertaken by the Research Team as a means to delineate the geographic extent to which this unit may serve as a prospective ethane storage reservoir. To this end, WVGES examined the 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.

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.

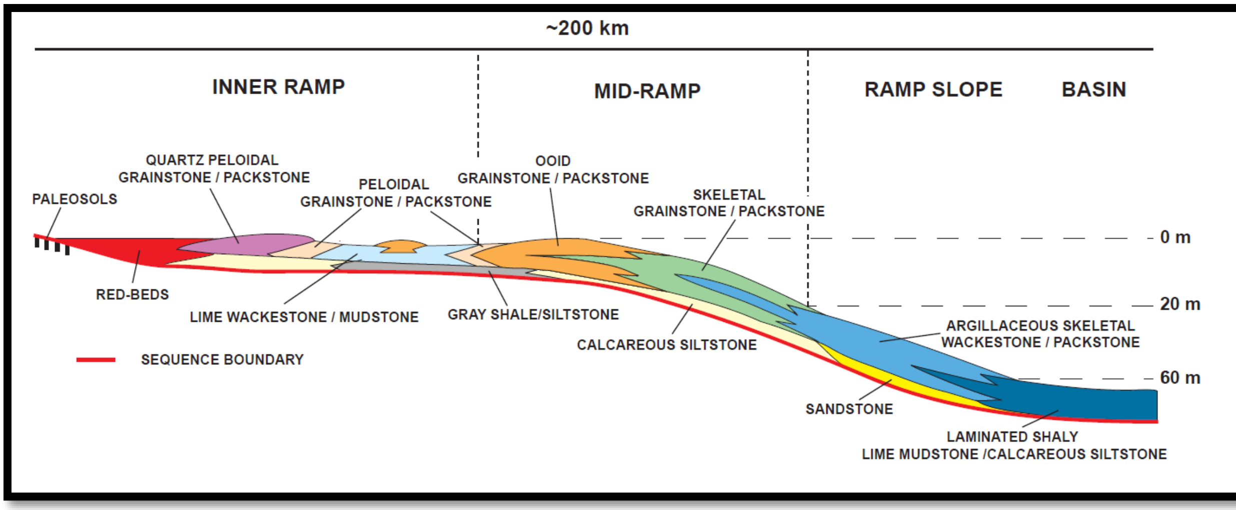


Figure 2.3.5. Schematic illustration of Mississippian facies distribution of the Appalachian basin (Wynn, 2003). The main facies types within the AOI were deposited in inner- to mid-ramp settings.

Wynn identifies approximately one dozen major facies types in the "Big Lime" lithologic succession in West Virginia, but only a few of these 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 2.3.6 illustrates the facies types deposited in the uppermost stratigraphic sequences of the Greenbrier interval. In West Virginia, these intervals comprise the Alderson and Union limestones.

