Mapping and Reservoir Characterization of Geologic Intervals for NGL Storage Applications*

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Abstract

The Appalachian Oil & Natural Gas Research Consortium recently completed the Appalachian Storage Hub for Liquid Ethane Study to identify potential storage reservoirs for natural gas liquids (NGLs) derived from the liquid-rich Marcellus and Utica shale plays. The project objective was to identify the best options for storage proximal to a proposed pipeline from areas of shale production in southwestern Pennsylvania to end users in southern West Virginia and northeastern Kentucky. The study's Area of Interest (AOI) included 50 counties centered along the Ohio River Valley corridor in the tri-state region of Ohio, Pennsylvania, and West Virginia. Survey geologists from each of these states collaborated to complete the study within a year's time, assessing three types of storage opportunities (mined-rock caverns, salt caverns, and depleted siliciclastic gas reservoirs) through their desktop evaluation of 10 discreet geologic intervals: the Mississippian Greenbrier Limestone for subsurface mining; the Upper Silurian Salina F4 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 Sandstone); and Upper Cambrian (Gatesburg Formation and Upper Sandy member). The research team prepared maps of depth, thickness and extent for each interval; compiled existing siliclastic reservoir data at the field level using multiple regional data sources; and conducted new qualitative petrographic analyses to support reservoir characterization activities. This information was used to identify a short list of the most promising NGL storage reservoirs, to which geology-based ranking criteria developed specifically for this study by the research team were applied. As a result of these efforts, we identified multiple prospects in the AOI where stacked NGL storage opportunities (i.e., a combination of mined-rock caverns, salt caverns, and/or depleted gas reservoirs at different depths within a given geographic area) are recommended for further investigation at the site level.

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Mapping and Reservoir Characterization of Geologic Intervals for NGL Storage Applications

Findings of the Appalachian Storage Hub Study

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- **Advisory Group**

BACKGROUND

- Liquids-rich Marcellus and Utica Shale production in the tri-state area of OH, PA and WV
- Desire to move natural gas liquids (NGLs) from wet gas areas to industrial sites throughout the greater Appalachian region
- A proposed "6-pack" pipeline from Monaca, PA to northeastern KY and Charleston, WV along the Ohio & Kanawha rivers
- Subsurface storage will be a necessary component along the pipeline route

STUDY GOAL

- Complete a geologic study of all potential options for subsurface storage of NGLs along and adjacent to the Ohio River from southwestern Pennsylvania to eastern Kentucky, including a similar study along the Kanawha River in West Virginia
  - Stratigraphic correlation of key units
  - Mapping thickness and structure of key units
  - Reservoir characterization studies
  - Development and application of rating and ranking criteria

Area of Interest (AOI)

RESEARCH PLAN

- Identify geologic intervals as potential candidates for NGL storage
- Correlate regional lithostratigraphy and characterize subsurface geologic units through mapping
- Construct/compile a regional database to include pre-existing (legacy) and new data
- Characterize potential reservoirs (three types)
- Develop criteria for rating and ultimately ranking candidates
- "Drill down" from regional to prospect level by performing reservoir assessments
- Manage these data and provide access through a Study website

THREE MAIN PRODUCTS

- Regional subsurface study with correlations, cross sections, thickness and structure maps
- Criteria with which to rate and eventually rank candidate formations and reservoirs as safe and secure storage containers
- A project database and website in which all of the data and research findings are located and can be accessed by the public and potential storage companies

GEOLOGIC INTERVALS OF INTEREST

Mined-rock caverns

- Greenbrier Limestone (≥40 ft thick; depths of 1,800 – 2000 ft)

Salt caverns

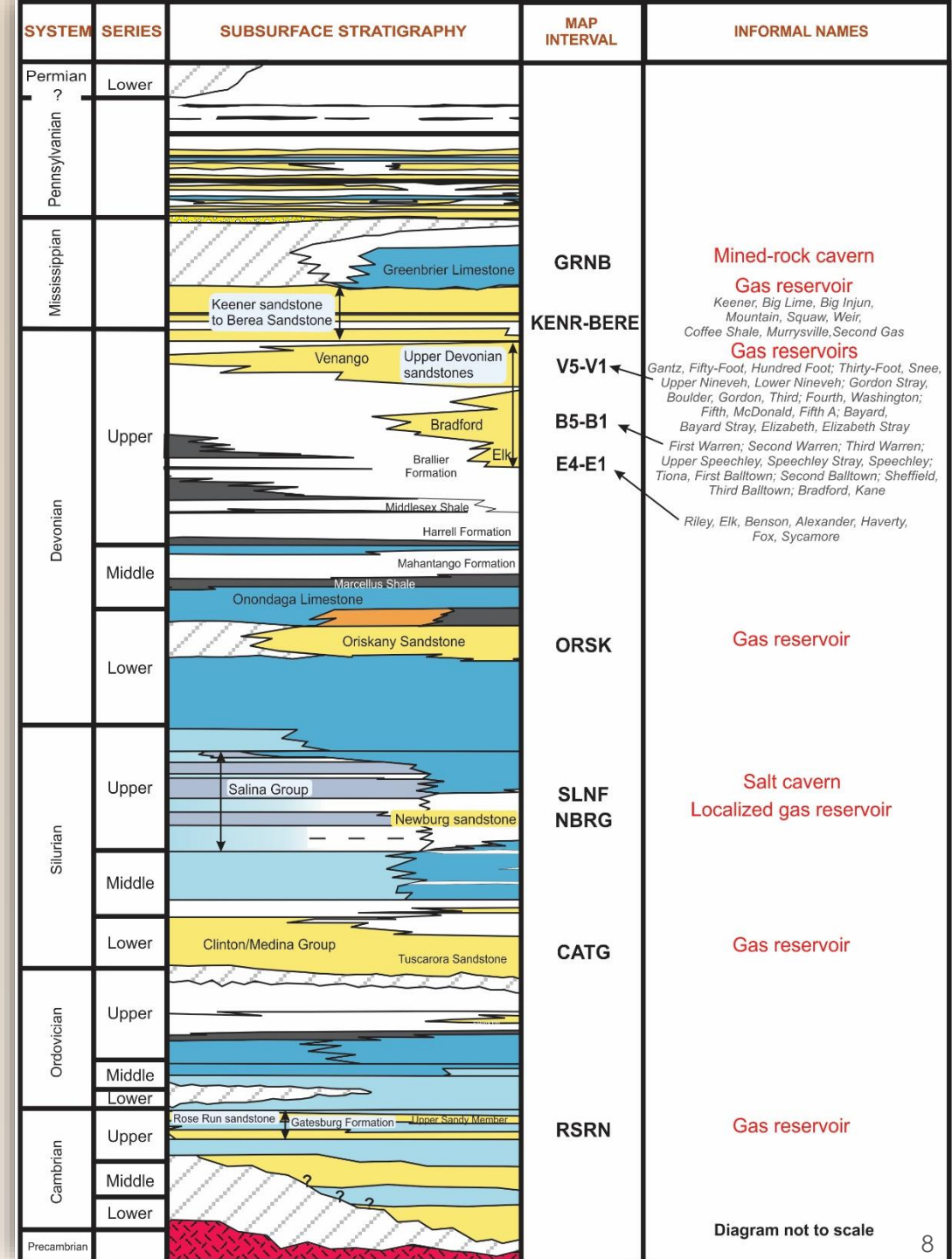
- Salina Group salts (≥100 ft thick)

Depleted gas reservoirs

- Keener to Berea sandstones
- Upper Devonian sandstones (Venango, Bradford, Elk)
- Oriskany Sandstone
- Newburg sandstone
- Clinton/Medina Group
- Rose Run-Gatesburg sandstones

REGIONAL STRATIGRAPHIC CORRELATION

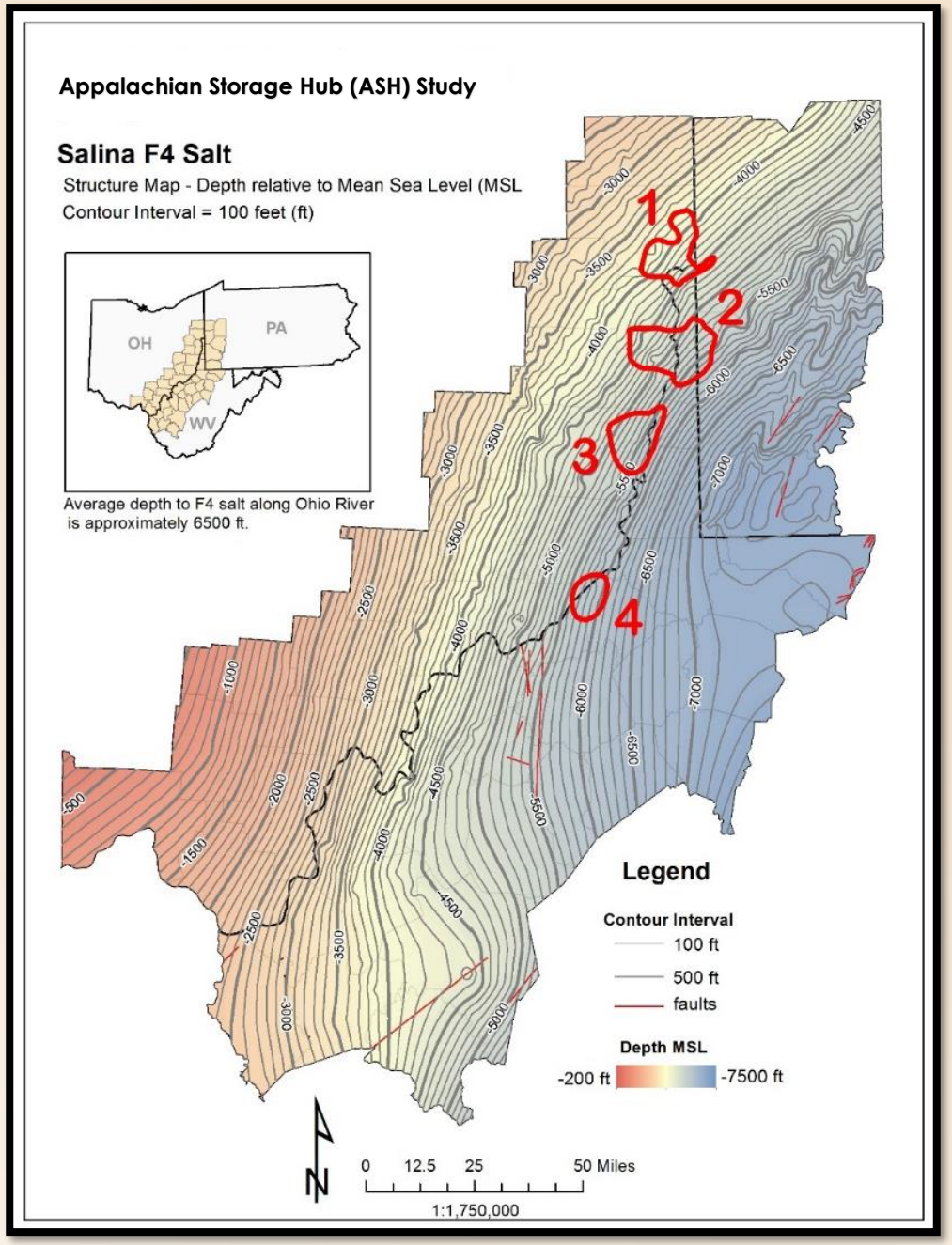
- 10 geologic intervals
- Lateral variations in lithology, facies and nomenclature
- Variations in depth and thickness of units based on depositional environment and post-depositional processes
- Thousands of pieces of data used to correlate lithostratigraphy throughout the AOI



REGIONAL MAPPING – SALINA F4 SALT: DEPTH

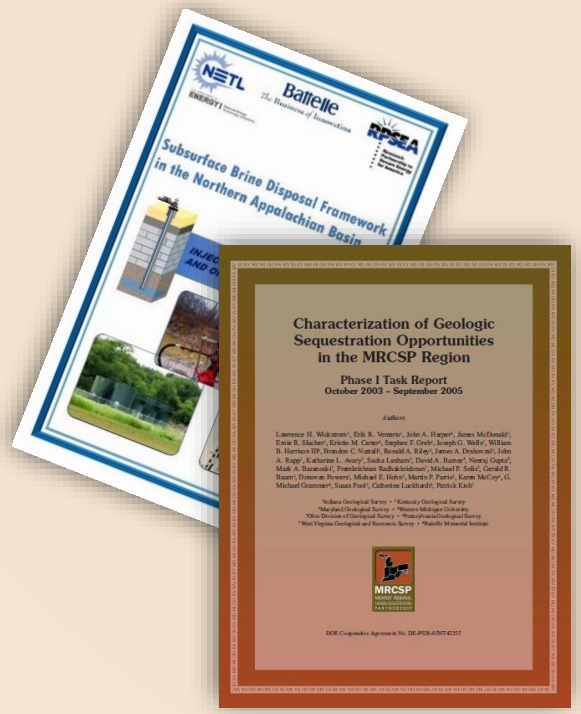
- Below deepest occurrence of fresh drinking water
- Not penetrated by many gas wells that could provide vertical migration routes
- Increase in salt plasticity limits lower cavern depths to <7,000 ft

