APPALACHIAN STORAGE HUB (ASH) FOR LIQUID ETHANE

QUARTERLY REPORT

November 2016 – January 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

FEBRUARY 2017

Quarterly Progress Report

1.0 INTRODUCTION

The Appalachian Oil & Natural Gas Research Consortium (Consortium) has reached the midpoint 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).

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; see 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.

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 (Bradford, Venango and/or Elk intervals), Lower Devonian (Oriskany 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 second quarter were to:

- Complete the Stratigraphic Correlation of Key Units (Strategy 2)
  - Complete correlation of key logs for cross sections through all stratigraphic intervals of interest
- Initiate the mapping program for all potential storage units (Strategy 3)
  - Maps to include thickness and areal distribution in the AOI and net sand (net-to-gross) maps
  - Structure maps to be included, as needed
- Initiate the Studies of Reservoir Character (Strategy 4)
  - Identify previous petrographic studies of cores and thin sections
  - Identify and assemble additional well log and core analyses
  - Continue to populate the project database

All milestones were met during the second calendar quarter of the project (see Appendix 6.3 for the project's milestone chart), although log correlations continue to be refined and mapping is continuing. Details follow in the Research Section.

2.0 RESEARCH

Second quarter project efforts focused on indexing and organizing geologic data relevant to the AOI for use by the Research and Advisory Group members; compiling and correlating additional well header, raster logs, digital curves and subsurface formation tops data; preparing cross sections and preliminary maps for geologic intervals of interest; and identifying and compiling relevant reservoir characterization information.

6.1 Data Collection & Database Creation

2.1.1 Study Website

A prototype website was created during the first quarter of the Study, and is updated regularly with information received from Research Team and Advisory Group members (see the complete list of Study members in Appendix 6.4). The website also is being redesigned, and will be presented at the March 2017 Partners meeting. Information that is periodically received and updated includes:

- PETRA® project files with digital logs (.las files) and well log correlations. The tops and logs submitted by each state geological survey will be assimilated into the Master PETRA® Project by OGS;
- Geophysical logs, including newly-digitized logs created from raster images in key areas and/or high-priority reservoir targets; and
- Annotated bibliography entries for relevant publications. These may include final reports from other basin-scale cooperatives, current literature and historical publications.

6.2 Stratigraphic Correlations and Mapping

Second quarter research efforts focused on the preparation, review and interpretation of well log data available for the AOI, as well as correlation of certain intervals across the Study area. As technical lead for the stratigraphic correlation and mapping work, OGS imported well data and formation tops provided by all three states into the Study's Master PETRA® project database. OGS performed a quality assurance/quality control review of both digital geophysical log curves and raster log images. Log corrections and depth registration were completed, as necessary. The digital data contained in this PETRA® project were then used to vet and refine correlations of the seven intervals of interest for the Study.

Particular emphasis was given to the stratigraphic correlation of the Greenbrier, Keener to Berea, Upper Devonian sandstones and Salina Group intervals during the second quarter (Appendix 6.2). PAGS refined its interpretation and correlation of the Greenbrier Limestone and equivalent units (e.g., Wymps Gap and Loyalhanna limestone members; see Figure 2.2.1) in the Pennsylvania portion of the AOI. 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 older, unconformity-bound sandstones of the Price Formation (Figure 2.2.1). In West Virginia, drillers' terms for depleted gas reservoirs from this portion of the section include the Keener, Big Injun, Squaw and Weir sands. The extent, thickness and nature of facies relationship vary significantly throughout the AOI. Correlations follow type log characteristics as outlined in the Atlas of Major Appalachian Gas Plays (Roen and Walker, 1996). For the purposes of this Study, the limestone units will be considered separately from the siliciclastic units, regardless of age, due to the different storage reservoir types (mined caverns versus intergranular porosity).

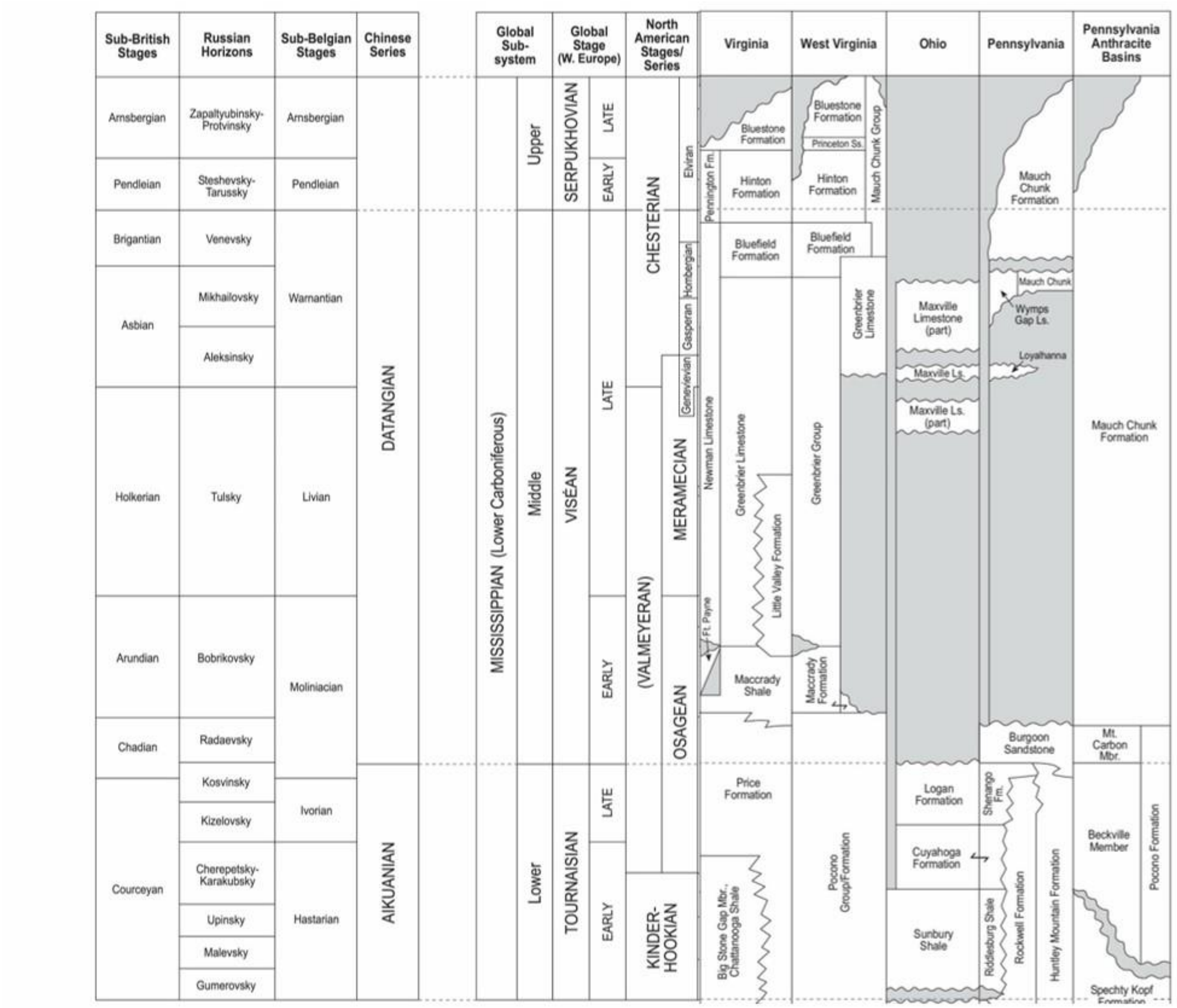

Figure 2.2.1. Mississippian stratigraphy of the study area (Ettensohn, 2009).

In addition, due to the number and sometimes complex nature of Upper Devonian sandstone reservoirs, the pseudo-chronostratigraphic framework suggested in the Atlas of Major Appalachian Gas Plays (Roen and Walker, 1996) was used to simplify the correlation and mapping of Upper Devonian depleted gas reservoirs (Figure 2.2.2).

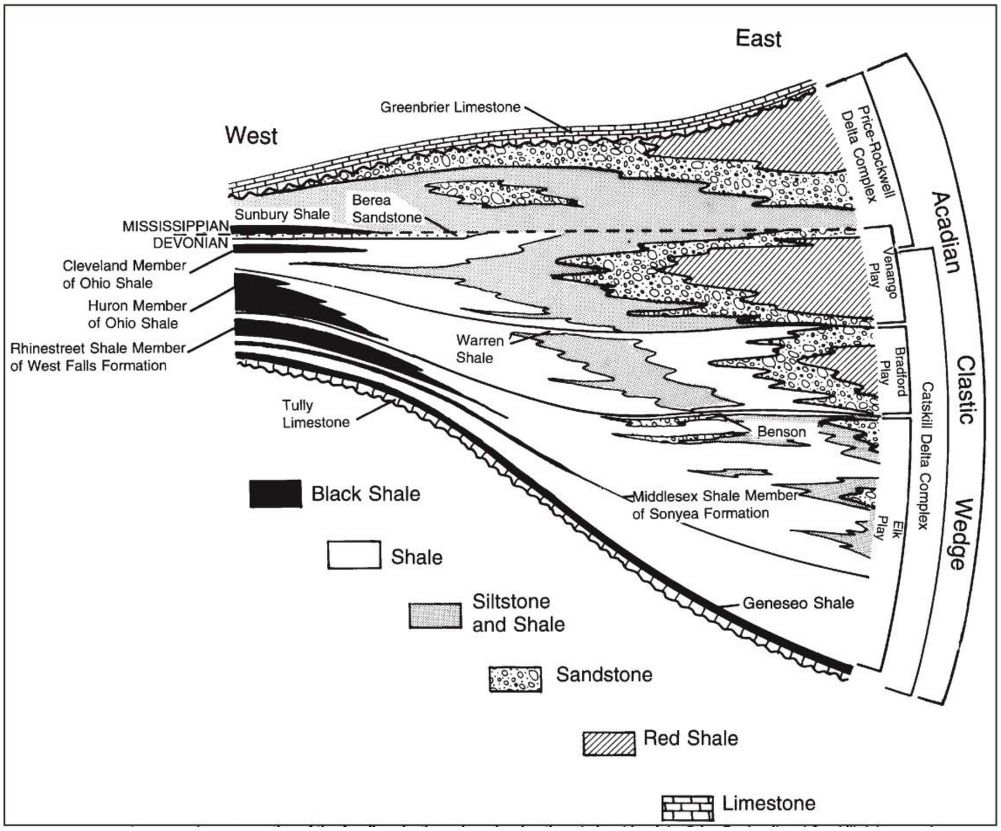

Fig. 2.2.2. Pseudo-chronostratigraphic cross section from the Atlas of Major Appalachian Gas Plays (Roen and Walker, 1996), showing the chronostratigraphic equivalents of the Acadian clastic wedge across the basin.