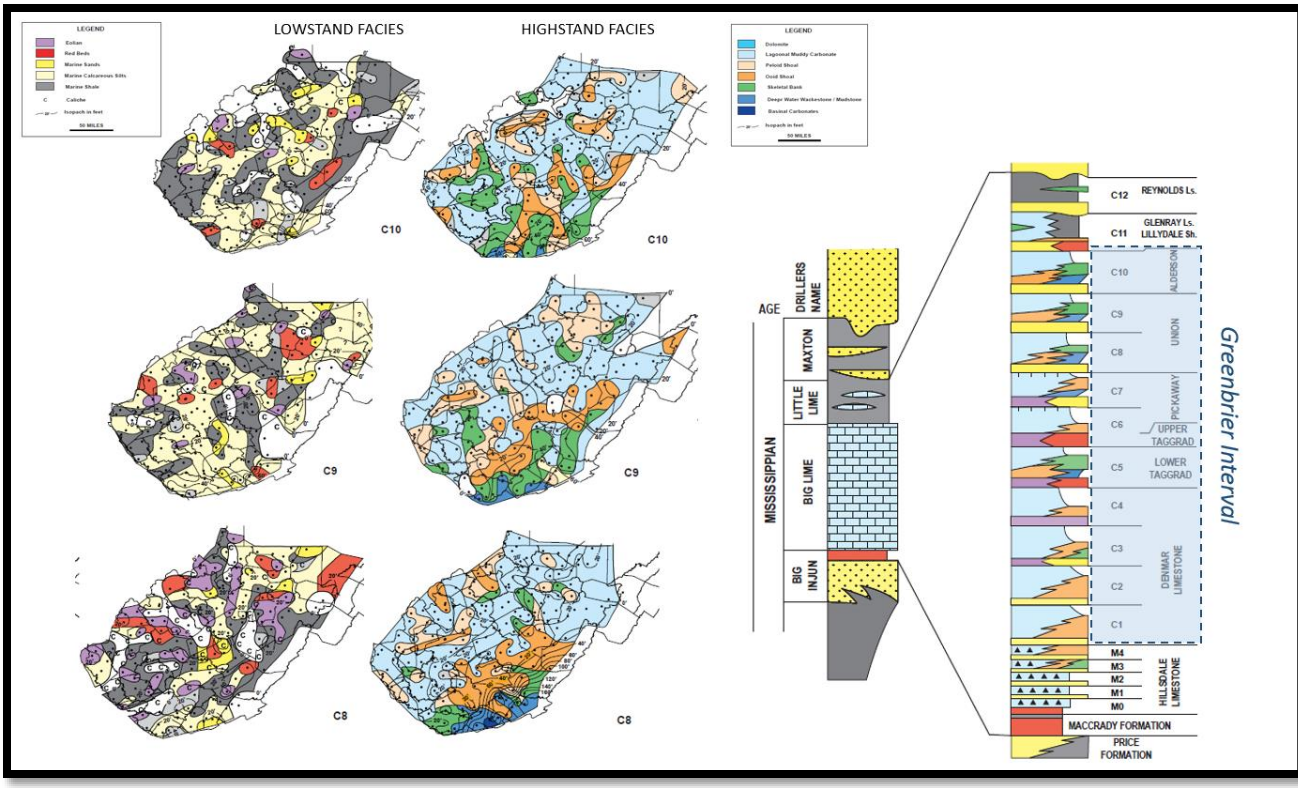


Figure 2.3.6. Lowstand and highstand facies types deposited in the uppermost stratigraphic sequences of the Greenbrier interval (Wynn, 2003).

The relationship between facies stacking patterns and their suitability for mined-rock caverns will be examined in more detail by PAGS as they analyze geophysical logs collected from selected wells in western West Virginia and Pennsylvania. To assist with this task, WVGES compiled a subset of approximately 100 geophysical logs to determine the individual facies types and stacking patterns. The logs determined to be most useful for this task are the bulk density/density porosity logs as well as the photoelectric factor, or Pe. When evaluated together, the logs give an indication of lithology type (i.e., sandstone vs. limestone or dolomite) (see Figures 2.3.7 and 2.3.8). In addition to the density and Pe measurements, logs should 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).