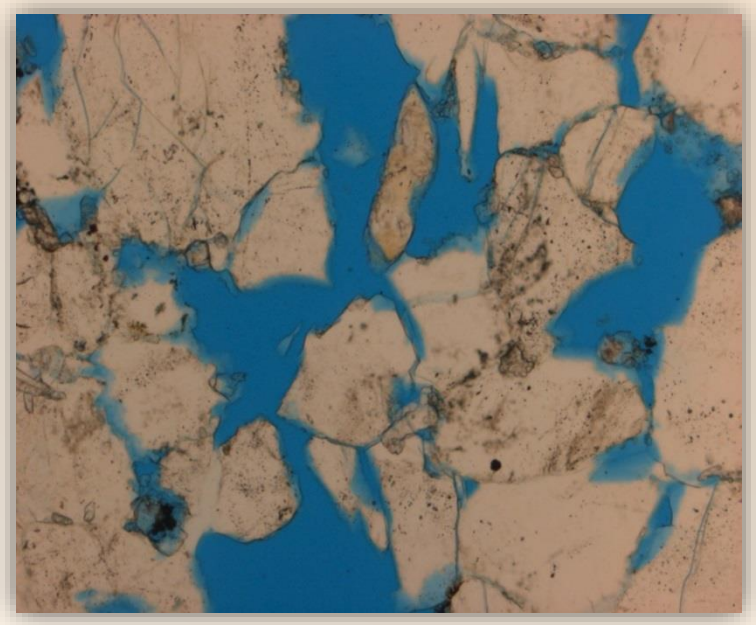
Area	1	2	3	4
Average Depth (ft)	5,300	6,200	6,650	6,600



RESERVOIR CHARACTERIZATION

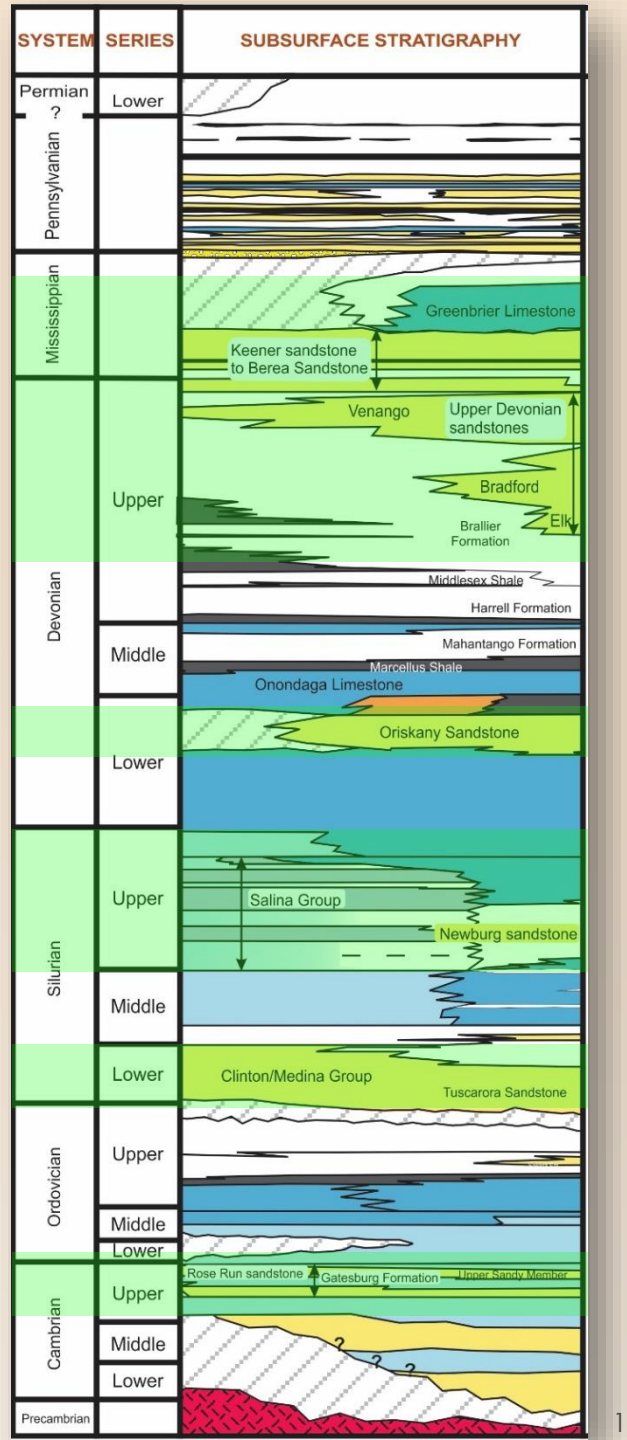
- Determine stratigraphic units or reservoirs with the best geologic and geomechanical properties to ensure long-term, secure storage of ethane and other NGLs
- Legacy data compilation
- Mapping
- Petrophysical calculations
- Qualitative thin section analyses





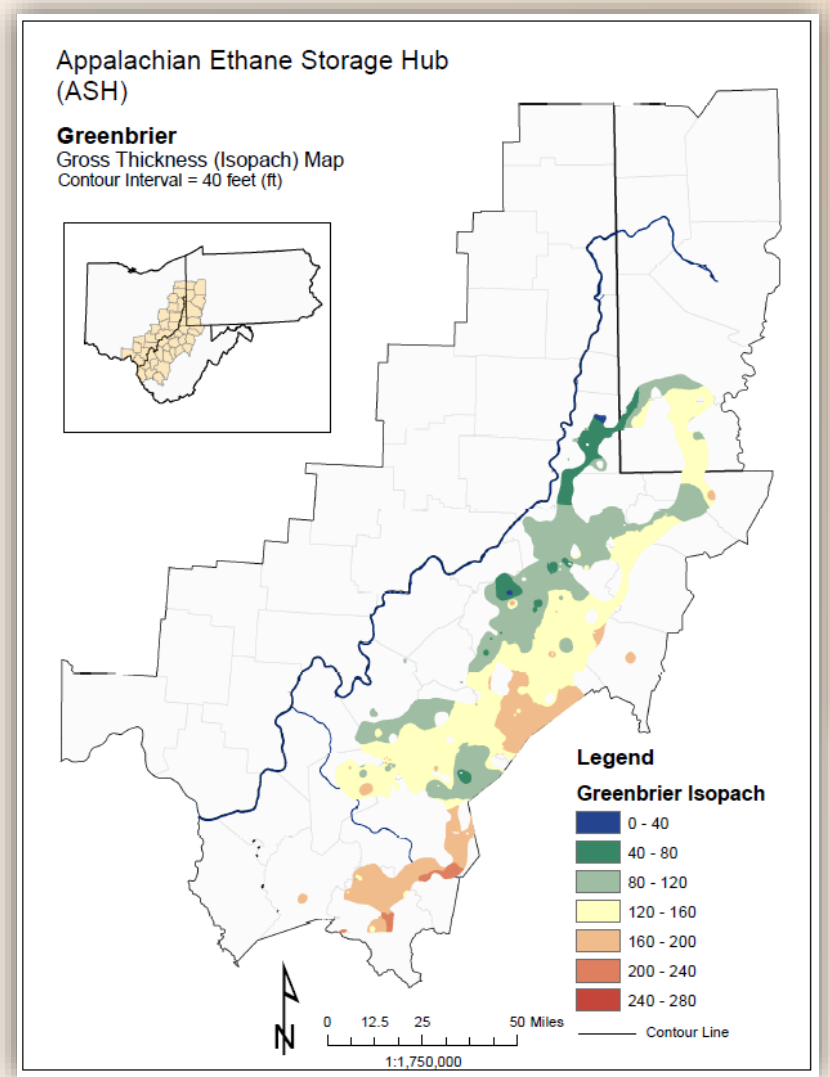
RESERVOIR CHARACTERIZATION EFFORTS

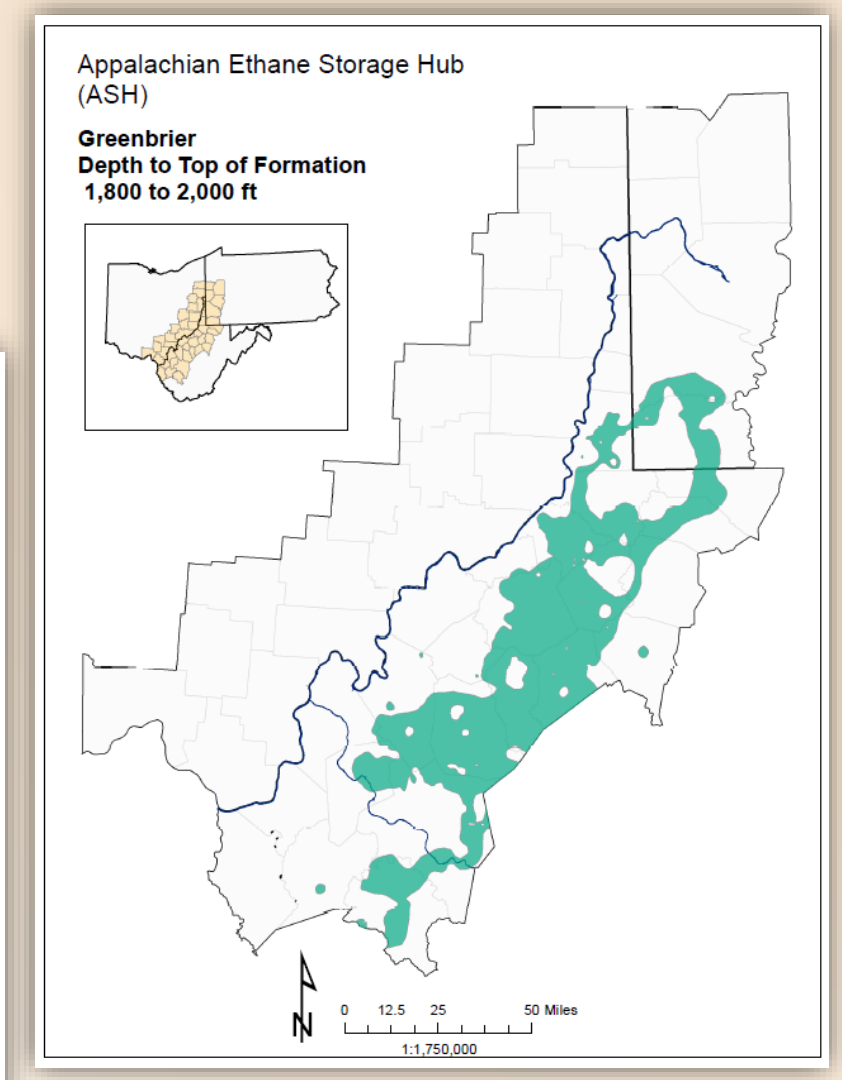
- Unique characterization efforts for each type of storage container
  - Depth – structure maps
  - Thickness – isopach maps
  - Extent – facies evaluation (Greenbrier) and clean vs. "dirty" salt intervals (Salina F4)
  - Preliminary assessment – screened field-level data for 2,700+ depleted gas reservoirs



GREENBRIER LIMESTONE (MINED-ROCK CAVERNS)

- Prepare regional structure and isopach contour maps
- Optimum net thicknesses – ≥40 ft
- Optimum depths – 1,800 – 2,000 ft