Finally, correlations of Silurian-age units, including the Salina Group's bedded evaporite-dolomite succession and age-equivalent Newburg sandstone, were refined in Ohio, Pennsylvania and West Virginia during the second quarter. In West Virginia, the Salina Group (as a whole) is thickest in the northwestern part of the state in counties adjacent to the Ohio border (Figure 2.2.3). Looking at individual Salina salt members, OGS prepared a preliminary north-south geologic cross section, and WVGES prepared some state-specific extent maps and cross sections (Appendix 6.5). Ohio's longitudinal line of section illustrates that approximately 100 feet (ft) of salt are present along the Ohio River Valley corridor. Correlation and preliminary mapping of the stratigraphically older Newburg sandstone by WVGES shows that this sandstone unit is present in southern West Virginia and can be up to 20 ft thick in some areas (Figure 2.2.4).

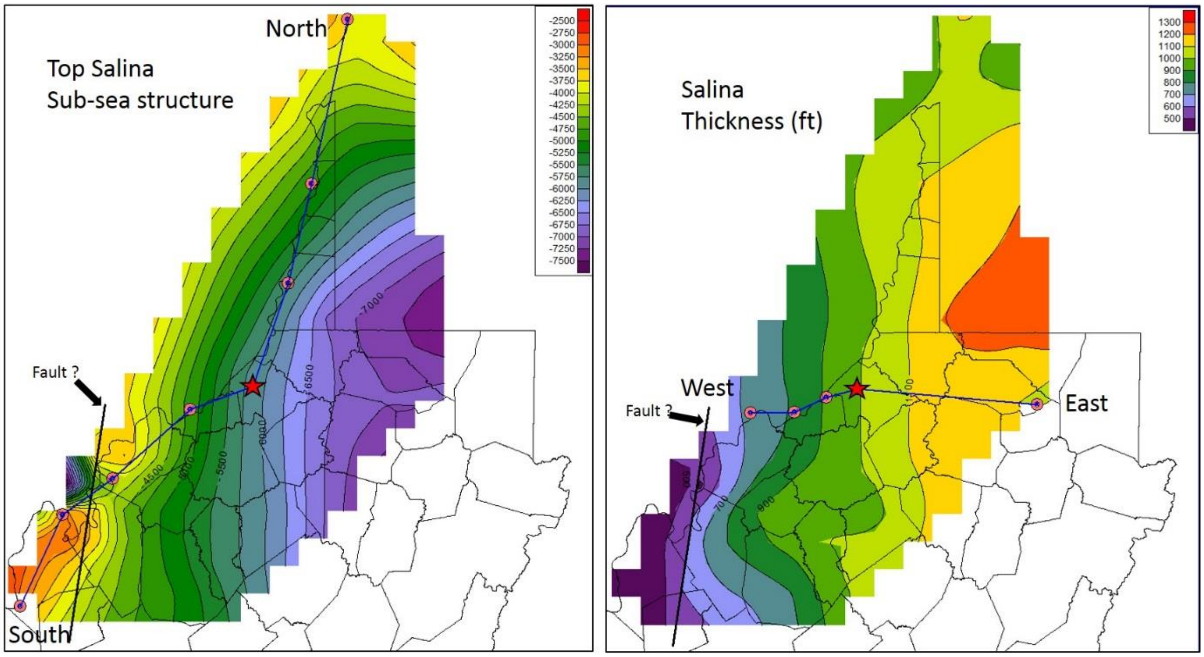

Figure 2.2.3. Preliminary Salina Group structure contour (left) and isopach (right) maps.

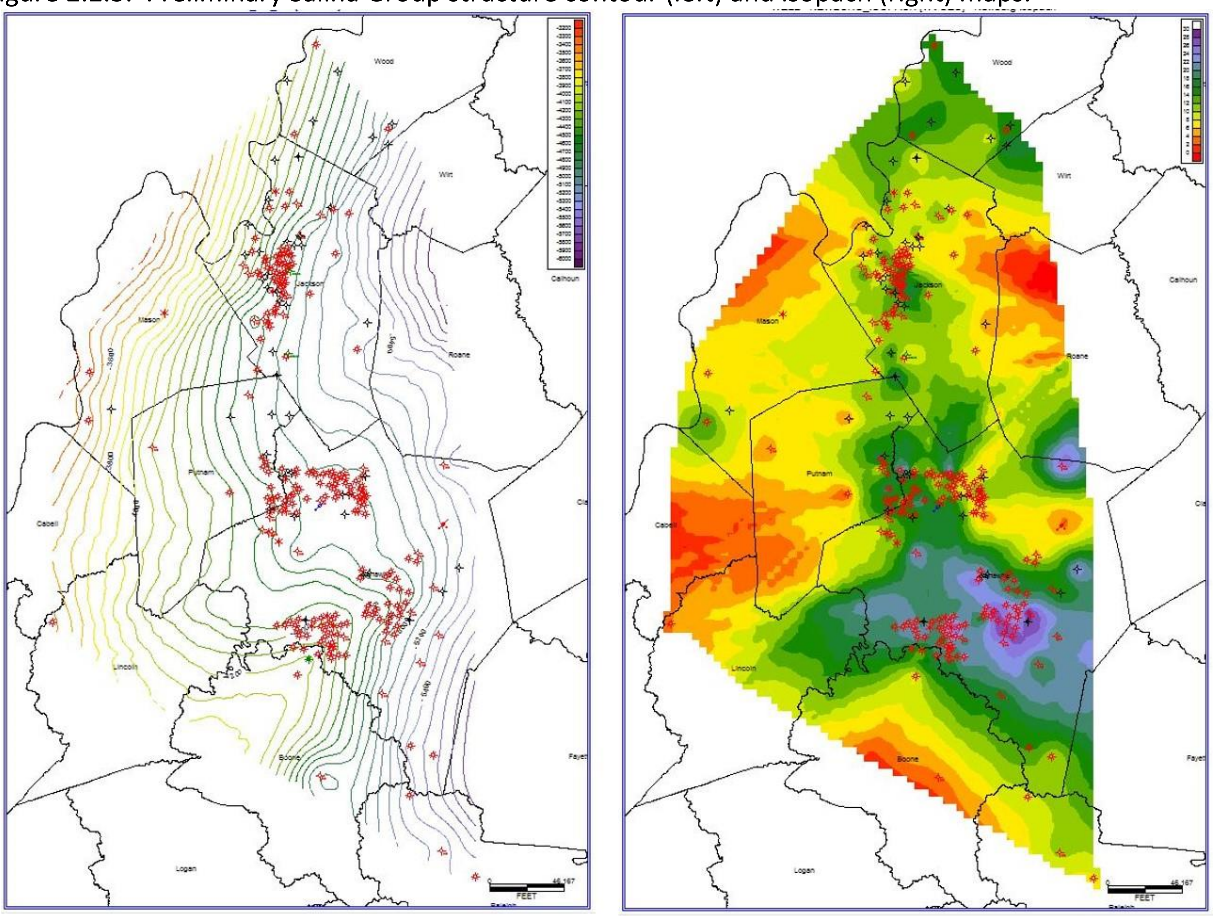

Figure 2.2.4. Preliminary Newburg sandstone structure contour (left) and isopach (right) maps.

Stratigraphic correlation activities were followed by the generation of preliminary draft subsurface structure (i.e., true vertical depth subsea elevation) and gross isopach (i.e., apparent thickness) maps for three of the AOI's intervals of interest: Greenbrier Limestone, Venango sands and Salina F salt. Subsurface structure maps utilized a 100-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 F salt isopach map illustrates net (i.e., true) thicknesses, as this mapped interval is interpreted to be entirely comprised of salt.

Figures 2.25 and 2.26 present the subsurface structure and gross isopach maps for the Greenbrier Limestone, respectively. This interval is present through much of the AOI, apart from certain Ohio counties along the western limit of the study area. Based on Figure 2.26, the apparent thickness of the Greenbrier Limestone varies from 0 to more than 150 ft. These data will be reviewed and refined in the coming quarter to better constrain the AOI's most prospective area(s) for creating a mined-rock cavern for storing ethane.

Figures 2.27 and 2.28 present the subsurface structure and gross isopach maps for the Venango Group sands, respectively. This is one of three dominantly sandstone packages included in the larger Upper Devonian sandstone interval, and is present throughout the entire AOI. As shown in Figure 2.28, the apparent thickness of the Venango sands interval ranges from less than 100 ft to approximately 1,500 ft, but the actual thickness of depleted gas-producing sand reservoirs within this interval is known to be much less. The Research Team will be refining these data during the next quarter, as net sand computations will be included in the Reservoir Characterization task.

Figures 2.29 and 2.30 present the subsurface structure and net isopach maps for the Salina F Salt (of the Salina Group). Based on Figure 2.30, this particular salt unit is generally restricted to the panhandle of West Virginia in the northern portion of the AOI. Here, the F Salt ranges from 0 to about 100 ft thick, with some areas potentially reaching 150 ft in thickness. These data will be reviewed and refined in the coming quarter to better constrain the AOI's most prospective area(s) for creating one or more salt caverns for storing ethane.