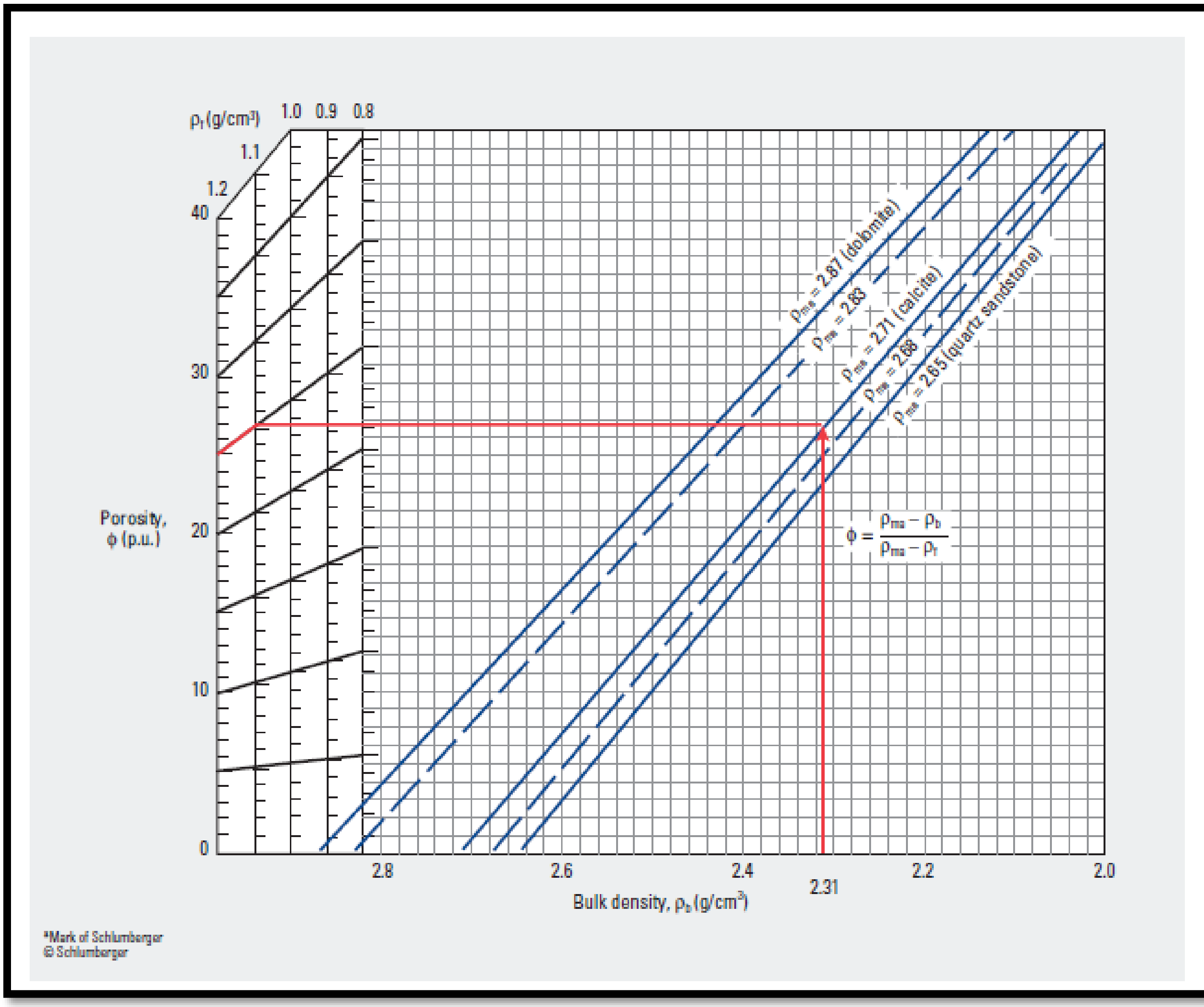
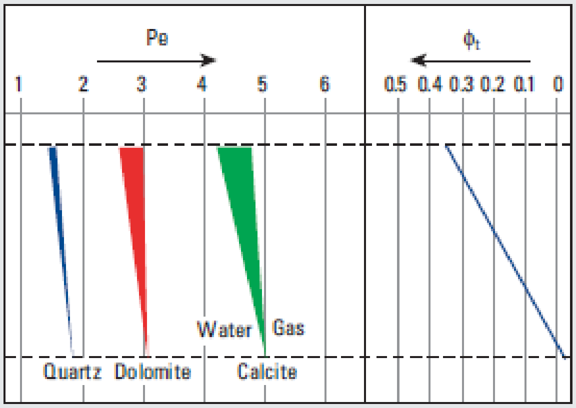


Figure 2.3.7. Chart used to convert grain density (grams per cubic centimeter, or g/cm^3) to density porosity (Schlumberger, 2009).



Porosity Effect on Pe			
Matrix	ϕ_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 2.3.8. Graph showing the effect of porosity, matrix type, formation water and presence of methane on photoelectric (Pe) measurements (Schlumberger, 2009).

Two type logs have been identified in the AOI that demonstrate the application of density and Pe log analysis to the determination of facies relationships. The first example, from Roane County, West Virginia (Figure 2.3.9a), 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 (Figure 2.39b), includes a lithology log calculated from density, Pe, resistivity and gamma-ray 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).