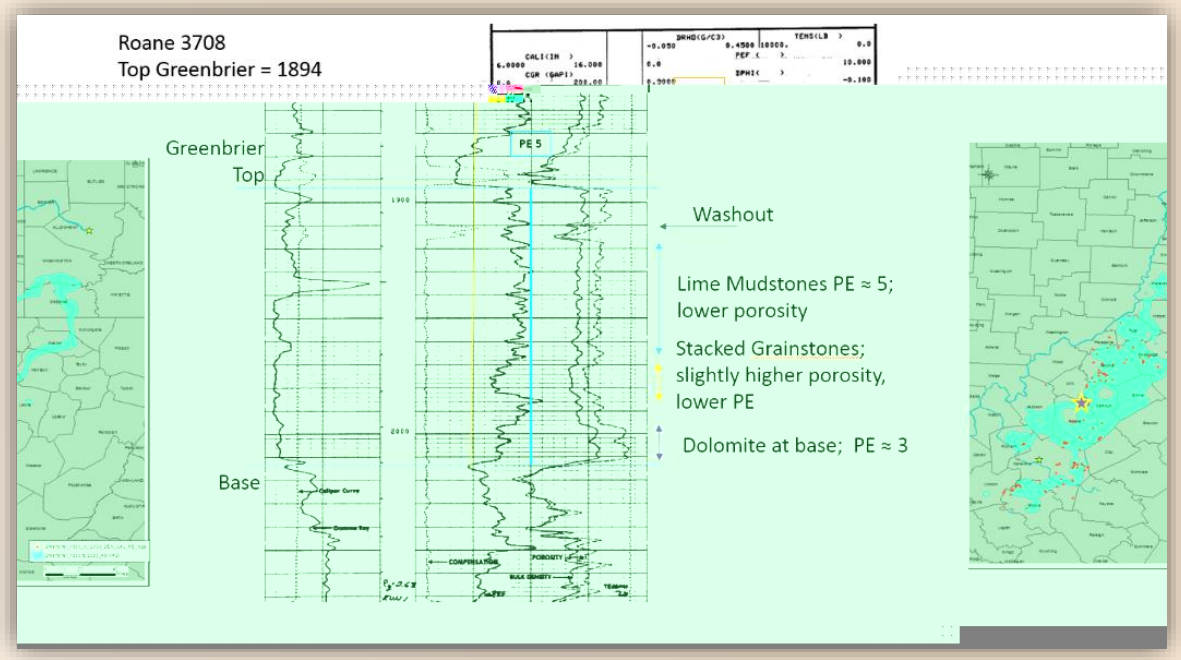


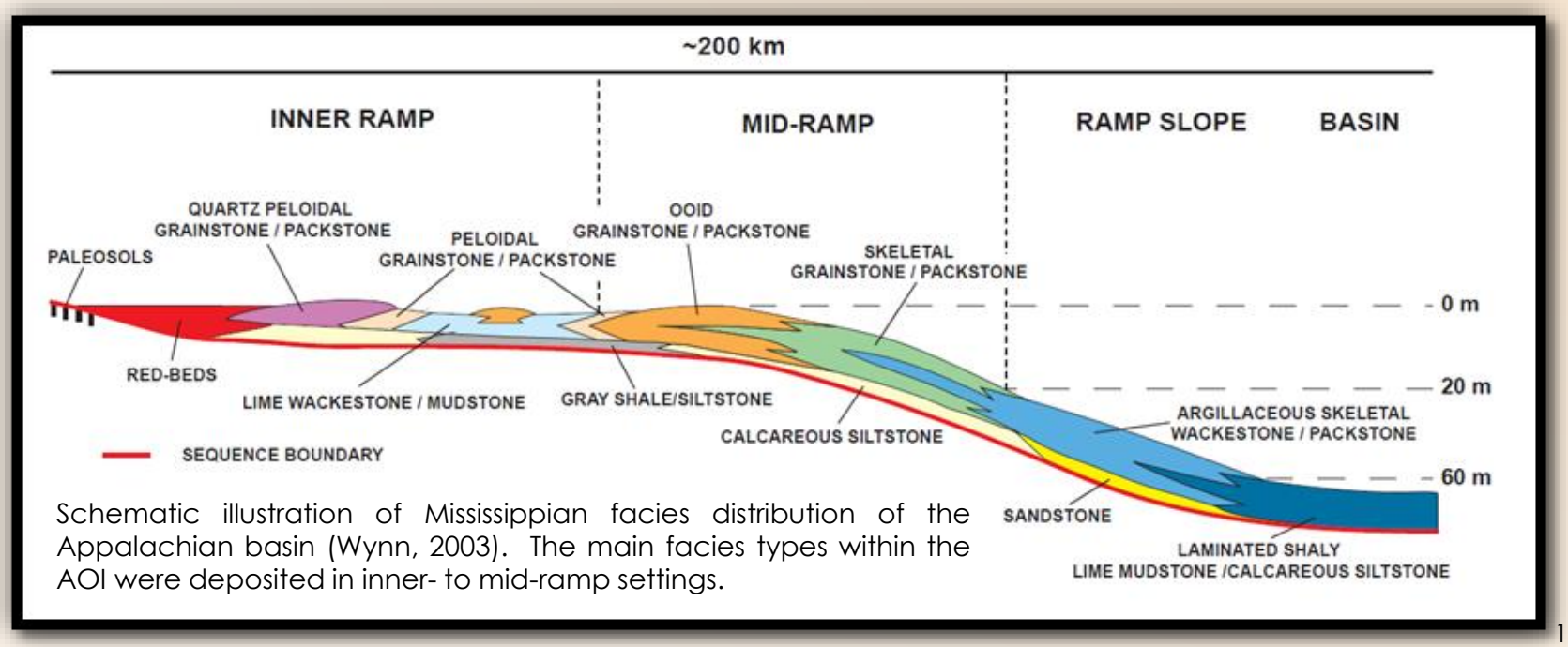


GREENBRIER LIMESTONE (MINED-ROCK CAVERNS)

- Characterize facies using geophysical logs (RHOB, DPHI, PE) and drillers' descriptions

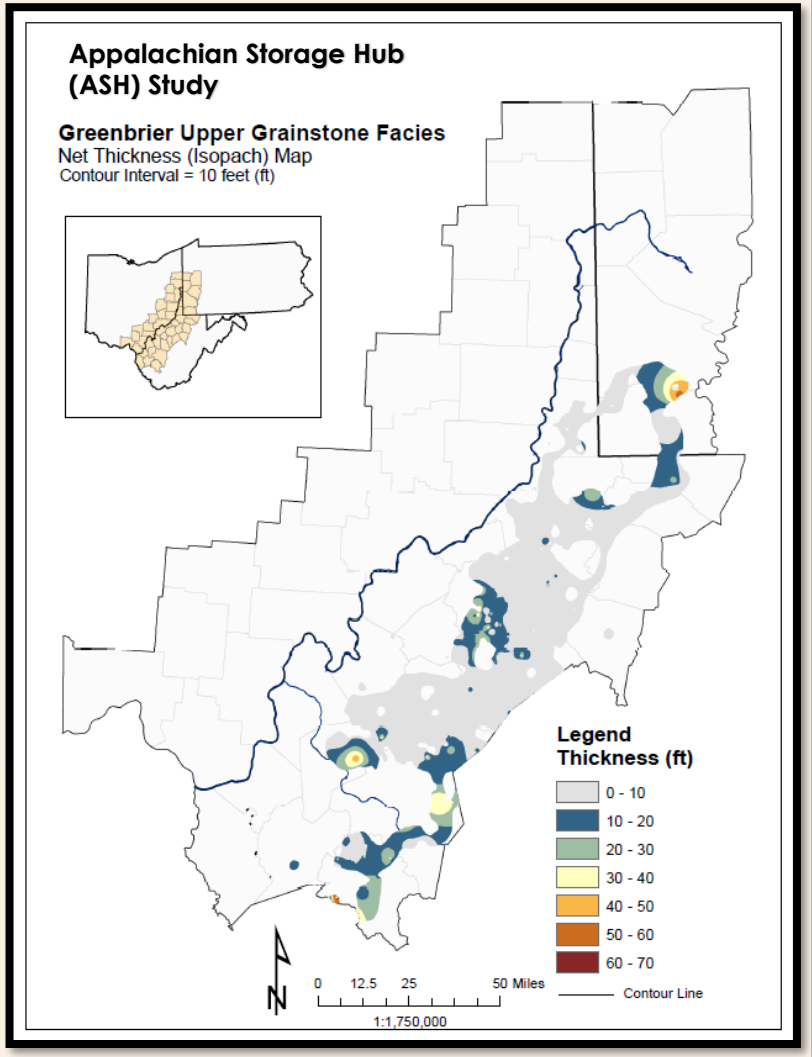
- Carbonate ramp environment of deposition

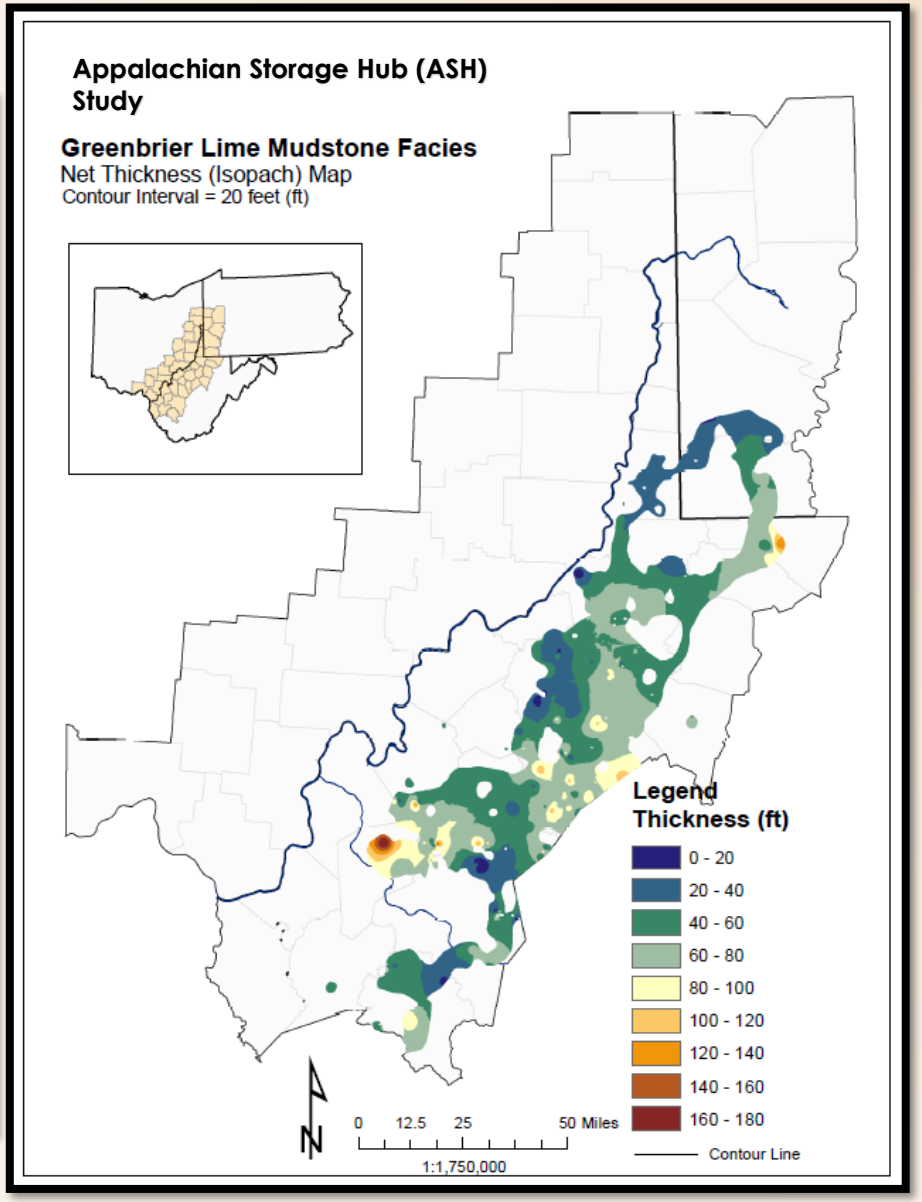


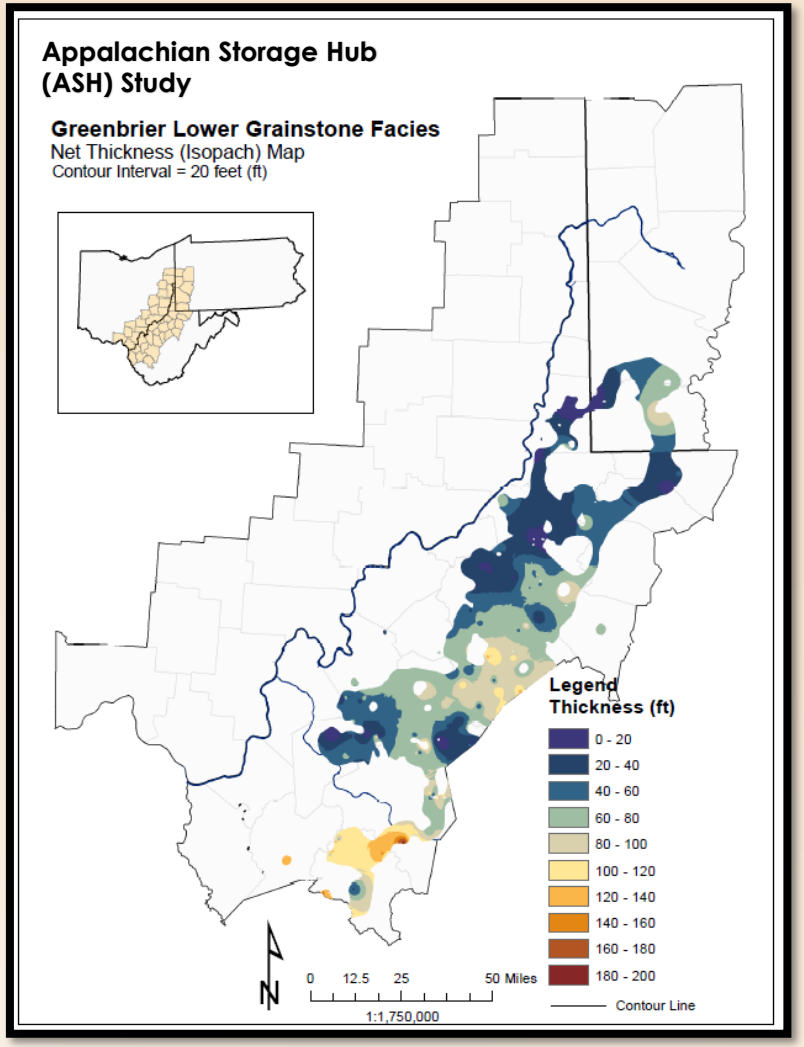


Schematic illustration of Mississippian facies distribution of the Appalachian basin (Wynn, 2003). The main facies types within the AOI were deposited in inner- to mid-ramp settings.