Regional correlation and mapping activities for these and the remaining intervals of interest will continue into the Study's third quarter.

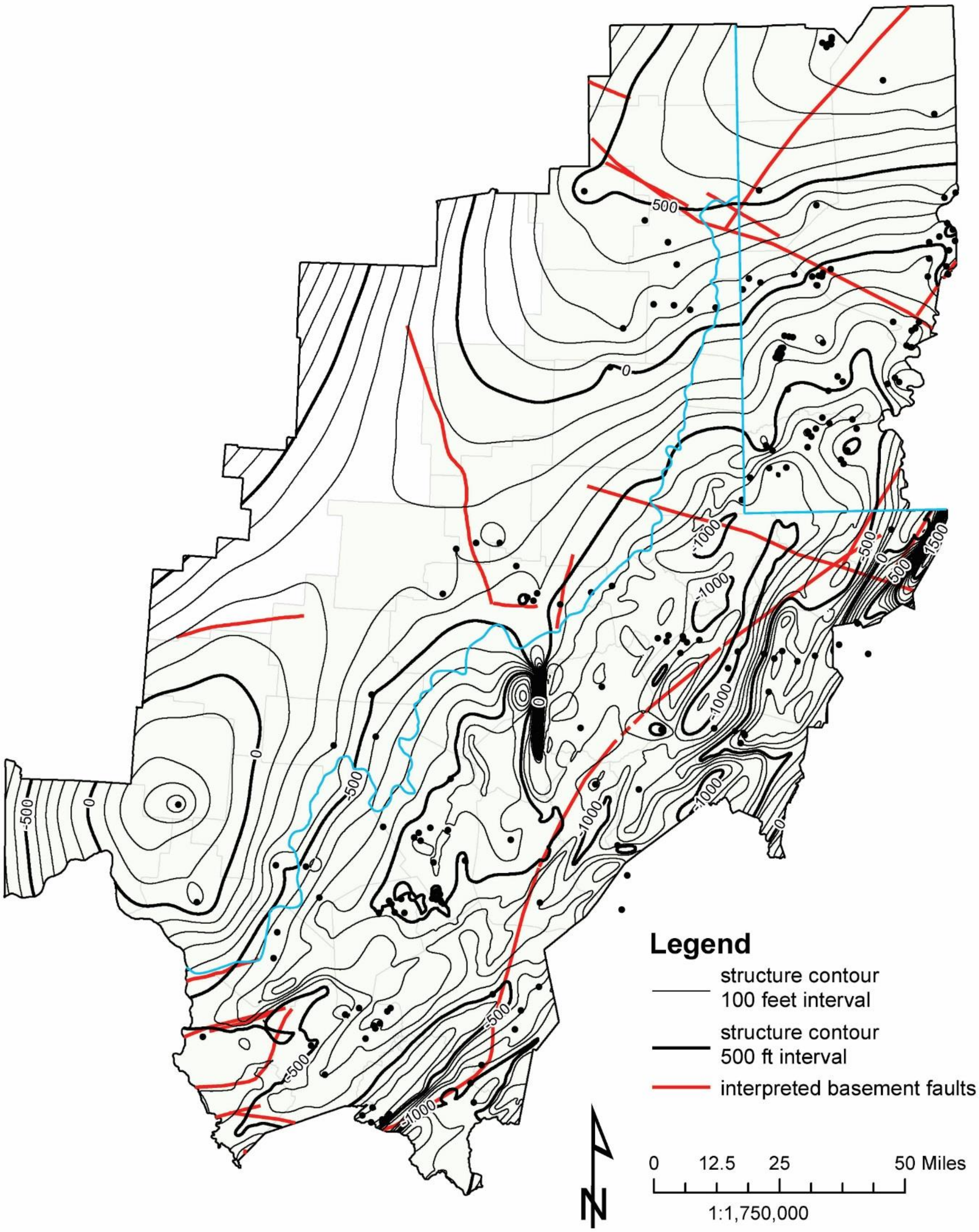

Figure 2.2.5. Preliminary draft structure contour map of the Greenbrier Limestone (true vertical depth subsea elevation map). Contour interval = 100 ft.

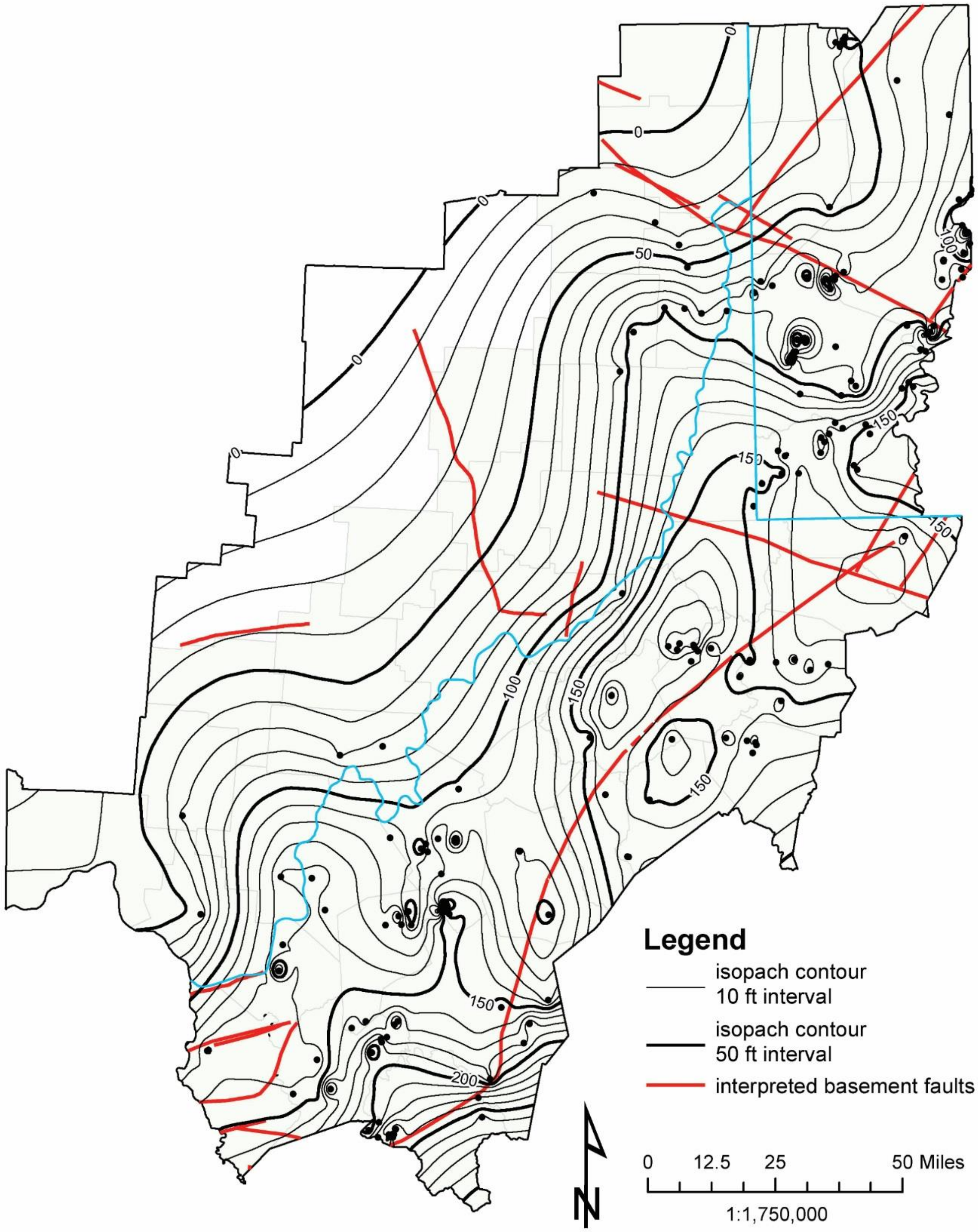

Figure 2.2.6. Preliminary draft gross isopach map of the Greenbrier Limestone (apparent thickness map). Contour interval = 10 ft.