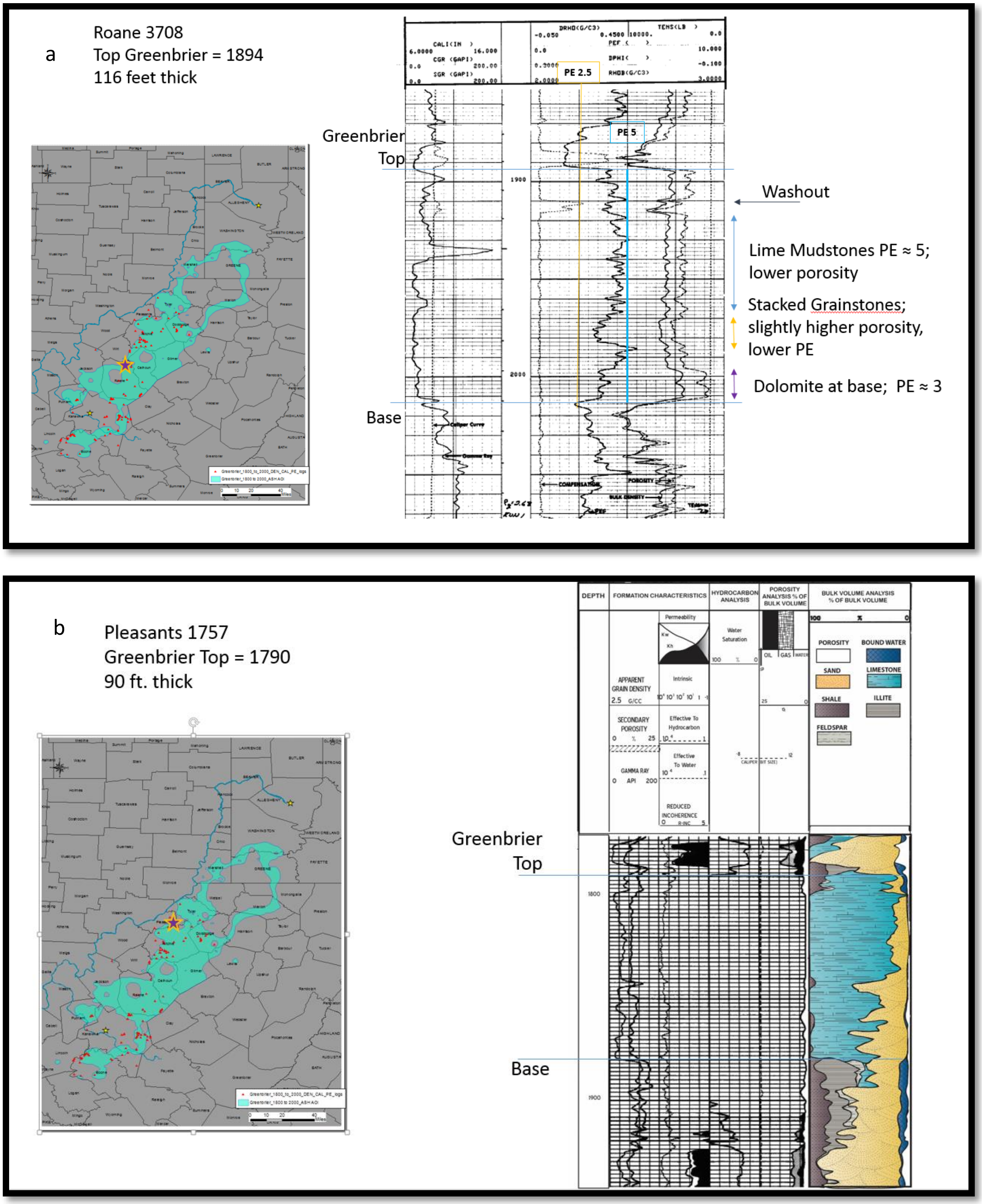


Figure 2.3.9. Type logs for the Greenbrier Limestone illustrating the relationship of density and Pe log curves to individual facies in (a) Roane County, West Virginia and (b) Pleasants County, West Virginia.

PAGS will use these type logs to examine facies and stacking patterns within the Greenbrier for the 100 wells identified by WVGES, as well as any additional wells in Pennsylvania for which geophysical logs can be used to identify Greenbrier facies. Depending upon the results of this evaluation, the Research Team may revise the depth to top of Greenbrier map to represent the location of preferred mining areas, as well as prepare net thickness maps of the upper lime mudstone and lower stacked grainstone packages. Final depth and thickness maps will be used to rank the Greenbrier Limestone for storage potential as part of Strategy 5.

2.3.2 Salina F4 Salt (Salt Caverns)

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. 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 part of the regional correlation and mapping work led by OGS, the Research Team determined early on that the only Salina salt member likely to occur in thicknesses of ≥100 ft was the Salina F4 Salt. OGS finalized the structure and net isopach maps for this member during the third quarter (Figures 2.2.13 and 2.2.14, respectively). Based on this detailed mapping, the Research Team identified four areas within the AOI where the F4 Salt has net thicknesses of 100 ft or more; these are illustrated in Figure 2.2.14 using pale orange to red shading and are centrally located in the panhandle of West Virginia. In this portion of the AOI, the average approximate depth of the Salina F4 Salt is 6,500 ft below ground surface.

During the final quarter of the Study, each of the four thick-bedded Salina F4 Salt areas will be ranked by the Research Team for their storage potential as part of Strategy 5.

2.3.3 Depleted Gas Reservoirs (Devonian- through Cambrian-Age Sandstones)

PAGS reviewed and compiled field-level reservoir data for depleted gas reservoirs using information from various projects and 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 and Carter and others, 2012). This digital dataset 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.

Using this GIS database, 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), PAGS chose to use this smaller digital dataset for its siliciclastic reservoir characterization and screening work.