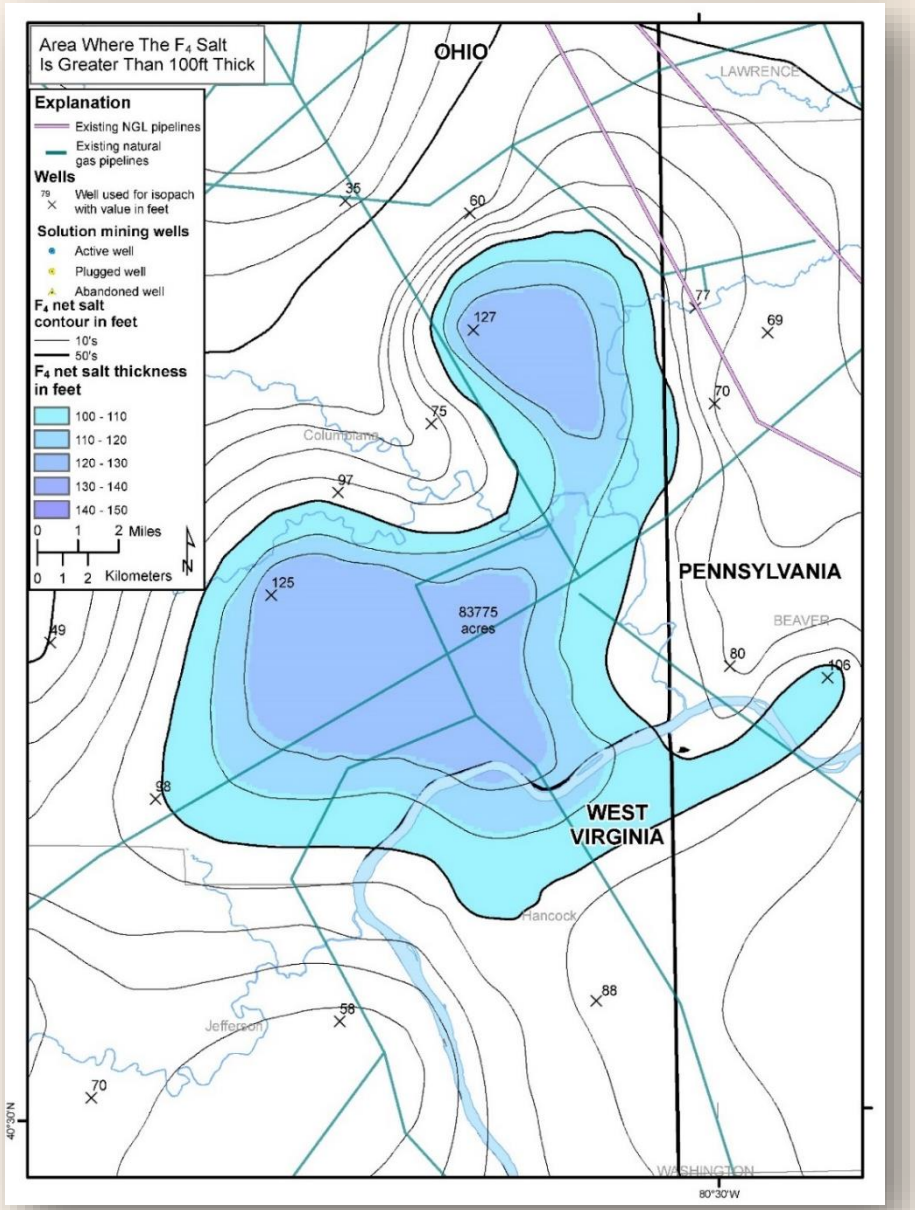
GREENBRIER LIMESTONE – THREE FACIES

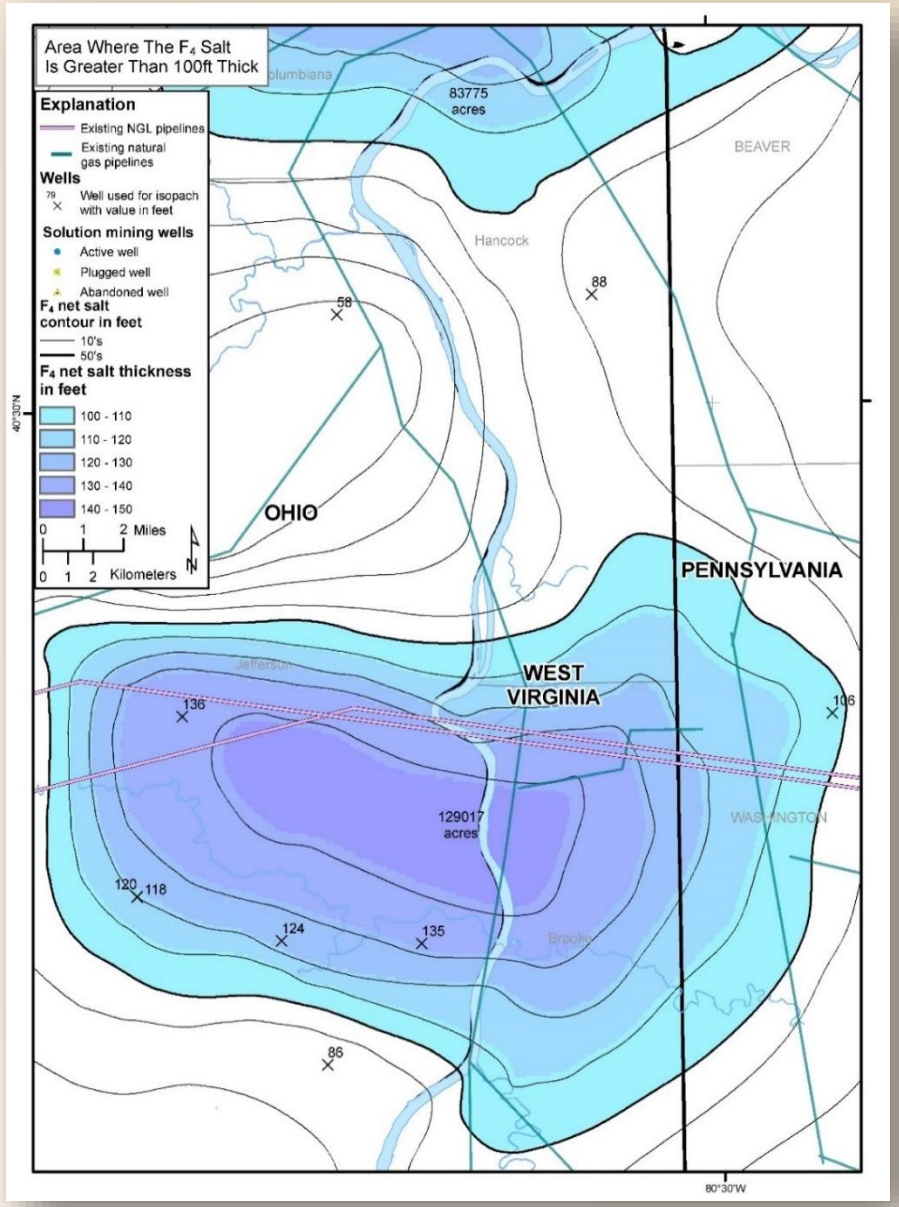




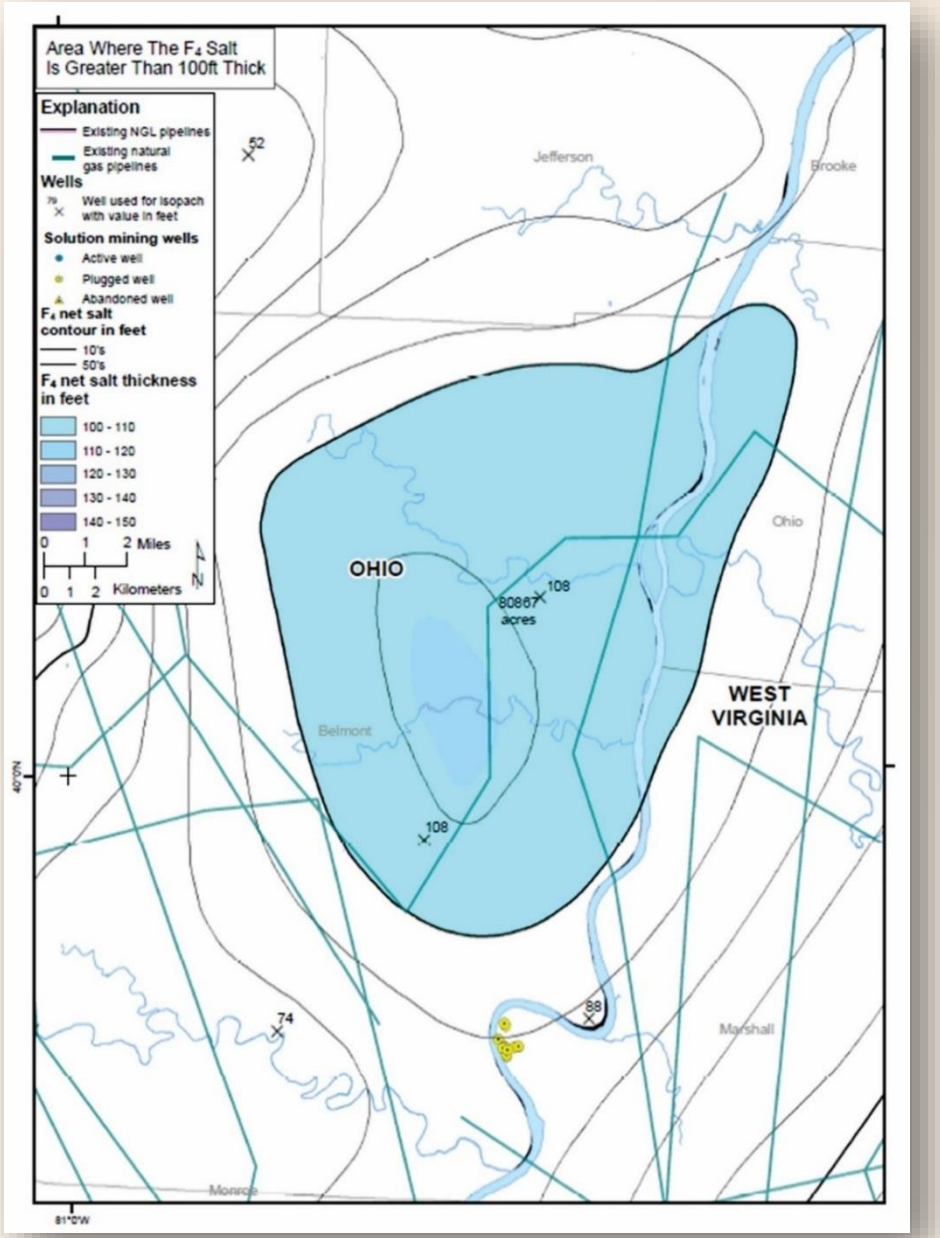


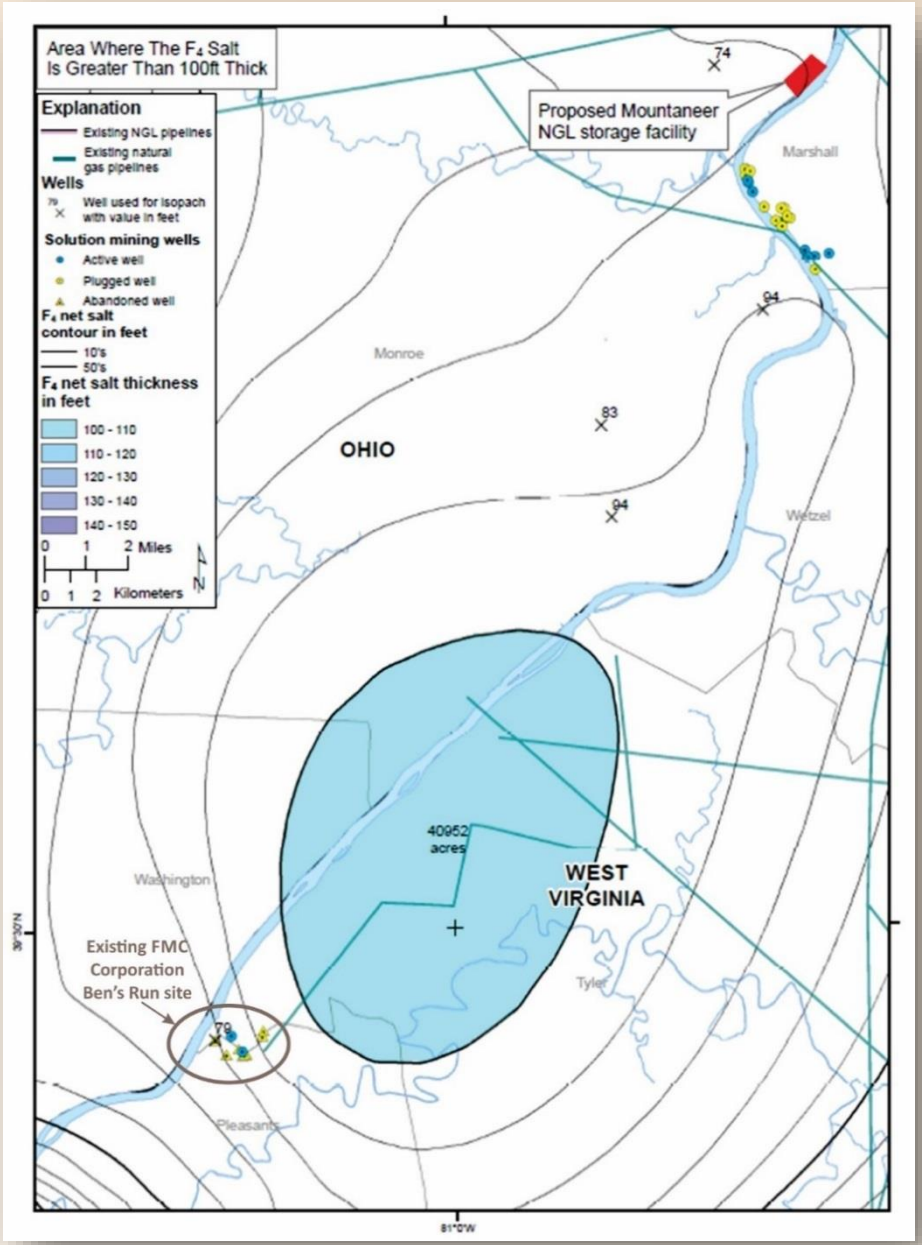
SALINA F4 SALT: AREAS 1 AND 2





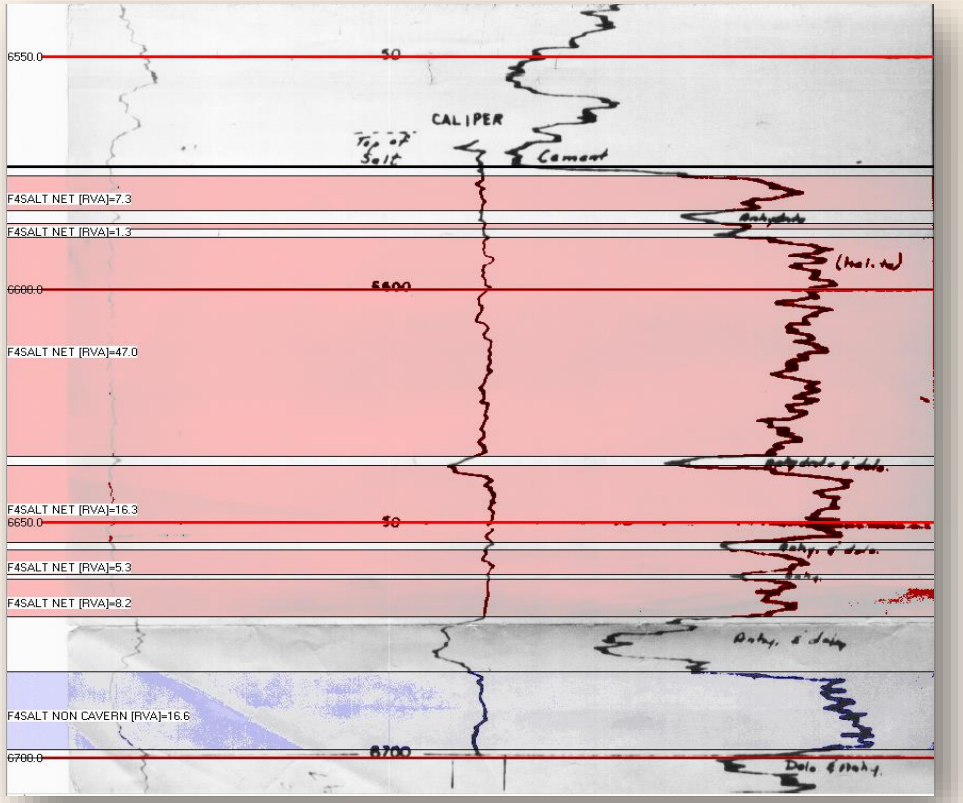
SALINA F4 SALT: AREAS 3 AND 4





SALINA F4 SALT (SALT CAVERNS)

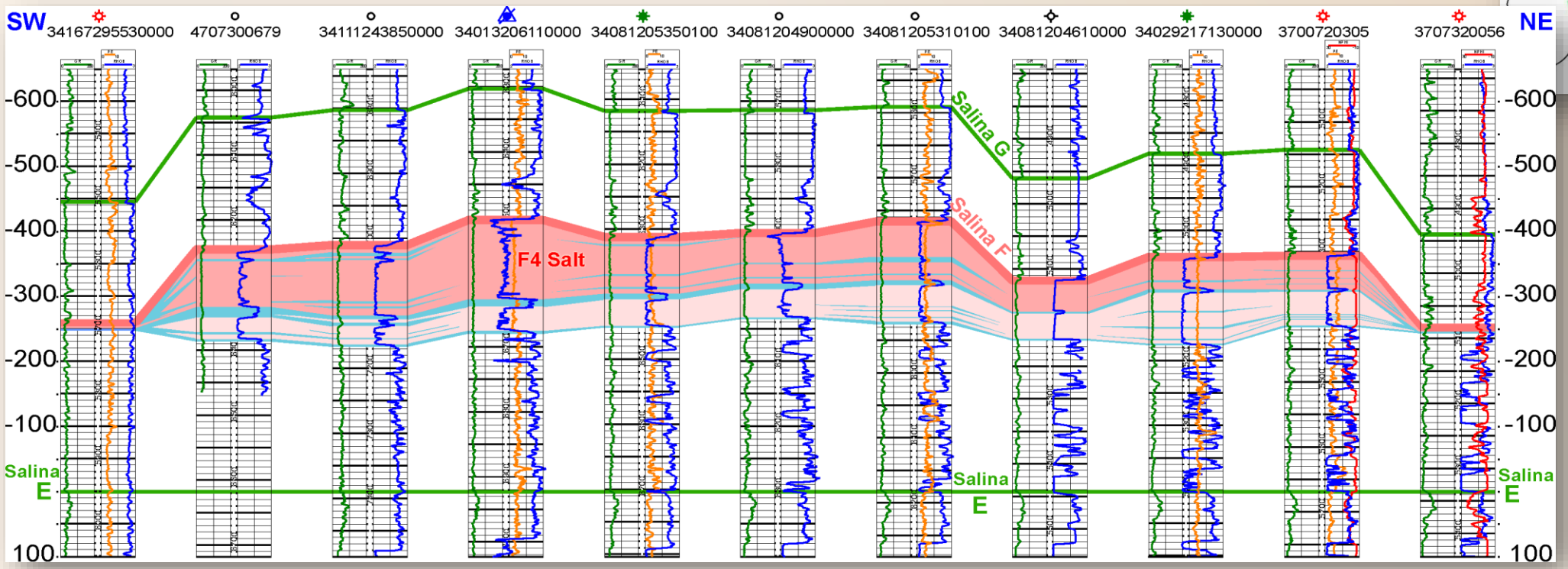
GEOPHYSICAL LOGS

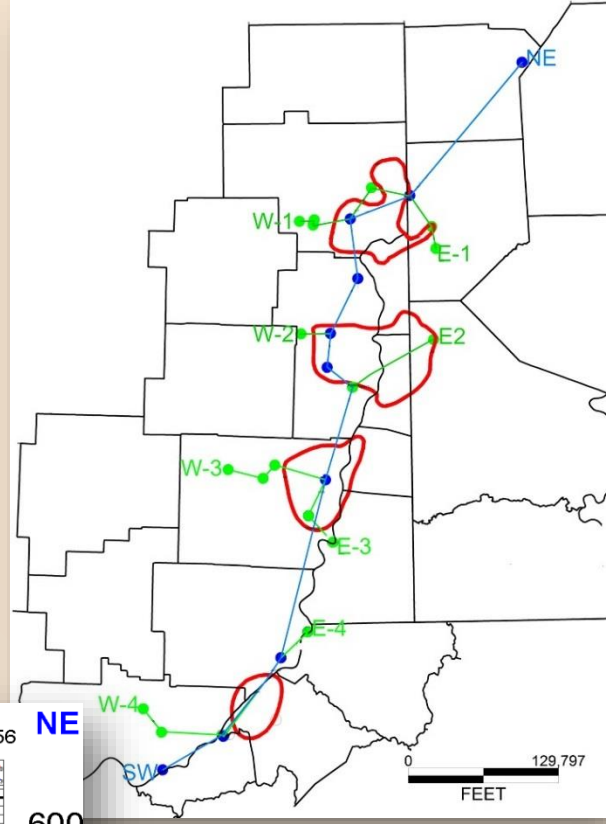