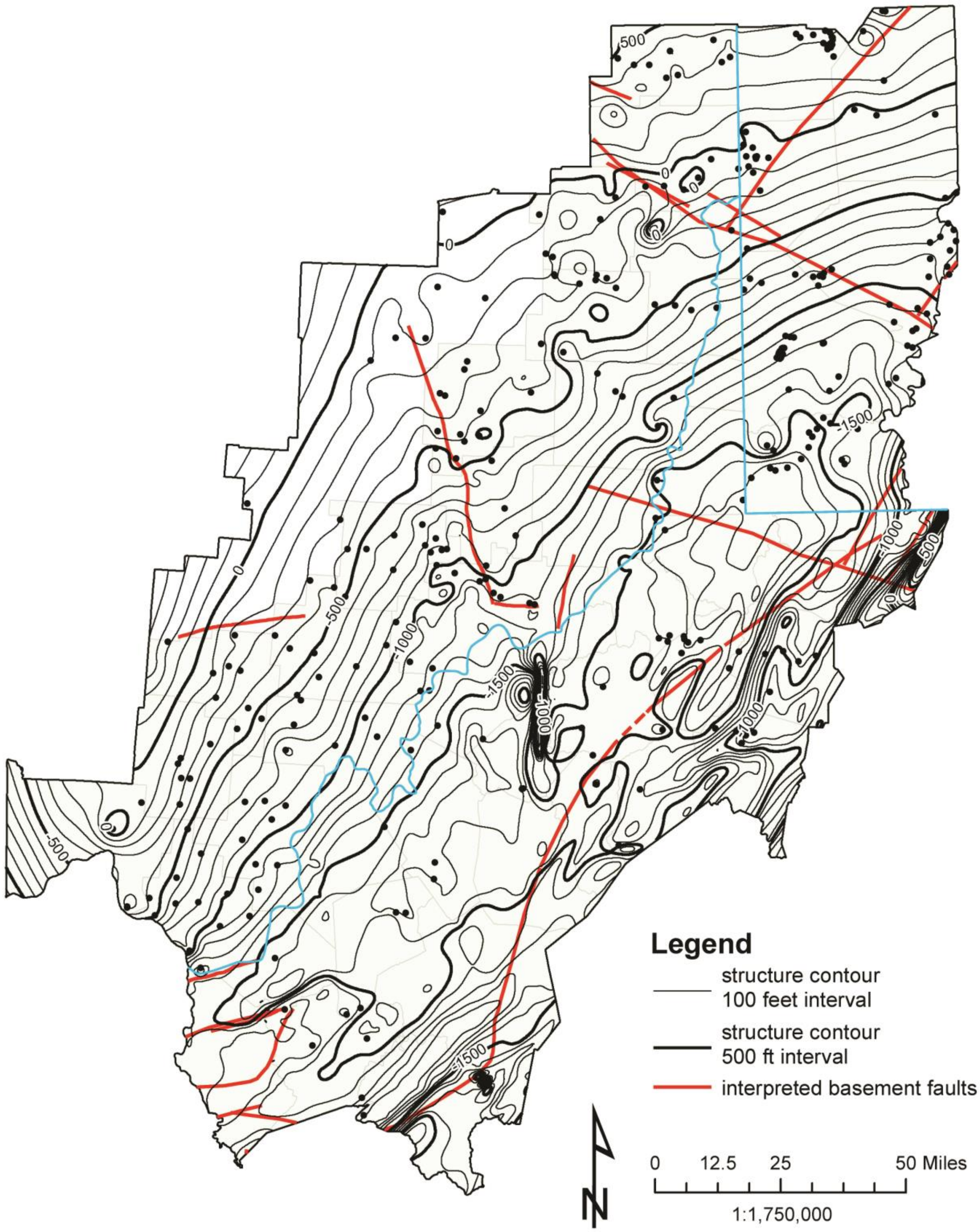

Figure 2.2.7. Preliminary draft structural contour map of the Venango sands interval (true vertical depth subsea elevation map). Contour interval = 100 ft.

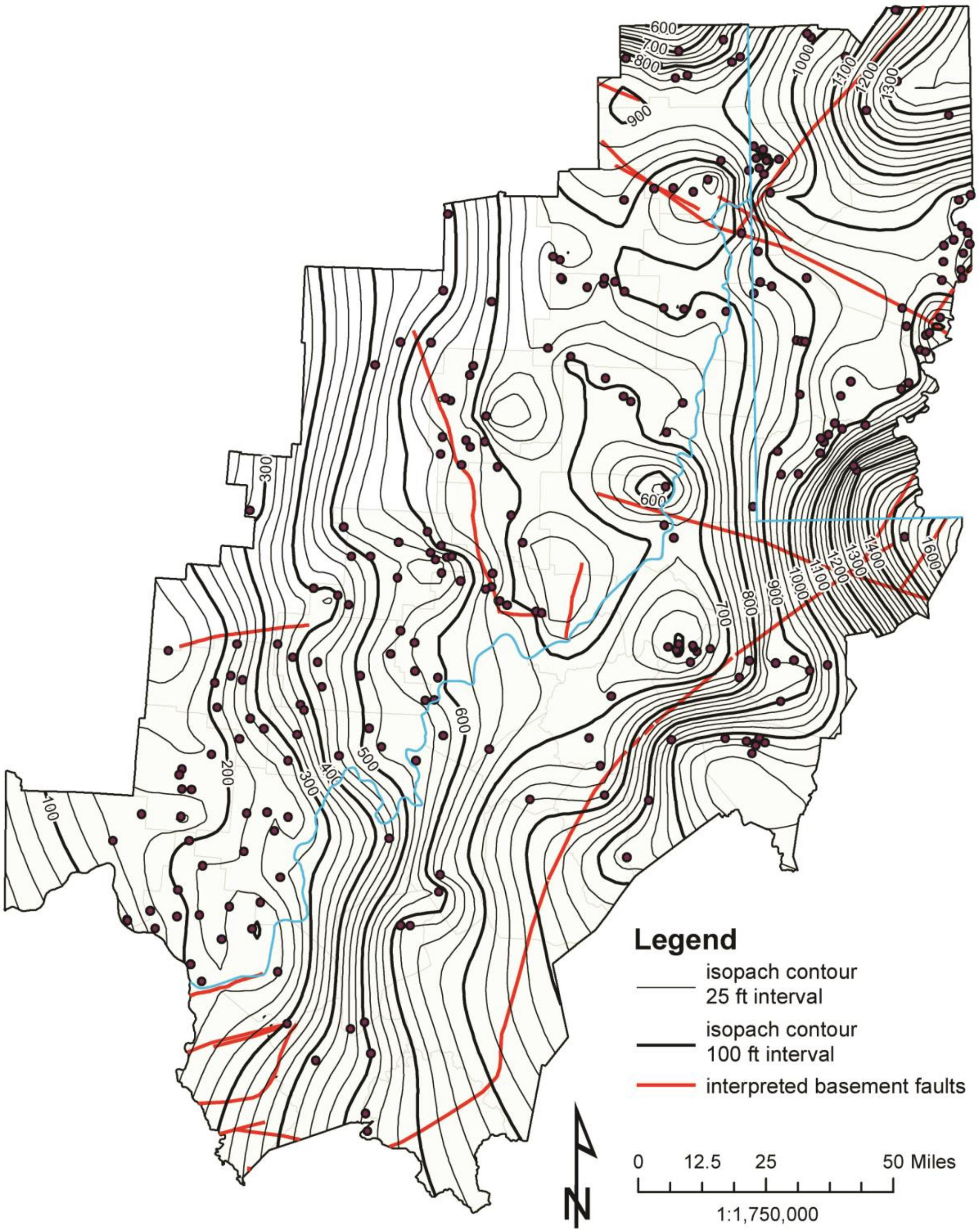

Figure 2.2.8. Preliminary draft gross isopach map of the Venango sands interval (apparent thickness map). Contour interval = 25 ft.

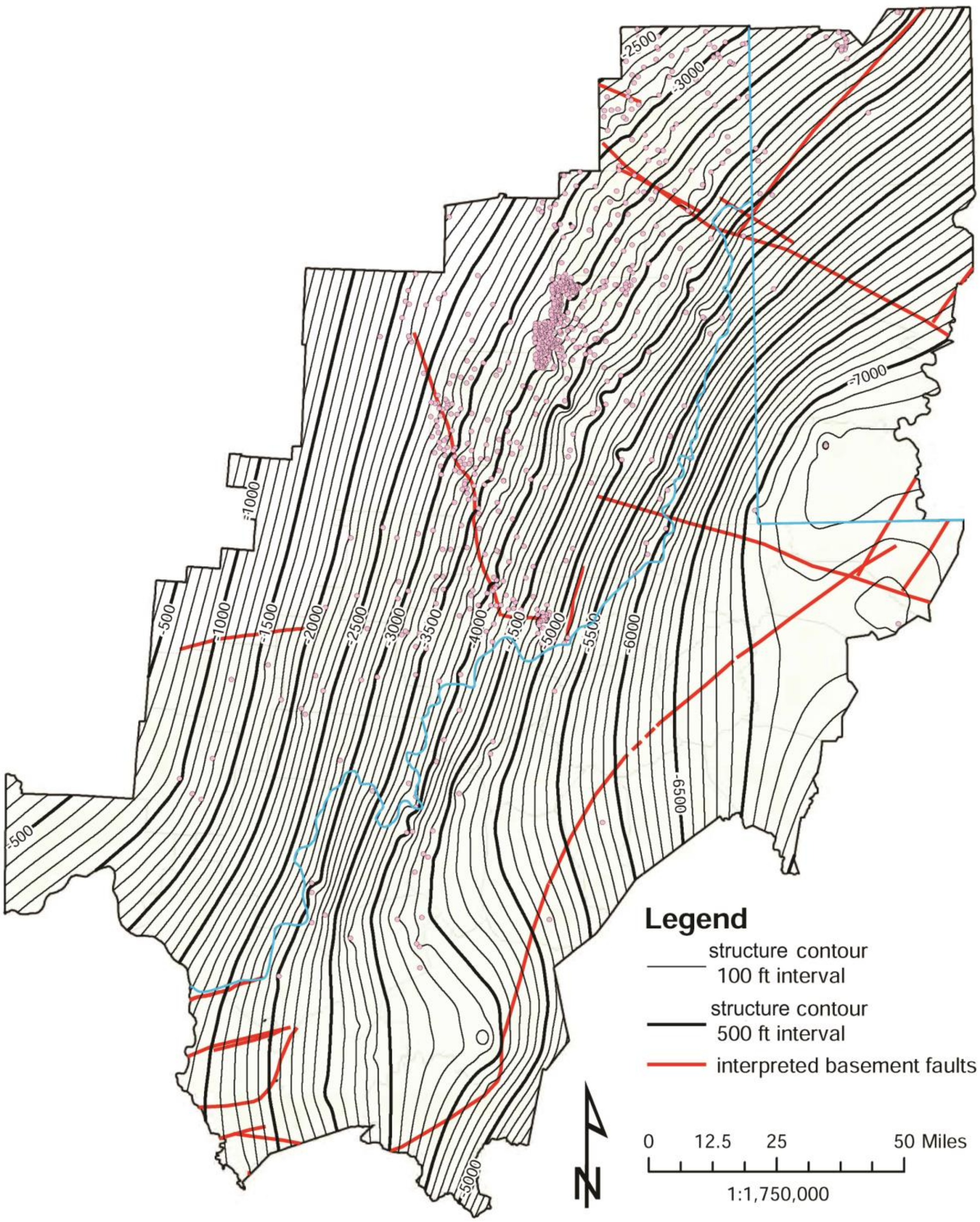

Figure 2.2.9. Preliminary draft structural contour map of the Salina F Salt (true vertical depth subsea elevation map). Contour interval = 100 ft.