Using the digital dataset of ~1,500 fields, PAGS identified areas where field-specific reservoir parameters were lacking and consulted relevant chapters of the Atlas of Major Appalachian Gas Plays (Roen and Walker, 1996) to fill in data gaps wherever possible. PAGS then screened these fields by reviewing key reservoir parameters – porosity, permeability and acreage – to determine a short list of the most promising fields for each sandstone interval of interest. The best siliclastic storage reservoirs will have porosities of approximately 10 percent (or more), permeabilities of several hundred millidarcy (or more), provide a storage 'container' with adequate thickness and size (acreage) and preferably be located proximal to existing or proposed infrastructure.

Tables 2.3.1 and 2.3.2 list the 113 depleted gas fields and 12 natural gas storage fields with the most favorable reservoir characteristics, respectively, as determined by the preliminary screening work conducted by PAGS. Due to 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 Table 2.3.1. The Research Team will rank these fields in detail as part of Strategy 5 during the final quarter of the Study.

Field Name	Geologic Interval(s)	Discovery Year	State
BIG RUN-BURCHFIELD	Keener - Berea	1902	WV
BURDETT-ST. ALBANS	Keener - Berea	1906	WV
CAMERON-GARNER	Keener - Berea	1977	WV
CONDIT-RAGTOWN	Keener - Berea	1898	WV
HENDERSHOT-OGDIN	Keener - Berea	1895	WV
MAPLE-WADESTOWN	Keener - Berea	1905	WV
SIDNEY	Keener - Berea	1959	WV
STANLEY	Keener - Berea	1966	WV
WHITES CREEK-GRAGSTON	Keener - Berea	1930	WV
WILBUR	Keener - Berea	1971	WV
CAMPBELLS RUN-MIRACLE RUN	Venango	1929	WV
COBURN-EARNSHAW	Venango	1913	WV
CONDIT-RAGTOWN	Venango	1914	WV
FRVW-STATLER RN-MT MORRS	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 FK-BLUESTONE CK	Venango, Bradford	1930	WV
STUMPTWN-NORMANTWN-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 FK-BLUESTONE CK	Elk	1977	WV
STUMPTWN-NORMANTWN-SHOCK	Elk	1977	WV
THURSDAY	Elk	1980	WV
WESTON-JANE LEW	Elk	1909	WV
BLUE CK (FALLING RK)	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 2.3.1. Top 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
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

Table 2.3.2. Top natural gas storage fields in the AOI with favorable reservoir characteristics, sorted by geologic interval and in alphabetic order for each interval.

2.3.4 Thin Section Examination

A total of 64 thin sections representing five different geologic intervals are being analyzed for the Study. The samples selected for this value-added work depended 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 where reservoir data gaps may exist being the largest drivers for selection (Figure 2.3.10). OGS provided PAGS with both existing thin sections and rock sample billets for 21 Rose Run-Gatesburg locations throughout southern Ohio. WVGES provided PAGS with both existing thin sections and rough-cut core samples for 43 sandstone locations throughout western and central West Virginia, representing the Weir, Oriskany, Medina and Newburg sandstones (Table 2.3.3.).