SALT CORE SAMPLES

SALINA F4 SALT: NET THICKNESS

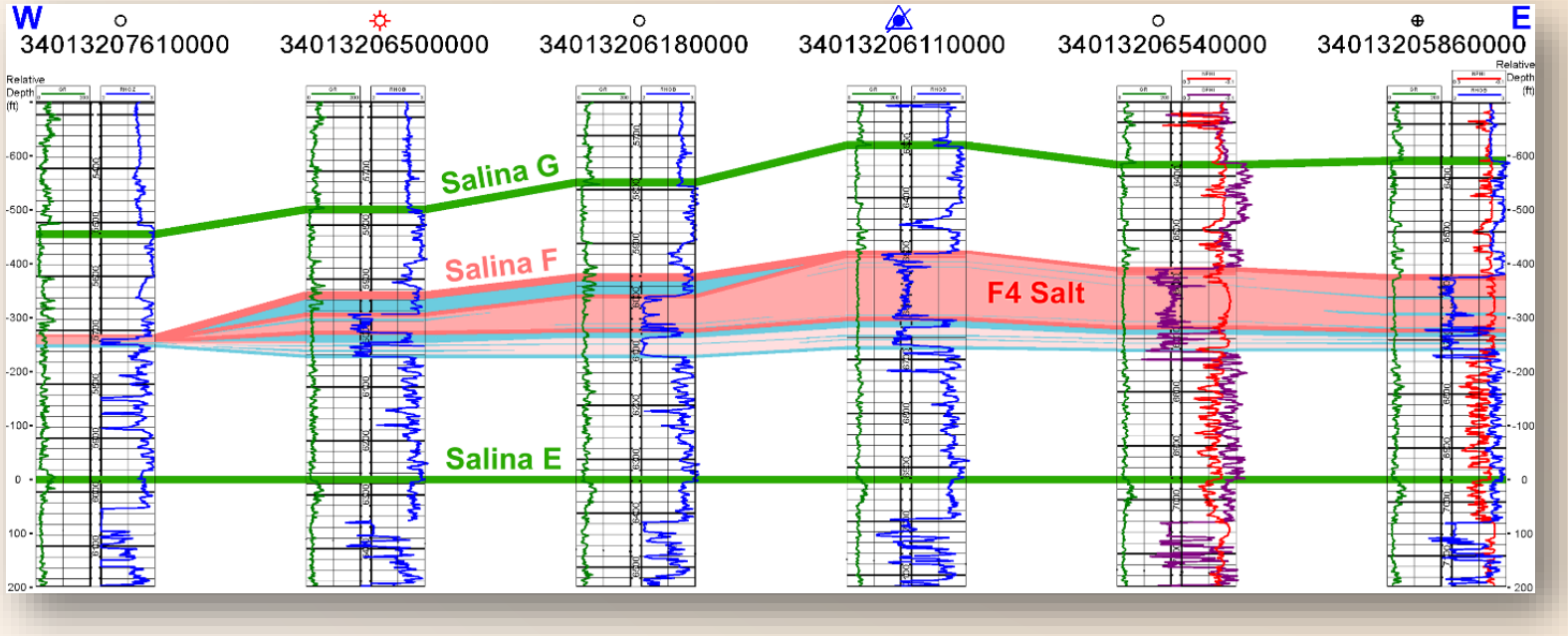
- Upper F4 Salt vs. lower salt
- Interbedded dolomite and anhydrite within larger salt package





SALINA F4 SALT: EXTENT

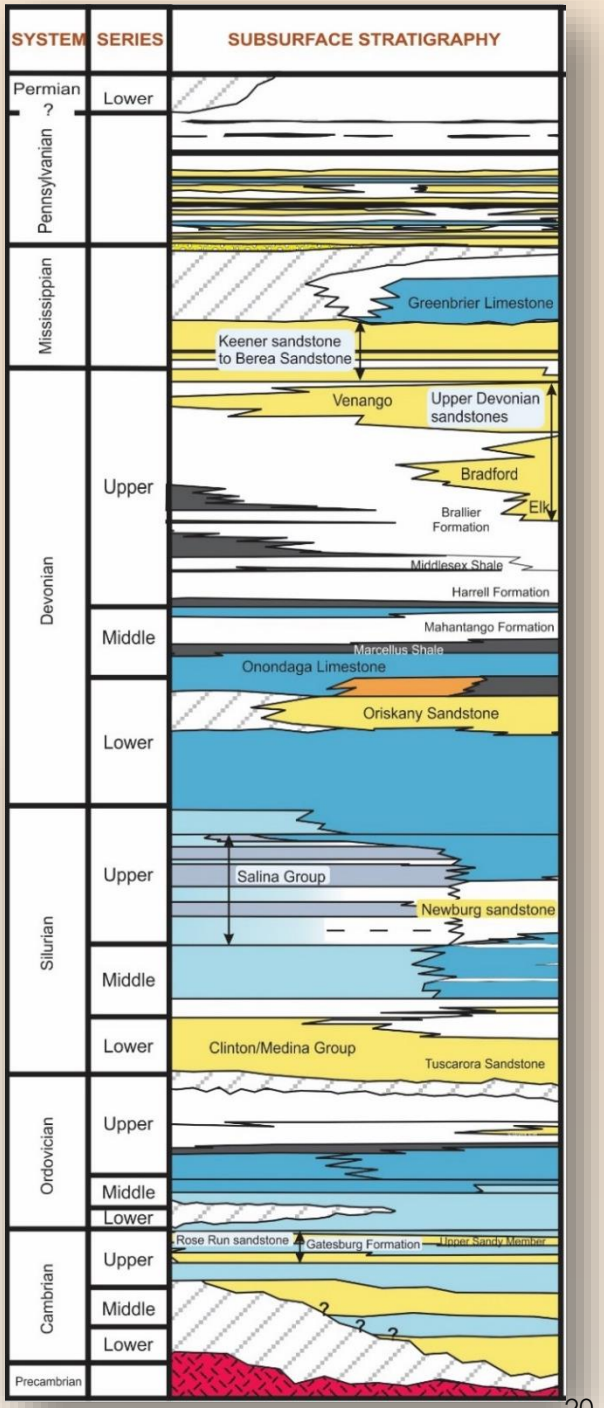
- Interbedded nature of salt with anhydrite and dolomite ("dirty" salt) is more extensive outside the 100-ft footprint
- Lateral migration pathways
- Roof collapse
- Casing integrity issues