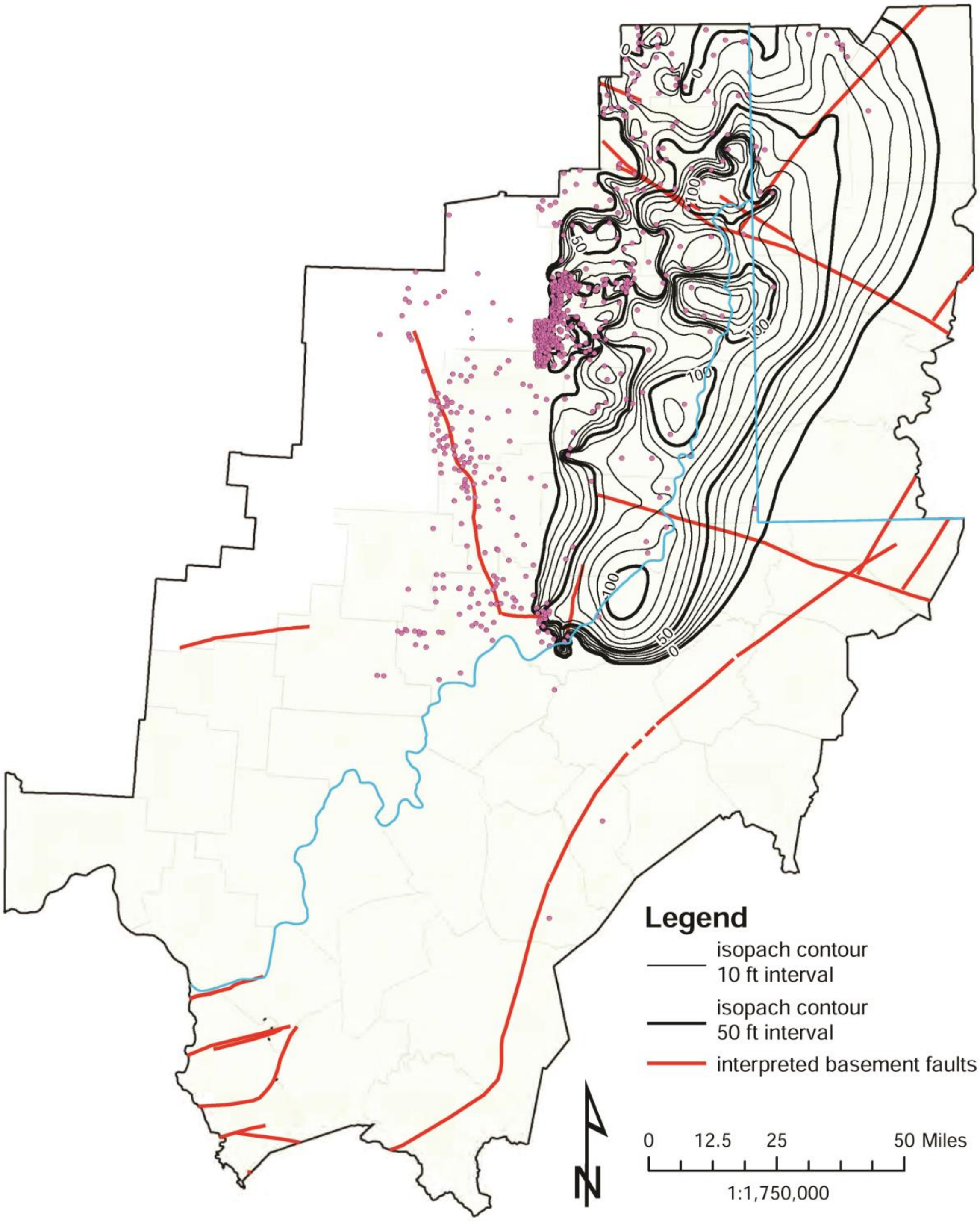

Figure 2.2.10. Preliminary draft net isopach map of the Salina F Salt (true thickness map). Contour interval = 10 ft.

6.3 Reservoir Characterization

PAGS initiated this task during the second quarter, organizing its efforts into three categories of activity: (1) legacy data compilation, (2) petrophysical analyses; and (3) thin section examination. Progress on each effort is reported below.

2.3.1 **Legacy Data**

PAGS has identified certain reports prepared by the Midwest Regional Carbon Sequestration Partnership (MRCSP) (i.e., Wickstrom et al., 2005; Carter et al., 2010; and Carter et al., 2012; and Lewis, 2013) and others (i.e., Riley and others, 1993; Laughrey and Harper, 2012) that contain relevant reservoir information for some of this Study's deeper geologic intervals – namely, the Oriskany Sandstone, Salina Group, Newburg sandstone, Clinton-Medina Group/Tuscarora Sandstone, and Rose Run/Gatesburg sandstones. These reports address various aspects of reservoir character, including lithology, thickness, nature of contacts, porosity, permeability, pore morphology and reservoir trapping mechanisms. In addition, PAGS has identified certain chapters of the Atlas of Major Appalachian Gas Plays (Roen and Walker, 1996) that are relevant to this Study. Legacy data from these important references will be compiled by geologic interval in the coming quarter.

2.3.2 **Petrophysical Analyses**

PAGS will utilize the geologic and geophysical log data in the Master PETRA® project to prepare calculations of gross and net thicknesses for all geologic intervals of interest in the AOI, and average porosity and porosity-ft values for the depleted gas sand intervals. This work will be conducted in the coming quarter, after the Master PETRA® Project has been finalized by OGS.

2.3.3 **Thin Section Examination**

Although this Study will not obtain new geologic samples for the purposes of reservoir characterization, PAGS has offered to perform qualitative thin section analyses for the depleted gas sand intervals associated with the project. PAGS queried Research Team members to determine if they had existing thin sections for any of these intervals and/or rock core that might be sampled to prepare new thin sections. A summary of the input provided by each state is given below and in Table 2.3.1.

Ohio

OGS reviewed its extensive core and thin section inventory, and identified several thin sections associated with geologic intervals of interest in the Ohio portion of the AOI. Following discussions with PAGS, 11 existing Rose Run thin sections and 10 thin section blanks (billets) were selected and provided to Pennsylvania for further analysis (Table 2.3.1).

Pennsylvania

There is only one well location within the Pennsylvania portion of the AOI that both has rock core samples and penetrates any of this Study's geologic intervals of interest. This well, J&L Steel #1 (API No. 37-007-00007), was drilled through the Oriskany Sandstone, and has already been analyzed for porosity and permeability by a commercial laboratory. PAGS has decided to report these laboratory-derived data for this location, rather than prepare qualitative estimates of porosity using thin sections.

West Virginia

WVGES reviewed its core and thin section inventory, identifying a total of 32 core samples from three wells associated with geologic intervals of interest within the West Virginia portion of the AOI. WVGES provided rough-cut samples to PAGS, which were taken from the Oriskany Sandstone in Lewis and Wood counties, and the Keener to Berea interval in Wetzel County. In addition, WVGES identified 42 existing thin sections from wells penetrating either the Venango sands or Newburg sandstone interval. Of these, PAGS cut billets from 28 samples for thin section preparation and analysis, and selected an additional 15 existing thin sections for analysis.

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

Table 2.3.1. Thin sections identified for examination by PAGS.

6.4 Ranking & Recommendations

Determination of ranking criteria is scheduled to begin in month 8 and will be followed by ranking of potential storage sites, scheduled to begin in month 10 of the Study.

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

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 and troubleshooting 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 will host 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 will present a more detailed technical status report on their areas of respective areas of responsibility (i.e., Strategies 1-4).

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.

3.3 Reporting

3.3.1 Quarterly Reports

During early October 2016, written reports from all Research Team members were compiled into the first 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 in early September.

4.0 FINANCIAL UPDATE

Cumulative expenditures during the first and second quarters of this one-year project are provided below.

CATEGORY	Funded	Expended	Remaining
Salaries/Fringe Benefits	$17,000		$17,000
Supplies	$200		$200
Travel – includes team meeting costs	$2,800		$2,800
Analytical			
Other - Subcontracts	$180,000	$23,437	$156,563
In-kind match	$60,000	$47,082	$12,918
Total	$260,000	$70,519	$169,481