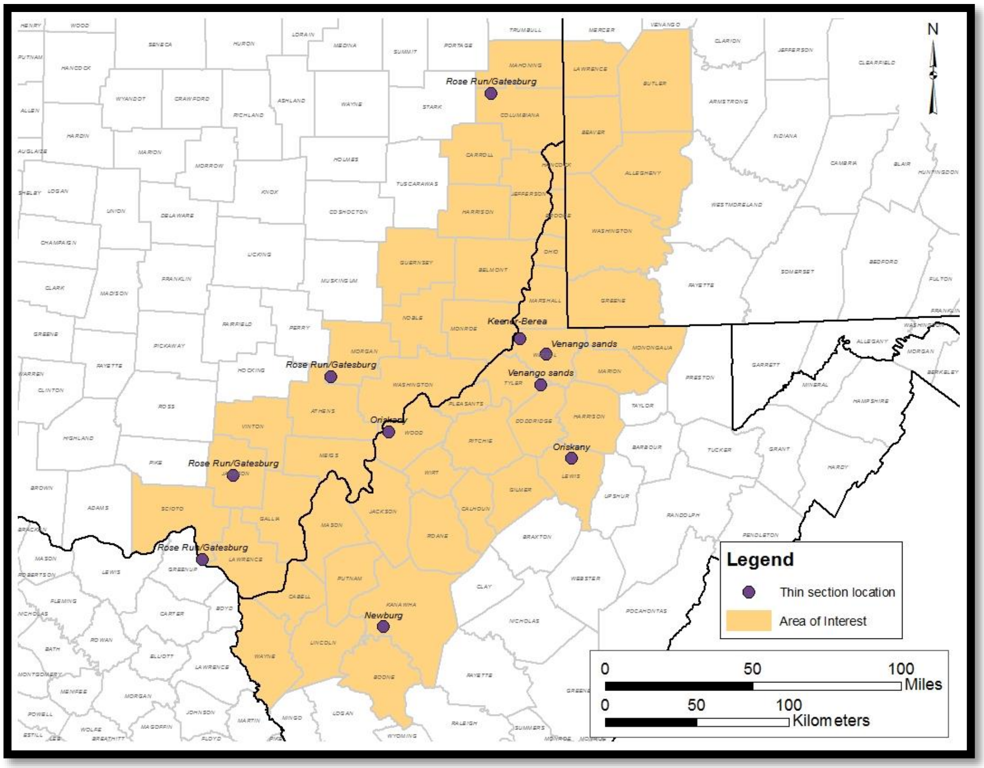


Figure 2.3.10. Locations of samples (with corresponding geologic intervals) to be examined in thin section for the Study.

State	Thin Sections		Well Location/API No.	Geologic Interval(s)
	Existing	New		
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 sands
	8		L.S. Hoyt #100/47-103-01685	Venango sands
	4		J. Woodrum #A-2/47-039-02112	Newburg Sandstone

Table 2.3.3. Thin sections to be analyzed as part of the Study.

PAGS began this work in earnest during the third quarter with the review of 11 existing Rose Run-Gatesburg thin sections provided by OGS. Detailed thin section analyses will be completed in the fourth quarter and included in the Study's final report.

2.4 Ranking & Recommendations

During the third quarter of the Study, Research Team members prepared a preliminary list of ranking criteria for each type of potential storage target – mined-rock caverns, salt caverns, depleted gas reservoirs and gas storage fields (Table 2.4.1). A 'y' is used in Table 2.4.1 to indicate where a given criterion will be evaluated for a particular storage target category.

Ranking activities will involve the assignment of a numeric value (ranging from 0 to 3) to each applicable criterion, followed by the summation of these values to create an overall ranking for each storage opportunity. For example, the closer the distance of a potential storage target to pipeline infrastructure or the greater the average porosity of a depleted gas reservoir, the higher the ranking values assigned. The Research Team may choose to weight certain ranking criteria more heavily than others, depending upon its ongoing work during the fourth quarter. Ultimately, the overall numeric rankings for each storage opportunity will be used to recommend the most favorable ethane storage reservoirs.

Criteria	Mined-Rock Caverns	Salt Caverns	Depleted Gas Reservoirs	Gas Storage Fields
Distance to infrastructure	y	y	y	y
Average depth	y	y	y	y
Average area	y	y	y	y
Average gross thickness			y	y
Average net thickness	y	y	y	y
Average porosity			y	y
Porosity-feet			y	y
Permeability			y	y
Pressure	y	y	y	y
Trap integrity	y	y	y	y
Legacy well penetrations	y	y	y	y
Stacked opportunity(ies)	y	y	y	y
Mode CO_2 storage (computed)			y	y
Estimated cumulative gas production			y	y

Table 2.4.1. Proposed ranking criteria for ethane storage prospects in the AOI (subject to change).

During the last quarter of the Study, the Research Team will modify, augment or otherwise refine these ranking criteria, as necessary, to provide for the most robust assessment of potential ethane storage opportunities. The Research Team will apply the final ranking criteria to geographic areas representing potential mined-cavern and salt cavern storage opportunities and to the short list of depleted gas and natural gas storage fields identified as targets as part of Strategy 4.

One example of how the ranking criteria for a given type of ethane storage prospect may be revised is provided in Table 2.4.2. Depending upon the ability of PAGS to identify certain Greenbrier facies using geophysical log data, the Research Team may add a lithology-based parameter to the ranking criteria for mined-rock caverns, or simply incorporate the geographic coverage of prospective facies into the average area estimates.

Mined-Rock Suitability Comparison

Poor to Fair	Good	Optimal
• Red Beds • Peloid/Ooid Grainstone • Skeletal Grainstone/Packstone • Argillaceous and/or Skeletal Wackestone	• Quartz Sandstone • Quartz Peloidal Grainstone • Marine Calcareous Silts	• Fine-Grained Lime Wackestone/Mudstone • 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*

Table 2.4.2. Criteria used to rank different carbonate lithology types for mined-rock cavern construction.