- Pressure, temperature and cavern shape primarily affect cavern stability

PRELIMINARY ASSESSMENT OF DEPLETED GAS RESERVOIRS

- 2,700+ fields with sandstone reservoir data
- Of these, ~1,500 fields were ≥2,000 ft deep
- Preliminary rating efforts were used to pare down this dataset for more focused work



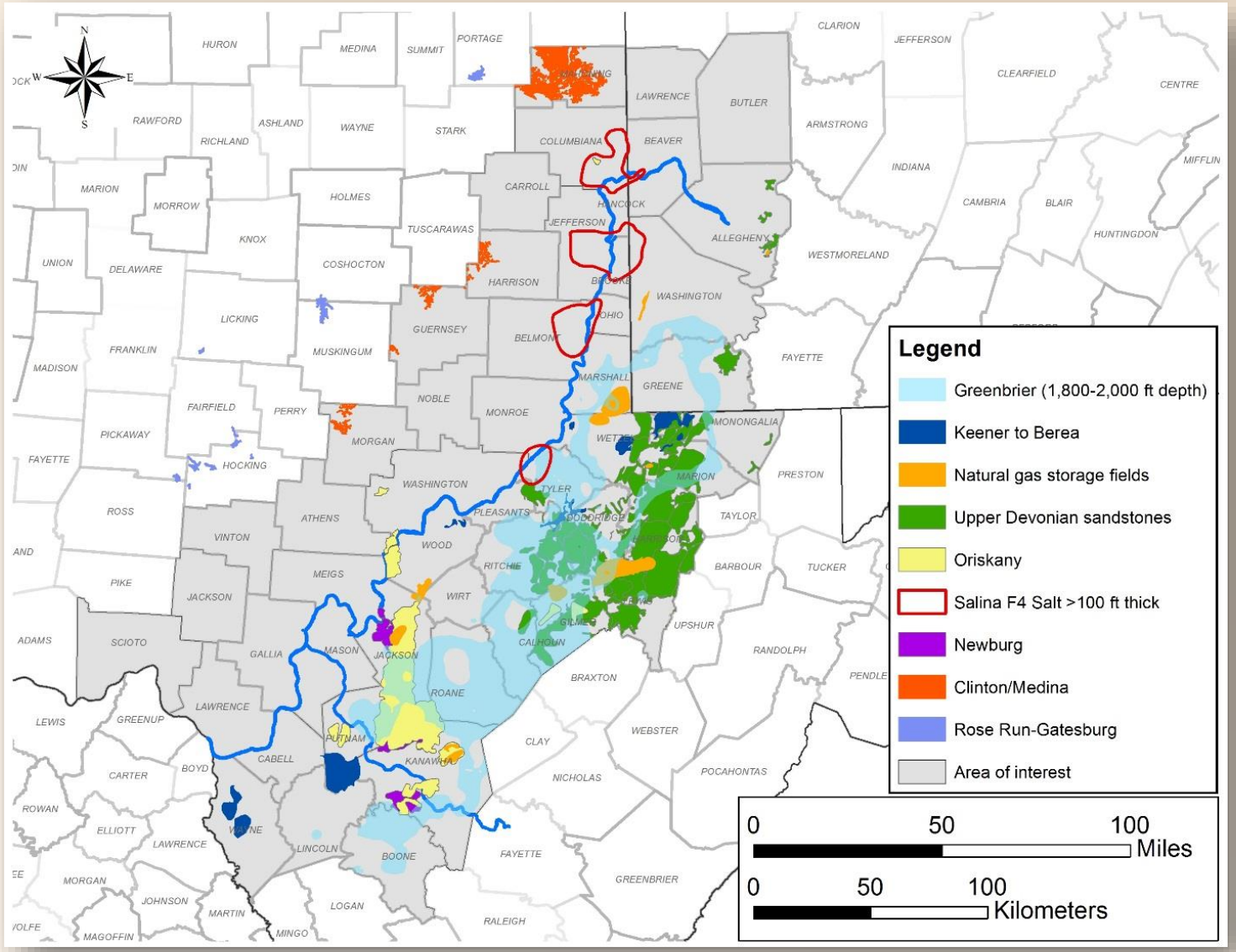
PRELIMINARY ASSESSMENT OF DEPLETED GAS RESERVOIRS

- Preliminary rating criteria
  - Distance to infrastructure
  - Acreage
  - Average depth
  - Average porosity
  - Net thickness
  - Permeability
  - Pressure
  - Stacked opportunity
  - Mode CO_2 storage

Criterion	Description	Range of Values
Distance to infrastructure >30 mi >20 mi but <=30 mi >5 mi but <=20 mi <=5 mi	Proximity of field to any of the existing or proposed pipeline infrastructure, as illustrated in Figure 4-26	 0 1 2 3
Acreage <=500 ac >500 ac but <=1,000 ac >1,000 ac but <=5,000 ac >5,000 ac	Measured size (or "footprint") of a field (ac)	 0 1 2 3
Average depth <=2,000 ft >5,000 ft >2,000 ft but <=3,500 ft >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	 0 1 2 3

PRELIMINARY ASSESSMENT RESULTS

- 134 opportunities
  - ➢113 depleted gas fields
  - ➢12 natural gas storage fields
  - ➢5 limestone areas
  - ➢4 salt areas



DETAILED RATING CRITERIA

Mined-Rock Caverns	Salt Caverns	Depleted Gas Reservoirs	Gas Storage Fields
Distance to Infrastructure	Distance to Infrastructure	Distance to Infrastructure	Distance to Infrastructure
Acreage	Acreage	Acreage	Acreage
Average depth	Average depth	Average depth	Average depth
Net Thickness	Net Thickness	Net Thickness	Net Thickness
Trap integrity	Trap integrity	Trap integrity	Trap integrity
Legacy well penetrations	Legacy well penetrations	Legacy well penetrations	Legacy well penetrations
Stacked opportunity	Stacked opportunity	Stacked opportunity	Stacked opportunity
	Pressure	Pressure	Pressure
		Average Porosity	Average Porosity
		Permeability	Permeability
		Mode CO_2 storage	Mode CO_2 storage
		Estimated cumulative gas production	Working gas capacity

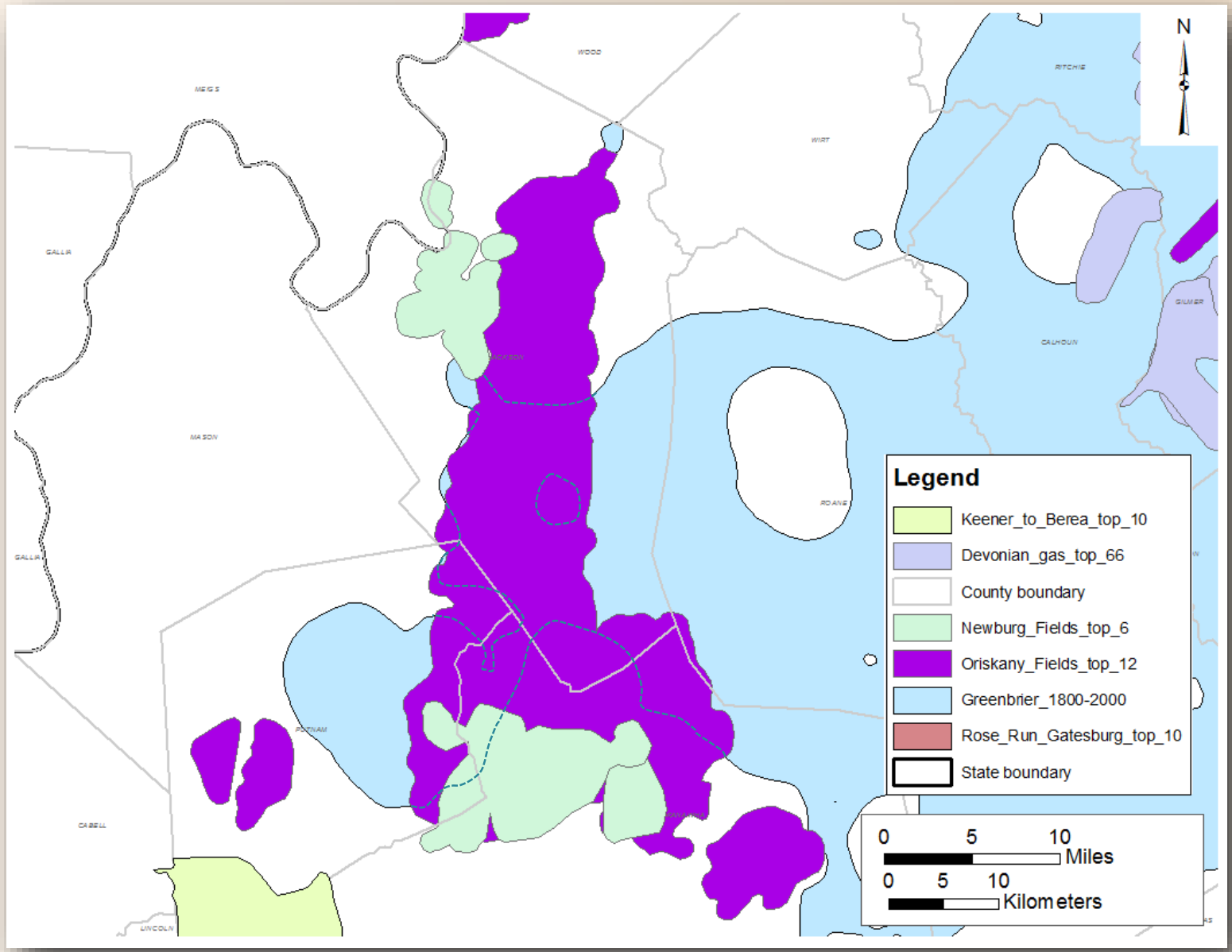
RATING MINED-ROCK AND SALT CAVERNS

Mined-Rock Caverns	Salt Caverns	Depleted Gas Reservoirs	Gas Storage Fields
Distance to Infrastructure	Distance to Infrastructure	Distance to Infrastructure	Distance to Infrastructure
Acreage	Acreage	Acreage	Acreage
Average depth	Average depth	Average depth	Average depth
Net Thickness	Net Thickness	Net Thickness	Net Thickness
Trap integrity	Trap integrity	Trap integrity	Trap integrity
Legacy well penetrations	Legacy well penetrations	Legacy well penetrations	Legacy well penetrations
Stacked opportunity	Stacked opportunity	Stacked opportunity	Stacked opportunity
	Pressure	Pressure	Pressure
		Average Porosity	Average Porosity
		Permeability	Permeability
		Mode CO_2 storage	Mode CO_2 storage
		Estimated cumulative gas production	Working gas capacity