5.0 REFERENCES CITED

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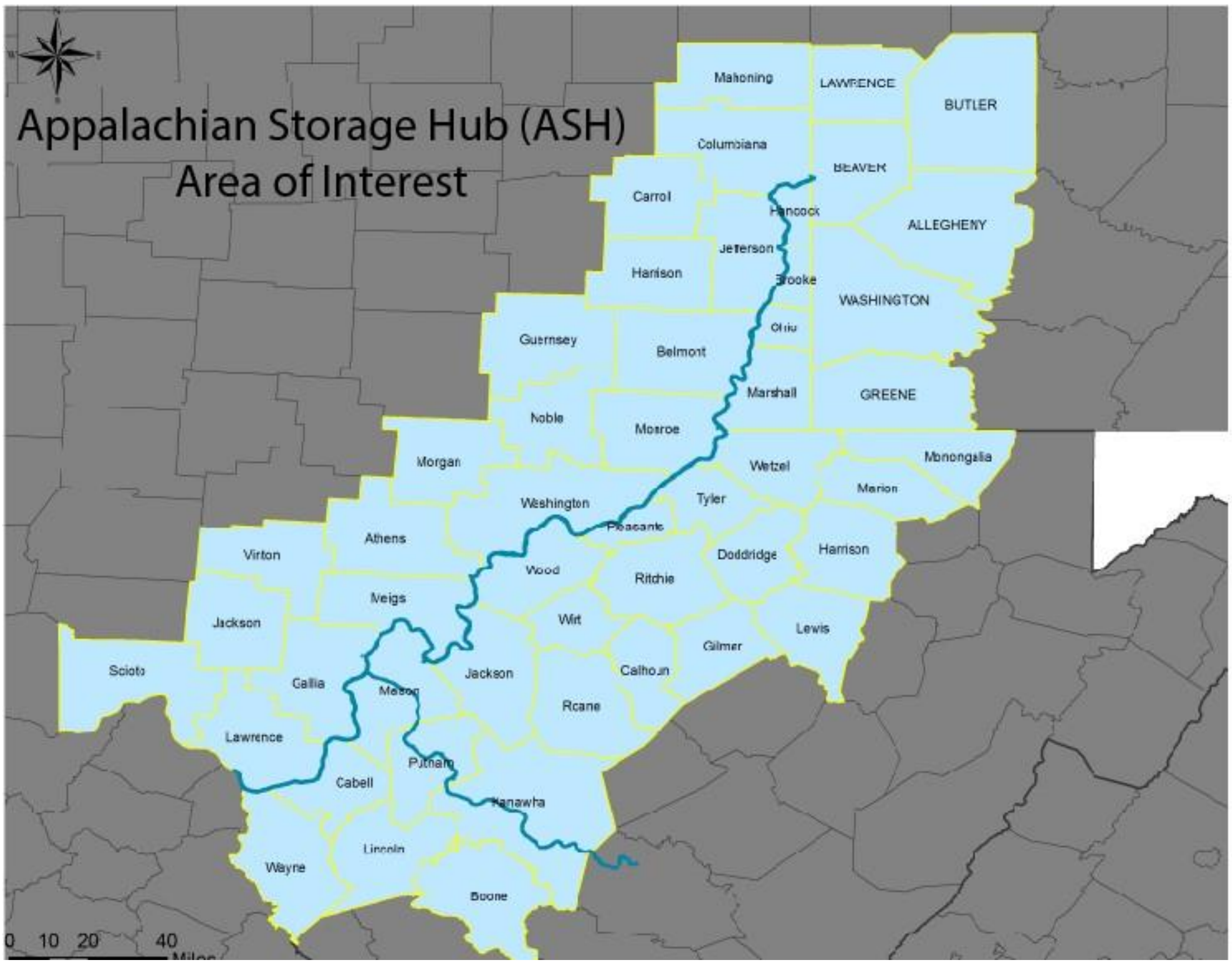
6.0 APPENDICES

6.1 Appalachian Storage Hub (ASH) Area of Interest



6.2 Regional Subsurface Rock Correlation Diagram (next page)

REGIONAL SUBSURFACE ROCK CORRELATION DIAGRAM
APPALACHIAN STORAGE HUB PROJECT

6.3 Project Milestone Chart (revised from initial proposal)

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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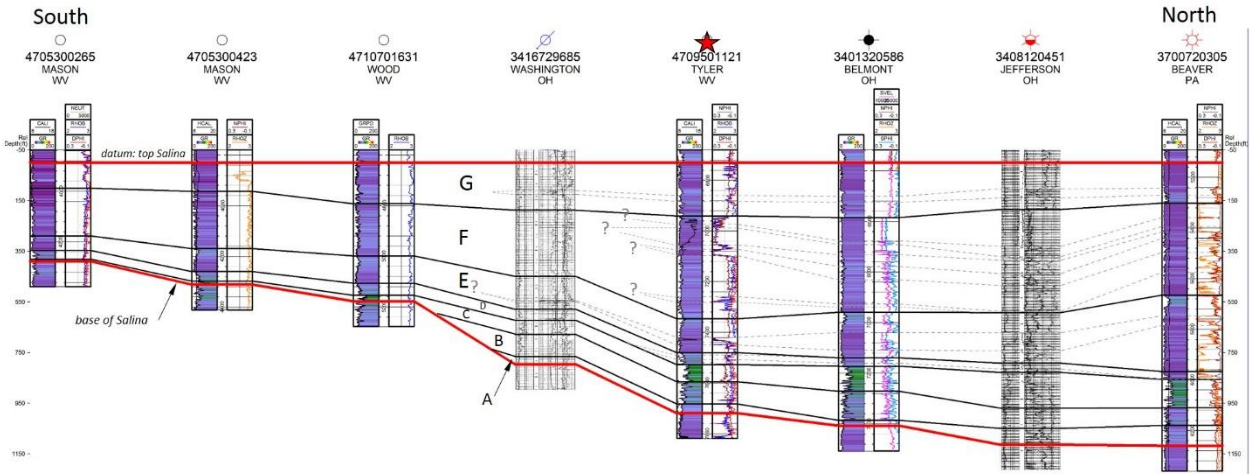
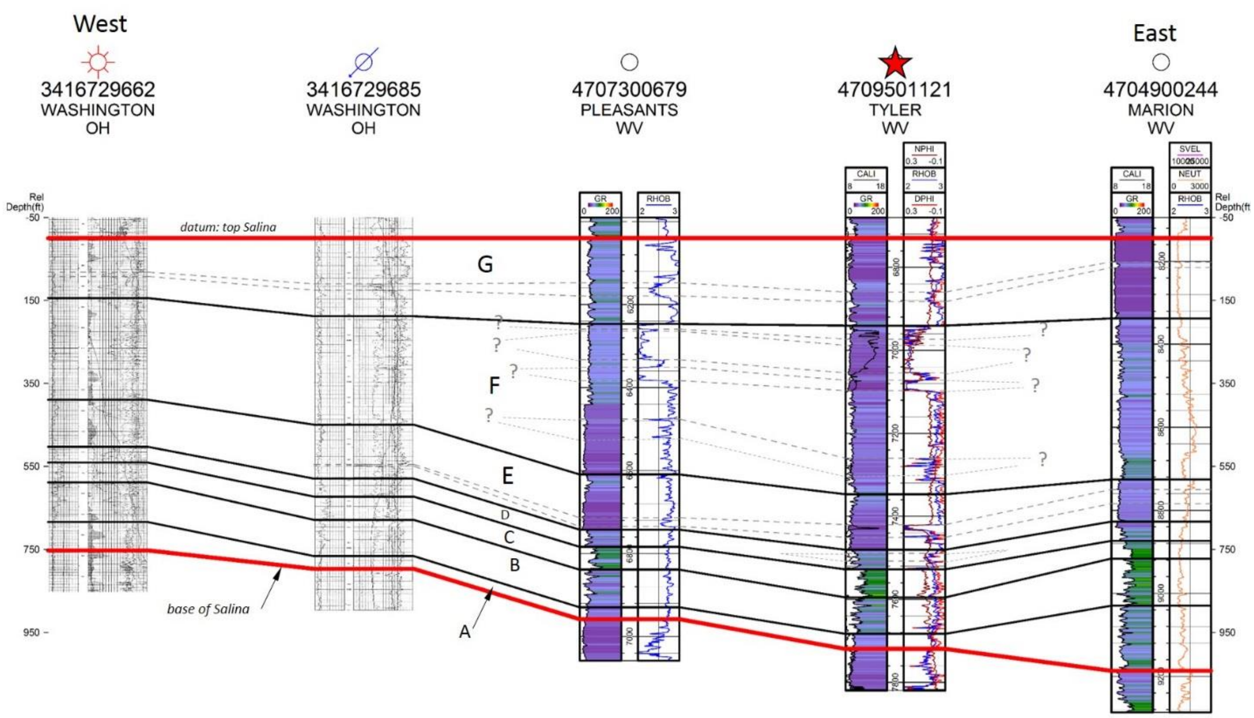
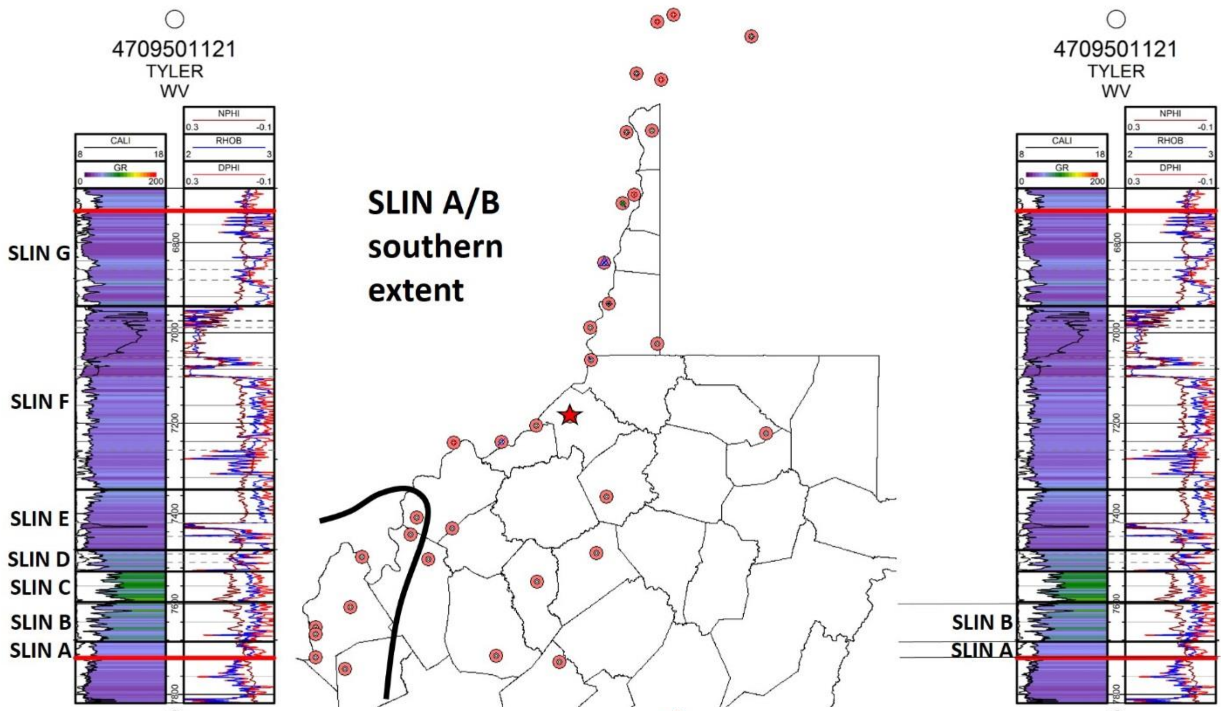
*Advisory Board members, including several from partner companies