3.0 ADMINISTRATION & TECHNOLOGY TRANSFER

3.1 Team Communication

3.1.1 User Groups

Communication within and among all Consortium member groups is essential to the success of this Study, as is the efficient, yet secure, assembly and transfer of information. For the purposes of this Study, lines of communication and data sharing are divided into three broad User Groups:

Research Group: Members of the Ohio, Pennsylvania and West Virginia Geological Surveys and the NRCCE

Industry Group: Representatives from organizations entered into agreement to support research efforts

Advisory Group: Small subset of individuals with professional experience that can be used to guide Research Group efforts. The Advisory Group is currently comprised of the following members:

Brian Anderson, WVU Energy Institute
Indrajit Bhattacharya, AEP
Ray Boswell, NETL
Dennis Carulli, DC Energy Consultants

Tom Eyermann, Mountaineer NGL
Michael Goodman, Chevron
Peter Swift, EQT

Contact information for all Consortium members is provided in Appendix 6.4.

3.1.2 Email Communication

Email listservs for each User Group have been established through the WVGES email provider, WVNet. The Research Group listserv was distributed in October 2016 and is the primary communication method between researchers. The Industry and Advisory Group listservs were subsequently distributed in November 2016. WVGES is responsible for the continued maintenance of the email groups.

3.1.3 Monthly Conference Calls

Research team members participate in monthly phone conferences, during which each member of the research team provides a status update on strategy progress to NRCCE.

3.2 Technology Transfer

3.2.1 Semi-Annual Partner Meeting

The West Virginia University Foundation hosted an ASH meeting for Research Team members and representatives of the industry partners on March 14, 2017, at the WVU Erickson Alumni Center, Evansdale Campus, in Morgantown, West Virginia. Following an overview of the Study, a research lead from each of the three geological surveys presented a more detailed technical status report on their areas of respective areas of responsibility (i.e., Strategies 1-4). The program ended with a very positive and productive discussion session during which members of the ASH Advisory Board offered valuable suggestions.

3.2.2 Public Release of Final Results

The primary technology transfer event will be a full-day workshop at the end of the project period, co-hosted by the Petroleum Technology Transfer Council's Appalachian Basin Regional Lead Organization (i.e., WVU), during which results will be made available to the public. This workshop will be held in early September 2017.

3.3 Reporting

3.3.1 Quarterly Reports

During early February 2017, written reports from all Research Team members were compiled into the second quarterly report, which was then submitted to the Benedum and WVU foundations, the WVU Research Corporation and the WVU Energy Institute. The report also was made available to Industry Partners and members of the Advisory Board through the Study website.

3.3.2 Final Report

A draft final report will be produced by the end of July 2017 and provided to our sponsors and partners for review and comment. A final version will be produced by the end of August, and released to the public following a technology transfer workshop for the formal release of the data, tentatively scheduled for early September 2017.

4.0 FINANCIAL UPDATE

Cumulative expenditures during the first three quarters of this one-year project are provided below. The entire obligation to provide matching funds has been met.

CATEGORY	Funded	Expended	Remaining
Salaries/Fringe Benefits	$17,000	$17,000	$0
Supplies	$200		$200
Travel – includes team meeting costs	$2,800	$453	$2,347
Analytical			
Other - Subcontracts	$180,000	$56,042	$123,958
In-kind match	$60,000	$68,265	($8,265)
Total	$260,000	$141,760	$118,240