RATING DEPLETED GAS RESERVOIRS/FIELDS

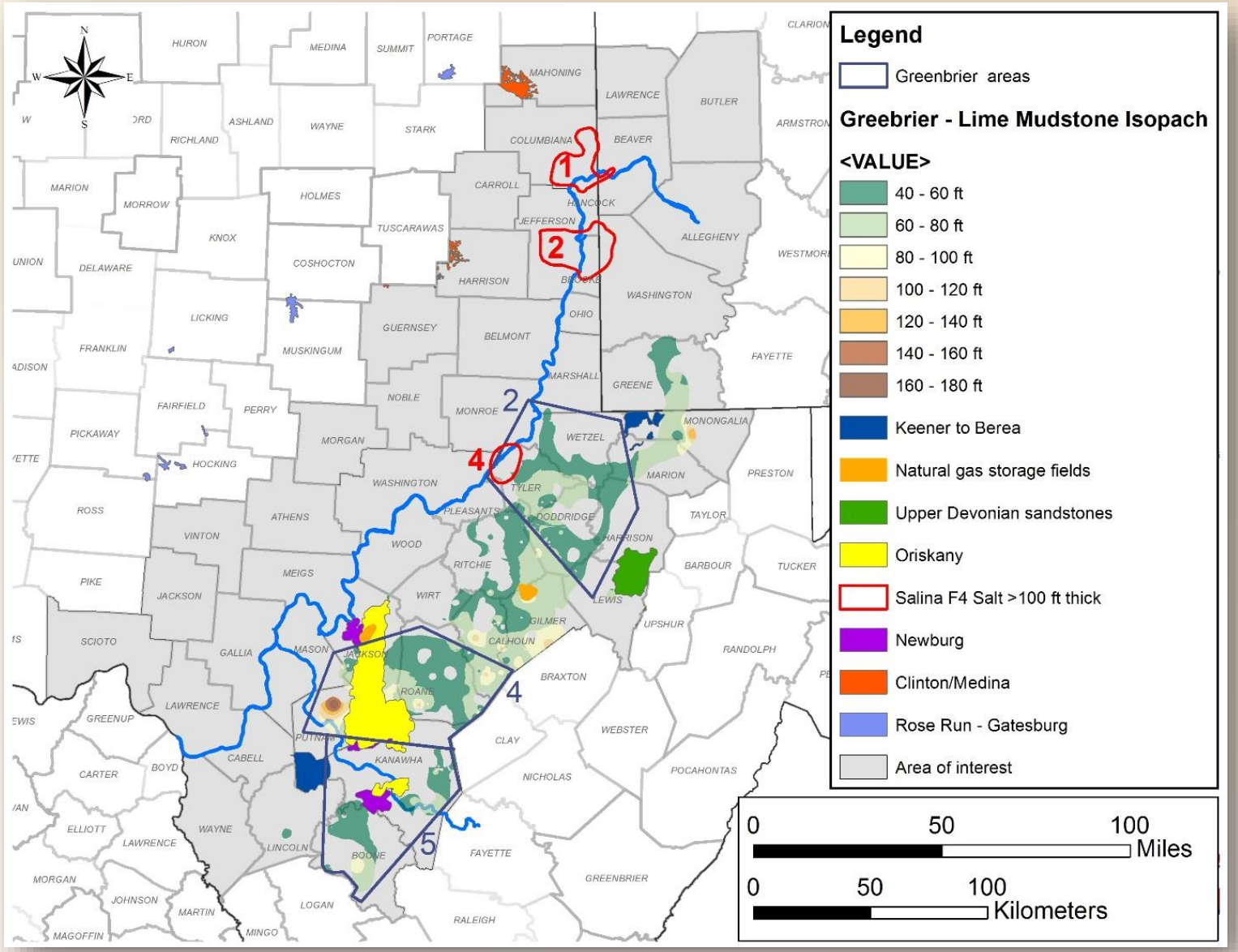
Mined Rock Caverns	Salt Caverns	Depleted Gas Reservoirs	Gas Storage Fields
Distance to Infrastructure	Distance to Infrastructure	Distance to Infrastructure	Distance to Infrastructure
Acreage	Acreage	Acreage	Acreage
Average depth	Average depth	Average depth	Average depth
Net Thickness	Net Thickness	Net Thickness	Net Thickness
Trap integrity	Trap integrity	Trap integrity	Trap integrity
Legacy well penetrations	Legacy well penetrations	Legacy well penetrations	Legacy well penetrations
Stacked opportunity	Stacked opportunity	Stacked opportunity	Stacked opportunity
	Pressure	Pressure	Pressure
		Average Porosity	Average Porosity
		Permeability	Permeability
		Mode CO_2 storage	Mode CO_2 storage
		Estimated cumulative gas production	Working gas capacity

STACKED OPPORTUNITY RATINGS



DETAILED RATING RESULTS

- 30 opportunities
  - 22 depleted gas fields
  - 3 salt areas
  - 3 mined-rock areas
  - 2 natural gas storage fields



RELATIONSHIP BETWEEN RATING AND RANKING EFFORTS

Mined-Rock Caverns	Salt Caverns	Depleted Gas Reservoirs	Gas Storage Fields
Distance to Infrastructure	Distance to Infrastructure	Distance to Infrastructure	Distance to Infrastructure
Acreage	Acreage	Acreage	Acreage
Average depth	Average depth	Average depth	Average depth
Net Thickness	Net Thickness	Net Thickness	Net Thickness
Trap integrity	Trap integrity	Trap integrity	Trap integrity
Legacy well penetrations	Legacy well penetrations	Legacy well penetrations	Legacy well penetrations
Stacked opportunity	Stacked opportunity	Stacked opportunity	Stacked opportunity
	Pressure	Pressure	Pressure
		Average Porosity	Average Porosity
		Permeability	Permeability
		Mode CO_2 storage	Mode CO_2 storage
		Estimated cumulative gas production	Working gas capacity

RELATIONSHIP BETWEEN RATING AND RANKING EFFORTS

Mined-Rock Caverns	Salt Caverns	Depleted Gas Reservoirs	Gas Storage Fields
Distance to Infrastructure	Distance to Infrastructure	Distance to Infrastructure	Distance to Infrastructure
Acreage	Acreage	Acreage	Acreage
Average depth	Average depth	Average depth	Average depth
Net Thickness	Net Thickness	Net Thickness	Net Thickness
Trap integrity	Trap integrity	Trap integrity	Trap integrity
Legacy well penetrations	Legacy well penetrations	Legacy well penetrations	Legacy well penetrations
Stacked opportunity	Stacked opportunity	Stacked opportunity	Stacked opportunity

FINAL RANKING RESULTS

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

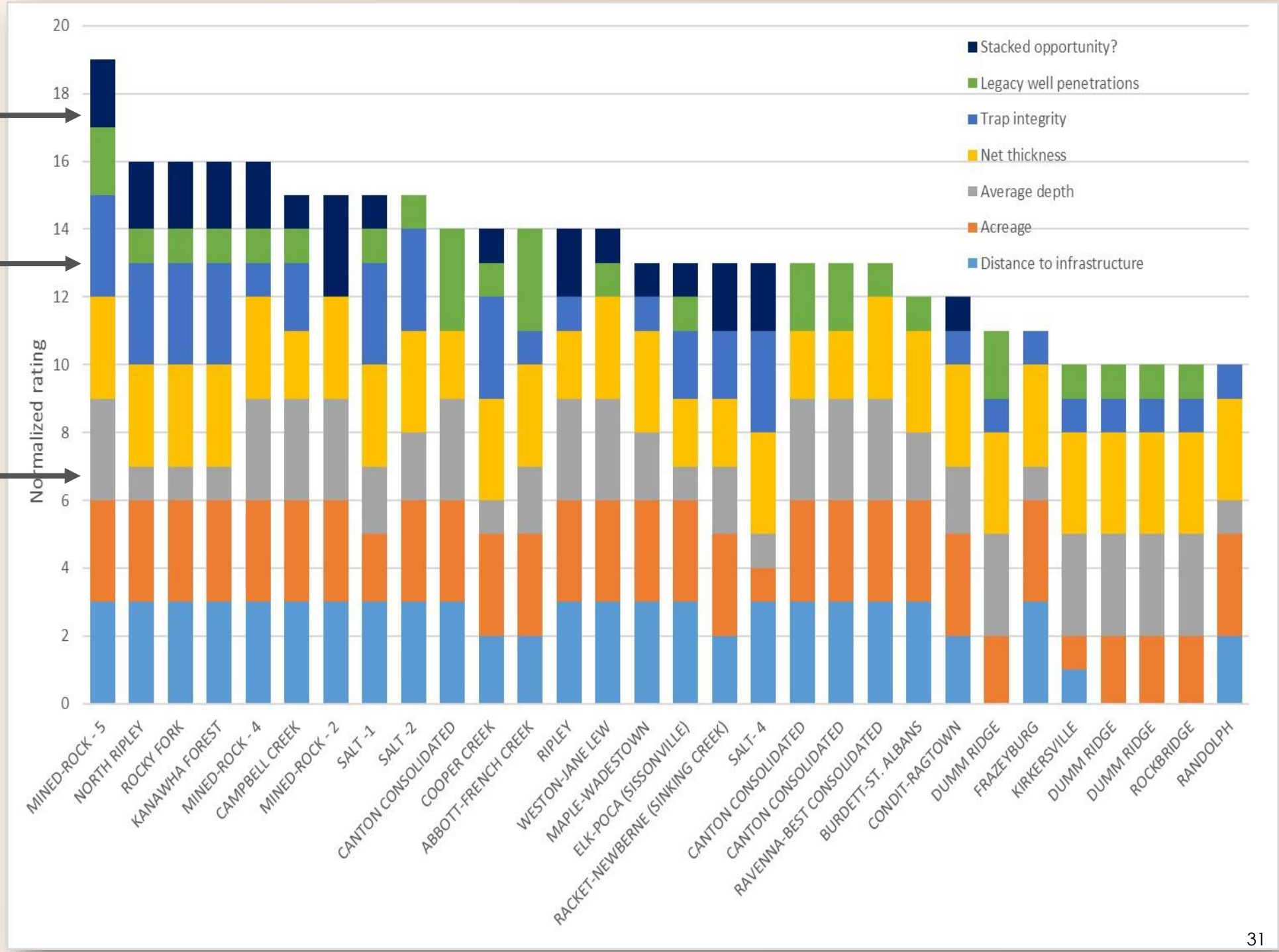
Ranking	Container Type	Field/Location	Geologic Interval	Normalized Rating
1	mined-rock cavern	5	Greenbrier	19
2	depleted gas reservoir	NORTH RIPLEY	Newburg	16
2	depleted gas reservoir	ROCKY FORK	Newburg	16
2	depleted gas reservoir	KANAWHA FOREST	Newburg	16
2	mined-rock cavern	4	Greenbrier	16
3	depleted 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