6.5 Preliminary Salina Group Mapping Products

6.5.1 West Virginia Cross Sections and Extent Maps






4709501121
TYLER
WV
CALI
GR
NPHI
RHOB
DPHI
SLIN A/B
southern
extent
SLIN G
SLIN F
SLIN E
SLIN D
SLIN C
SLIN B
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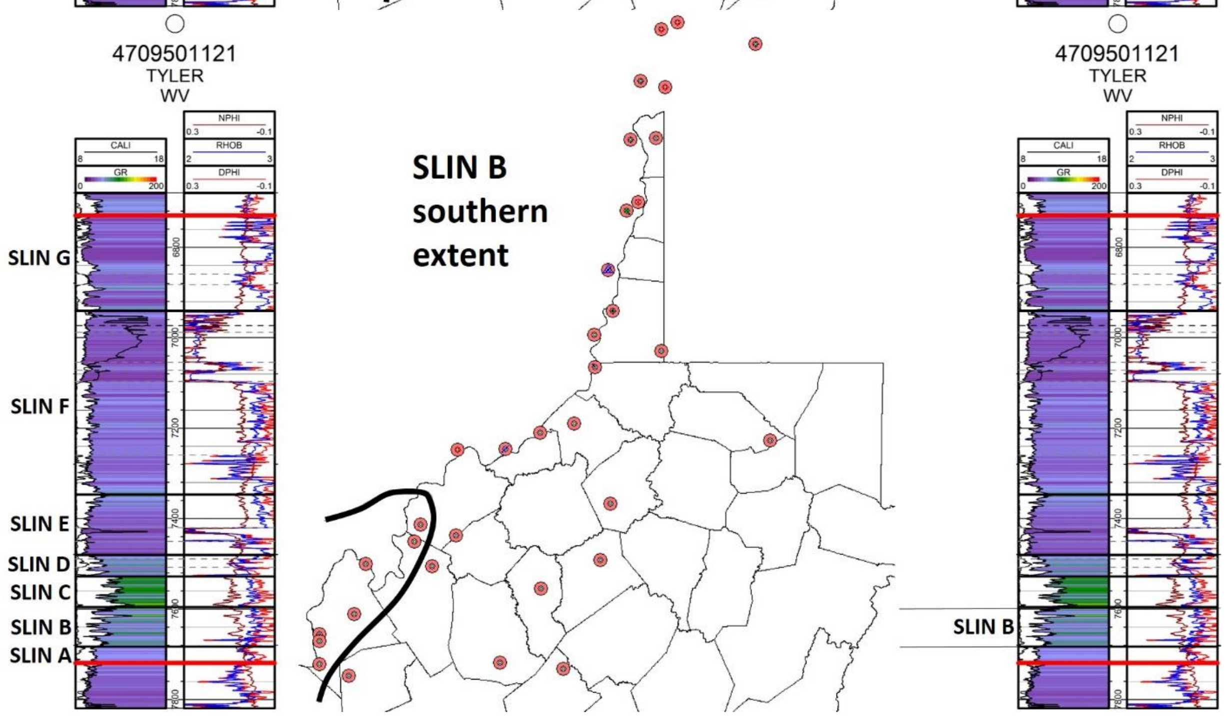
WV
SLIN B
SLIN A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DPHI
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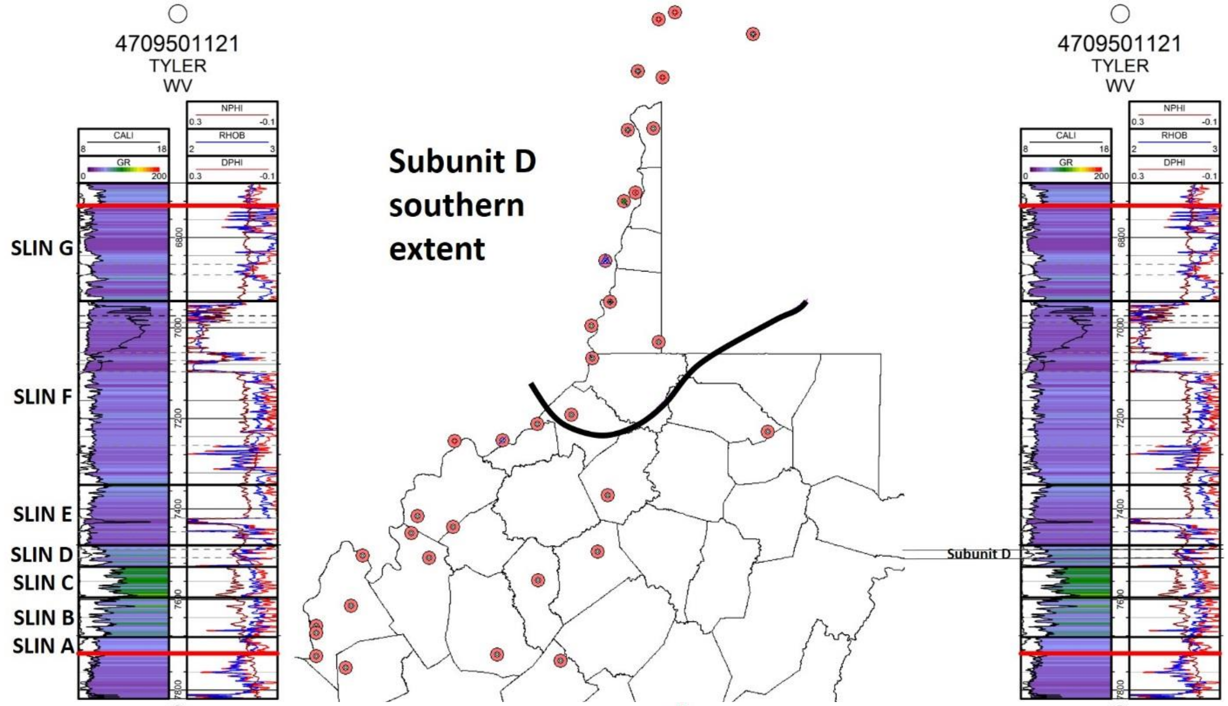
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WV
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GR
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SLIN C
SLIN B
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Subunit D
southern
extent
Subunit D
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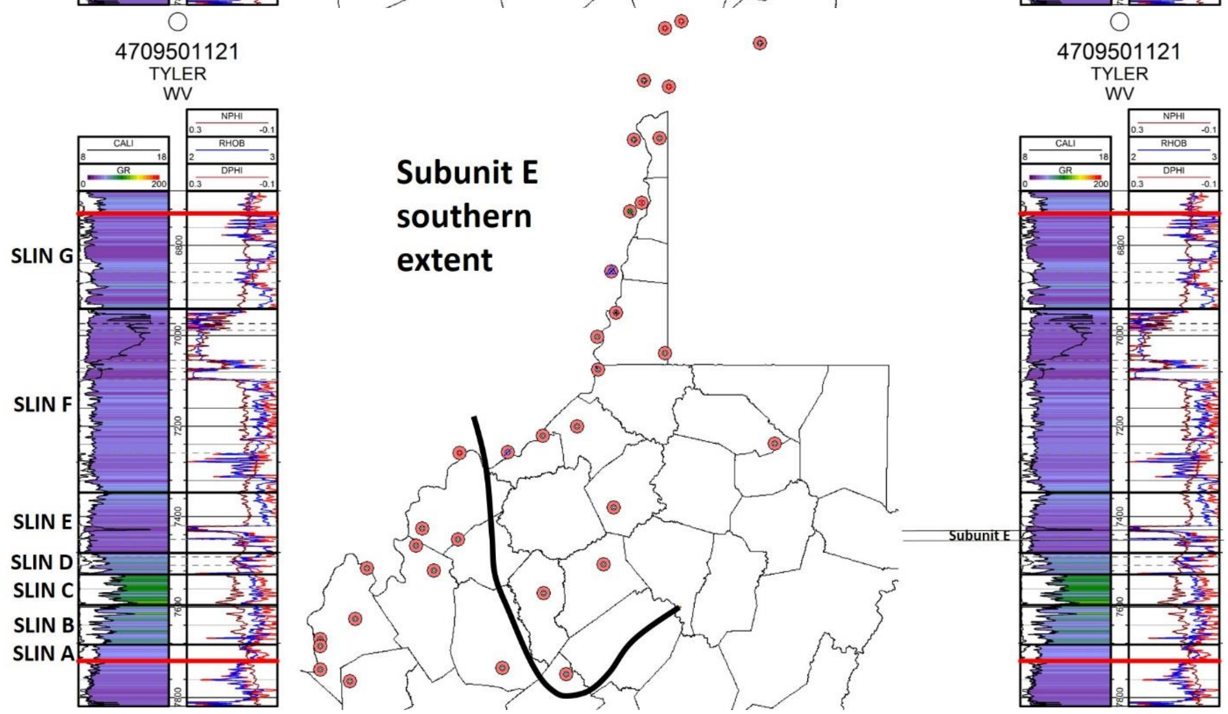
TYLER
WV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SLIN A
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southern
extent
Subunit E
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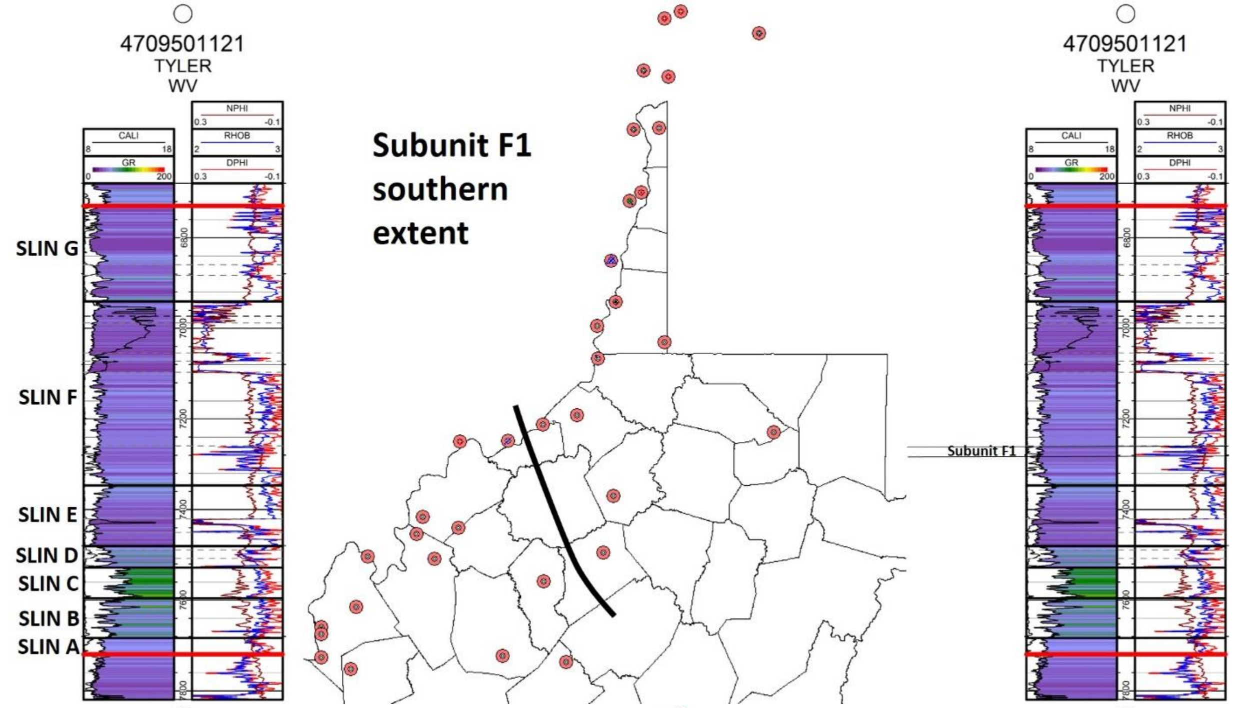
WV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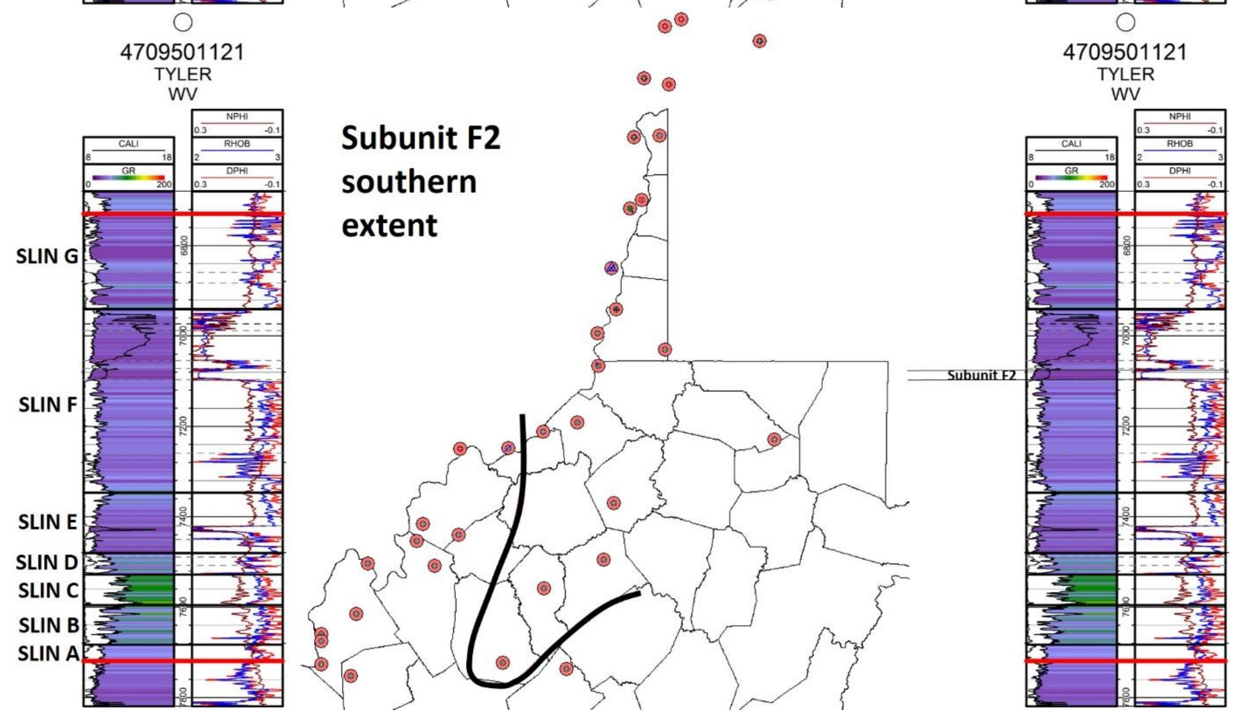
TYLER
WV
NPHI
RHOB
DPHI
CALI
GR
SLIN G
SLIN F
SLIN E
SLIN D
SLIN C
SLIN B
SLIN A
Subunit F1
southern
extent
4709501121
TYLER
WV
Subunit F1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TYLER
WV
NPHI
RHOB
DPHI
CALI
GR
SLIN G
SLIN F
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Subunit F2
southern
extent
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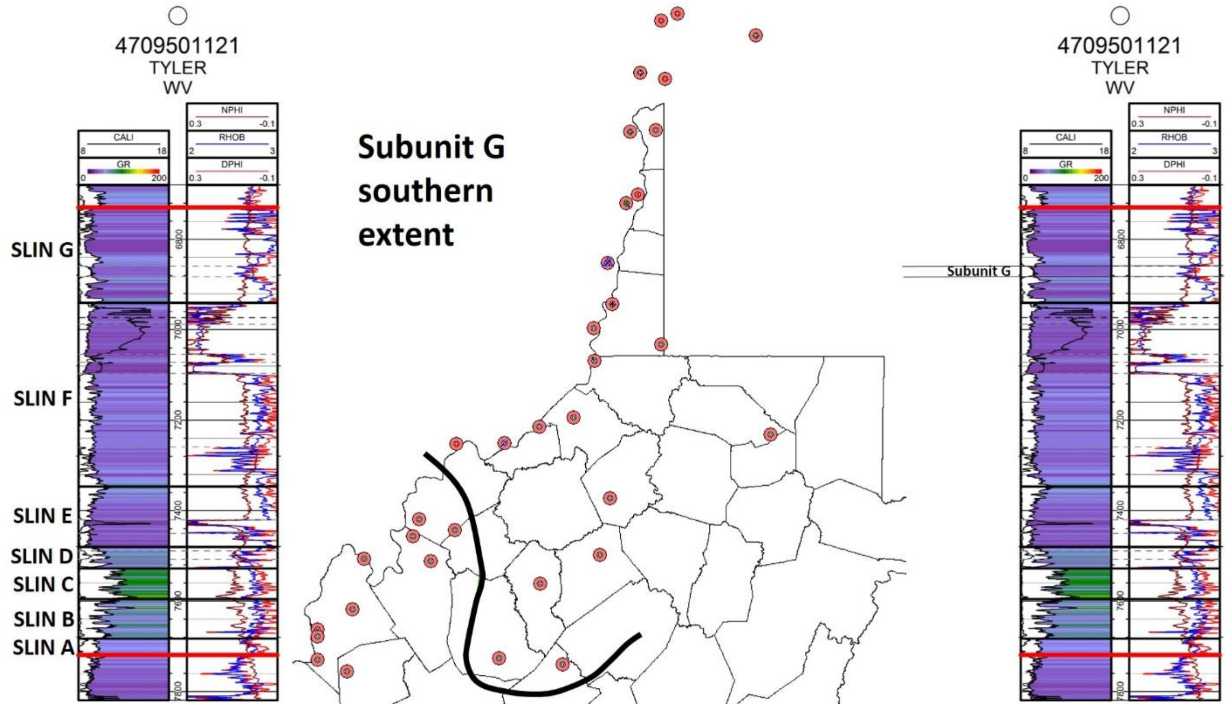
WV
Subunit F2