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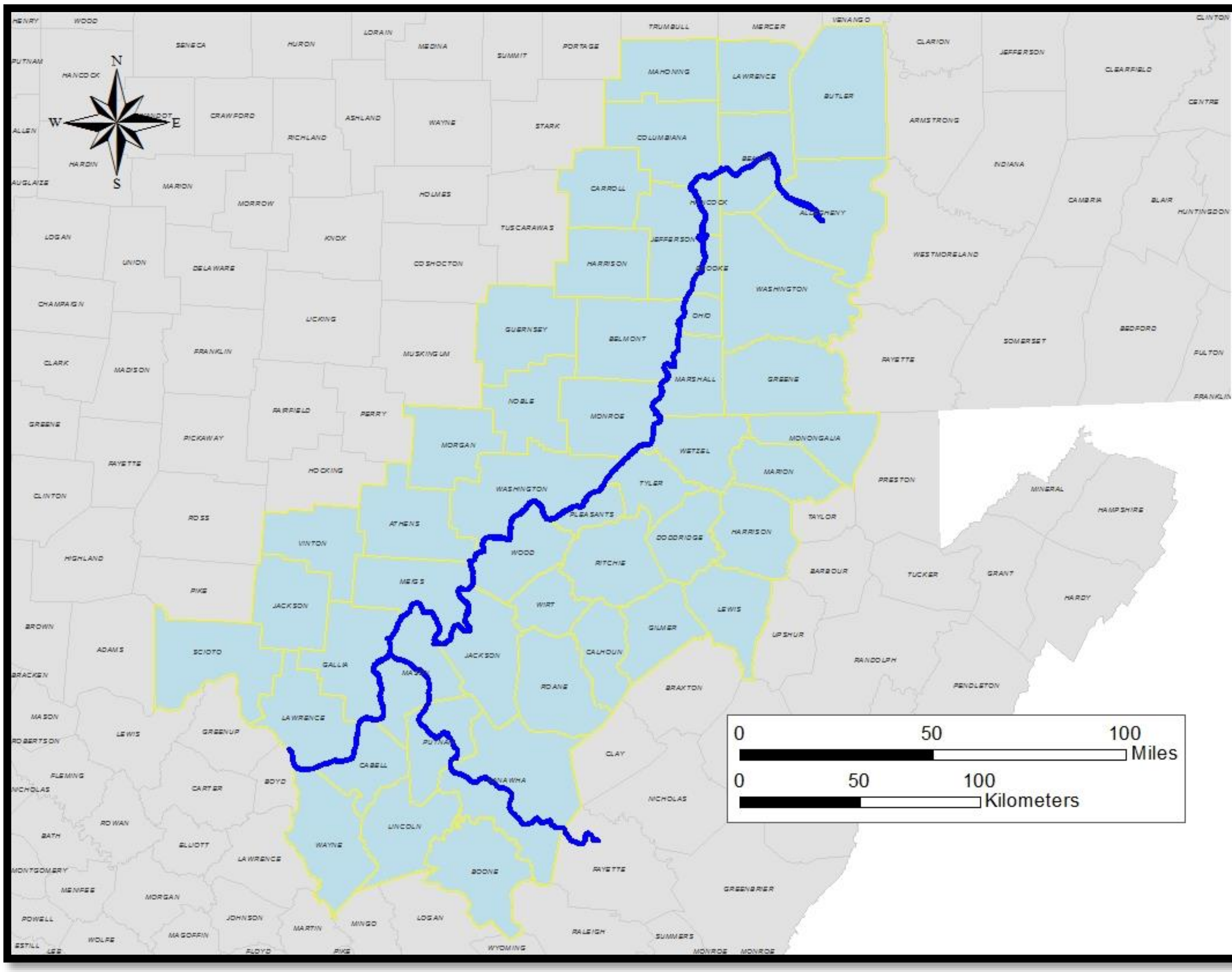
6.0 APPENDICES

6.1 Appalachian Storage Hub (ASH) Area of Interest



6.2 Regional Subsurface Rock Correlation Diagram (next page)

6.3 Project Milestone Chart

Strategy 1: Data Collection		
• Identify and assemble well log and core data	Month 1	Month 2
• Identify previous studies of interest	Month 1	Month 2
• Create a project database (format, prototype)	Month 1	Month 2
Strategy 2: Stratigraphic correlation of key units		
• Develop cross sections of the Salina Formation	Month 3	Month 8
• Develop cross sections of the Greenbrier Formation	Month 3	Month 8
• Develop cross sections of the Keener to Berea Interval	Month 3	Month 8
• Develop cross sections of the Upper Devonian Sandstones	Month 3	Month 8
• Develop cross sections of the Oriskany Sandstone	Month 3	Month 8
• Develop cross sections of the Clinton-Medina through Tuscarora Interval	Month 3	Month 8
• Develop cross sections of the Rose Run and Upper Sandy Member of the Gatesburg Formation	Month 3	Month 8
Strategy 3: Map the thickness, extent, and structure of potential storage units in the study area		
• Map the Salina Formation	Month 5	Month 7
• Map the Greenbrier Limestone	Month 5	Month 7
• Map the Keener-Berea, Upper Devonian, Oriskany, Clinton-Medina, and Gatesburg Formations	Month 5	Month 7
Strategy 4: Conduct studies of reservoir character		
• Characterize potential storage intervals in the Salina Formation	Month 5	Month 8
• Characterize potential storage intervals in the Greenbrier Formation	Month 5	Month 8
• Characterize potential storage pools in gas-depleted sandstone reservoirs	Month 5	Month 8
Strategy 5: Develop ranking criteria for potential storage zones		
• Determine criteria and weighted priority of potential storage zones	Month 8	Month 9
Strategy 6: Recommendations		
• Rank all candidates within each category	Month 10	Month 11
• Rank the top candidates in each category	Month 10	Month 11
Strategy 7: Suggestions for engineering follow-up study		
• Make suggestions for additional field and lab studies	Month 10	Month 11
Strategy 8: Project management and technology transfer		
• Project management	Month 1	Month 12
• Final Report	Month 11	Month 12
• Technology transfer		Month 12+ ongoing

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6.5 Regional Geologic Cross Sections (next 13 pages)