FINAL RANKING RESULTS

Stacked opportunities

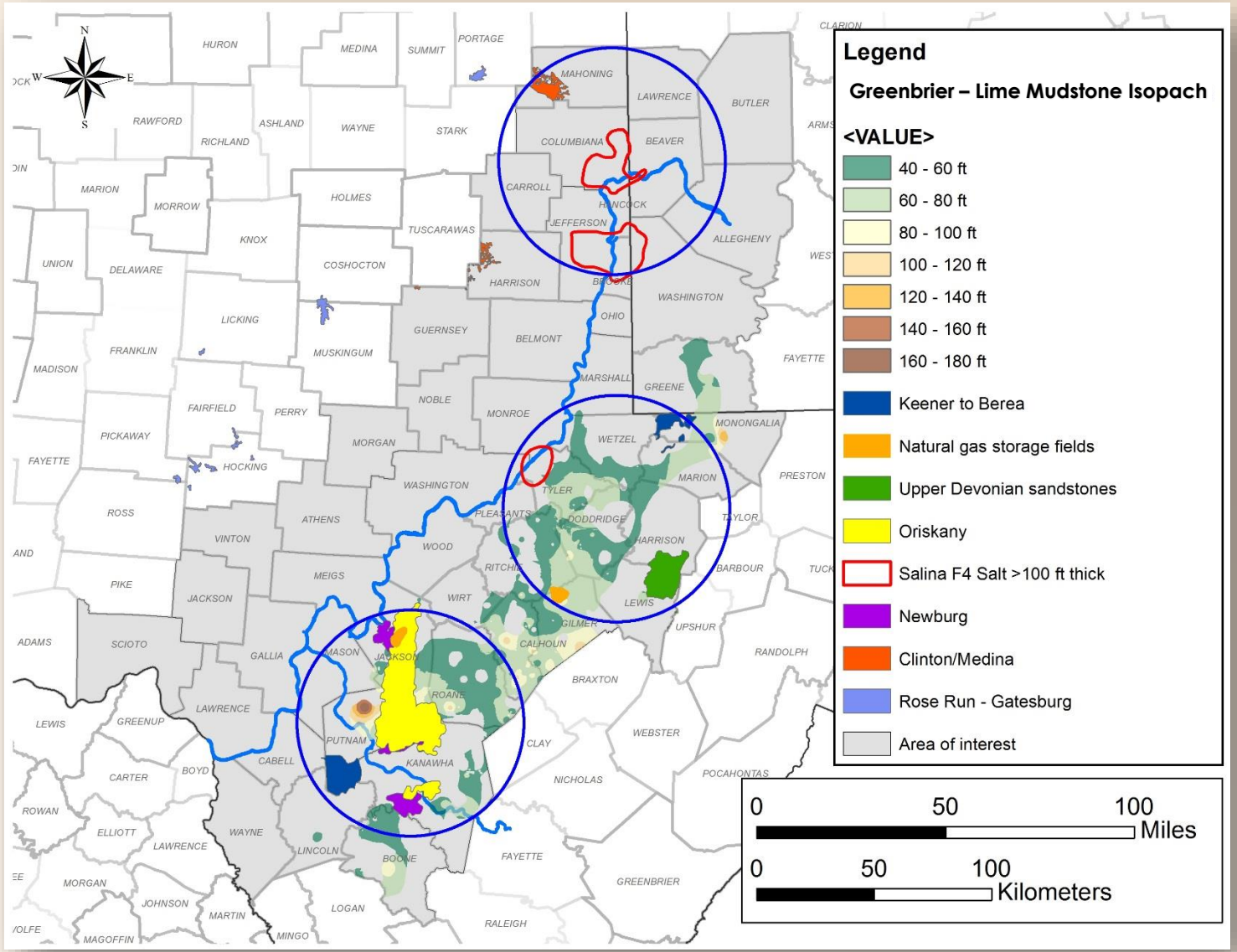
Trap integrity

Average depth



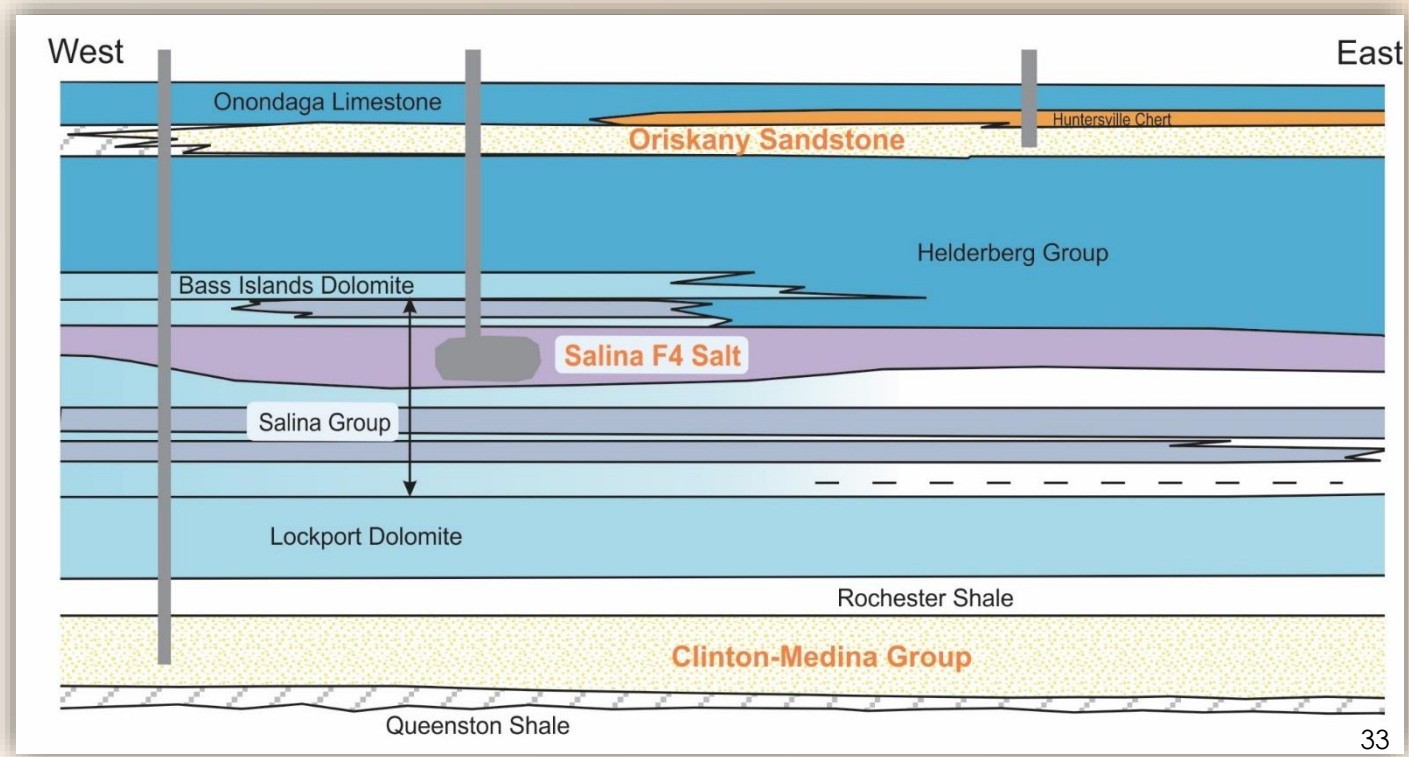
THREE PROSPECTS FOR NGL STORAGE

- Demonstrate how this Study's regional and field-level geologic data can be applied to underground storage siting work
- Ascertain what site-level data might be necessary as part of a follow-on study
- Stacked storage plays an important role



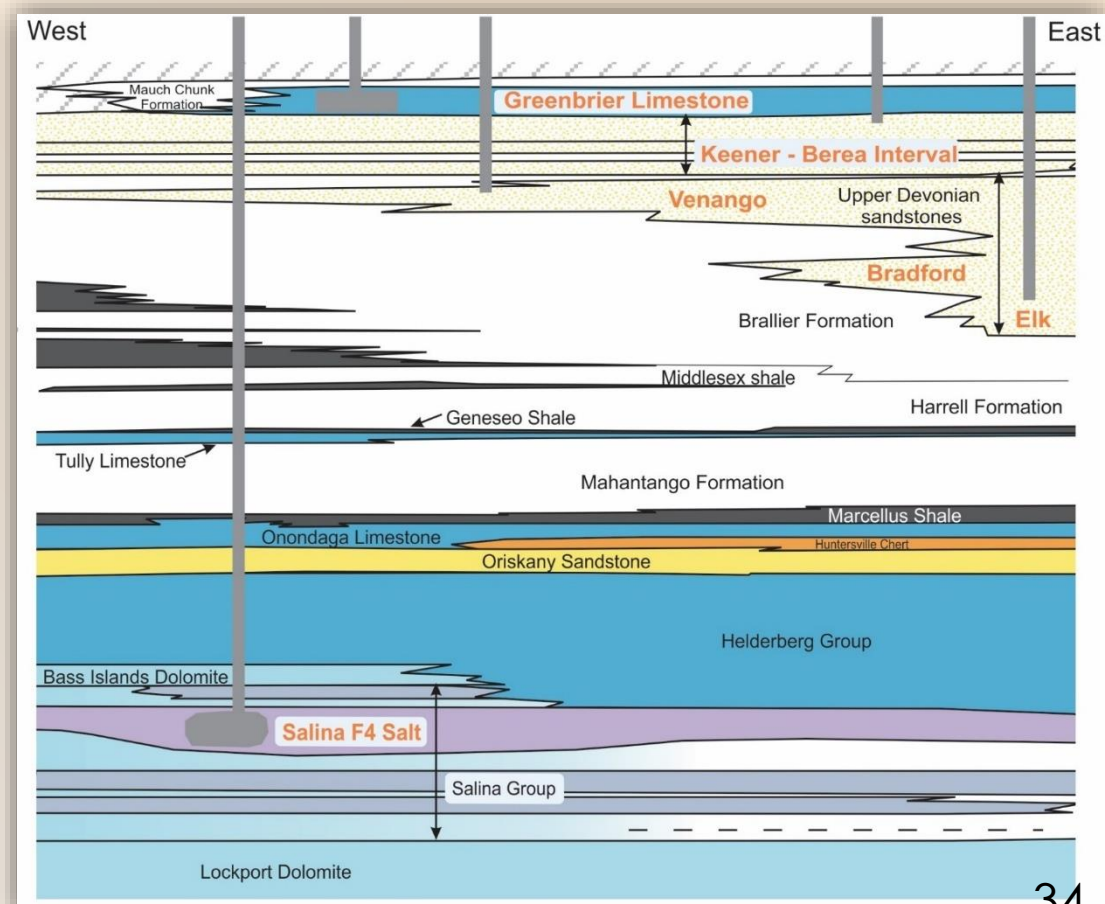
NORTHERN PROSPECT AREA

- Clinton/Medina sandstones in Ohio's Ravenna-Best Consolidated Field
- Two Salina F4 Salt cavern opportunities on both sides of the Ohio River
- Oriskany core data indicates another opportunity; suggests stacked potential



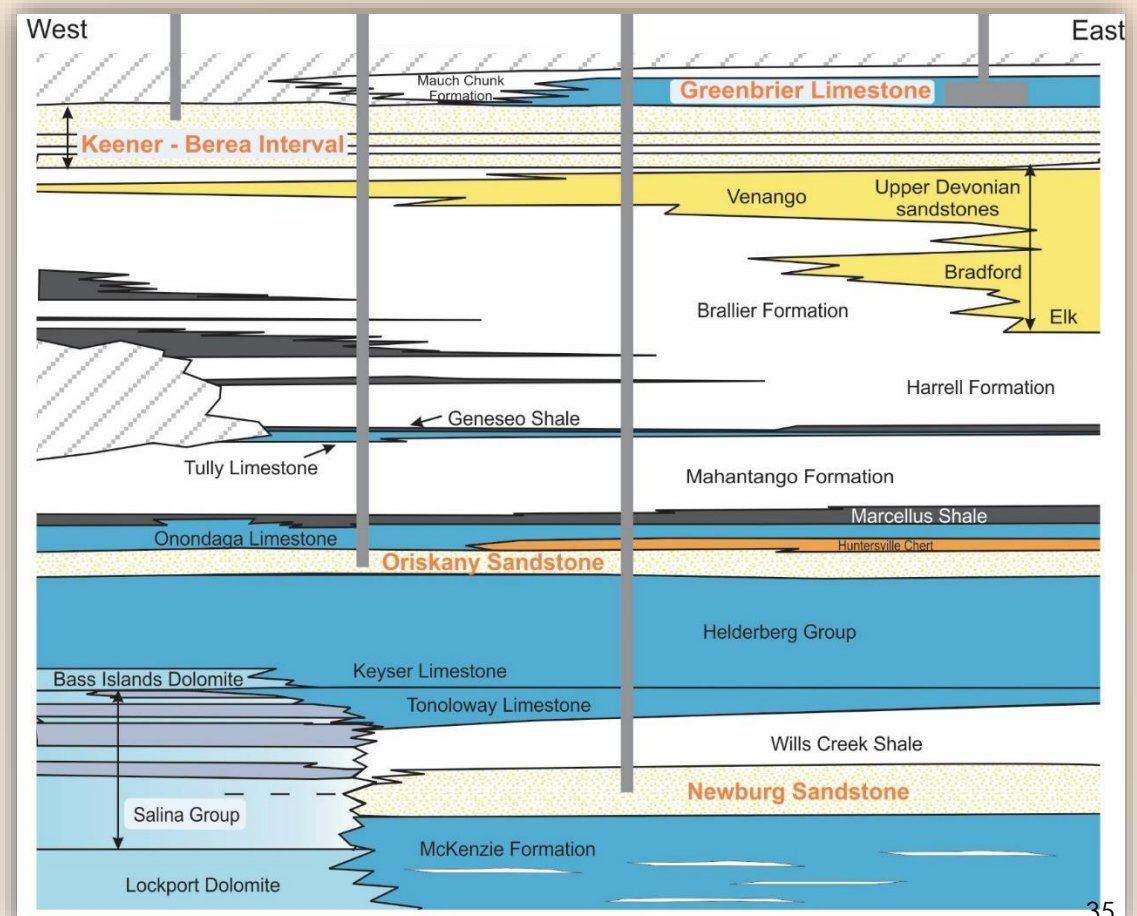
CENTRAL PROSPECT AREA

- Greenbrier Limestone mined-rock cavern opportunities
- Keener to Berea Interval depleted gas field
- Venango Group inactive gas storage field
- Upper Devonian depleted gas field to the east
- Salina F4 Salt near Ben's Run



SOUTHERN PROSPECT AREA

- Greenbrier Limestone mined-rock cavern opportunities
- Depleted gas fields in the Keener to Berea Interval
- Oriskany Sandstone (depleted gas and natural gas storage)
- Newburg fields(North Ripley, Rocky Fork, Cooper Creek and Kanawha Forest) are among the very best of all depleted gas fields



SUMMARY

- **Mined-rock caverns**

  Greenbrier Limestone
  - Depth
  - Thickness
  - Facies distribution

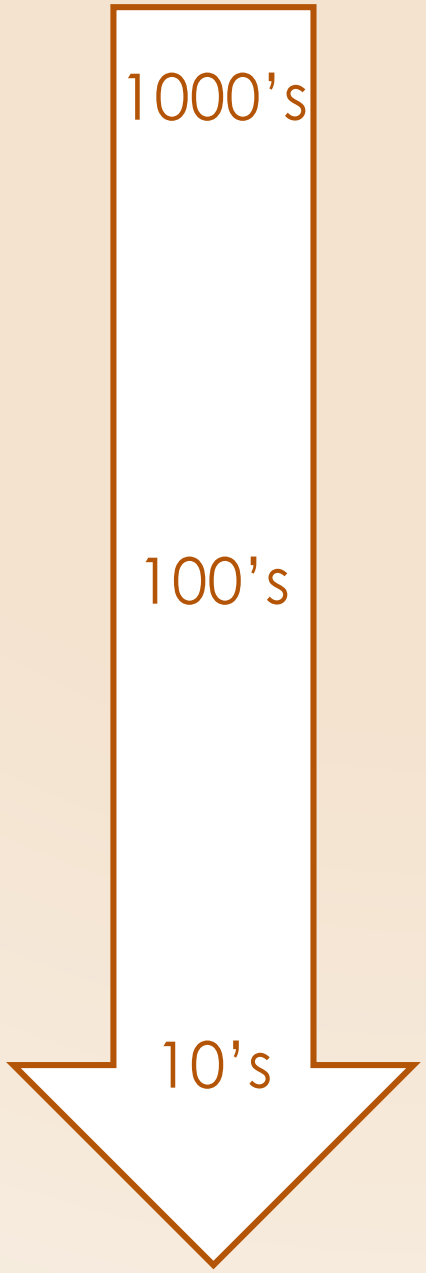
- **Salt Caverns**

  Salina Group salts
  - Depth
  - Thickness
  - Extent

- **Depleted gas reservoirs/natural gas storage fields**

  Devonian-Cambrian age units
  - Reservoir data compilation
  - Preliminary assessment (through rating)

- **Detailed rating and ranking efforts**
  - Criteria for each storage type
  - Detailed rating results
  - Normalized ratings used for ranking purposes



WHAT WE DID NOT CONSIDER

- Who owns or operates a depleted gas field or gas storage field that was rated highly
- Or if this operator would be interested in NGL storage
- Who owns the rights to the Greenbrier Limestone or Salina Salt
- And again, if the owner might be interested in NGL storage
- If a candidate is in an area of future Marcellus or Utica drilling
- Surficial activities, other than towns or cities
- Cost implications for storage and pipelines
- Focus was entirely on subsurface geology

SUMMARY AND CAVIATS

- Multiple options are present along the Ohio and Kanawha rivers where storage could be constructed in three different types of storage containers
- Storage capacity and deliverability will ultimately depend on the NGL product(s)
- Storage capacity and deliverability may require more than one facility and/or more than one geologic container per facility (stacked storage)
- We recommend a follow-on engineering and geologic site assessment at any potential site

THANK YOU!

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