6.5.1 Ohio River Valley Cross Section (next page)

S
N
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WILFONG UNIT 3
<12.09MI>
34167296850000
NEWELL RUN DISPOSAL WELL(SWIW #10) 1
<30.93MI>
34111244590000
ORMET CORP PAD 2 10-15 UH
<8.36MI>
34111243650000
MONROE NORTH UNIT 2S
<7.72MI>
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MRCSP-FEGENCO 1
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GEORGETOWN MARINE (SWIW #1) 1
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ZIMNOX 17-5-2 3H
<3.62MI>
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HUBERTA MINING CO. INC 2
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J. & J. JACKSON ET AL 341465
<14.87MI>
34029207200000
REEDER 1
<13.92MI>
34099225580000
JOHN MUNIA # 1
BILOG (SALT_EST)
SLING (SALT_EST)
SLINF (SALT_EST)
SLINE (SALT_EST)
SLIND (SALT_EST)
SLINC (SALT_EST)
SLINB (SALT_EST)
SLINA (SALT_EST)
LCKP (SALT_EST)
F4SALT=93.9 (7349-7443)
F4SALT=87.8 (7069-7157)
F4SALT=65.4 (6586-6651)
F4SALT=59.4 (6558-6617)
F4SALT=86.2 (6312-6398)
F4SALT=92.9 (6248-6341)
F4SALT=41.6 (6355-6396)
F4SALT=74.6 (5135-5210)
F1SALT=51.1 (5415-5466)
F1SALT=44.0 (4978-5022)
DSALT=41.8 (5647-5688)
TD : 6,360
TD : 7,332
TD : 10,230
TD : 10,930
TD : 8,384
TD : 13,727
TD : 15,333
TD : 8,053
TD : 6,783
TD : 6,732
TD : 6,323
Salina Salts
Initial Correlation Along
Ohio River
N
Location Map
Salina F4 salt is the thickest, about 100 feet in olive green color