Mapping And Reservoir Characterization of Geologic Intervals for NGL Storage Applications

Robin V. Anthony[1], Doug Patchen[2], Jessica Moore[3], Michael Solis[4]

[1]PA DCNR, Bureau of Topographic & Geologic Survey
[2]Appalachian Oil and Natural Gas Research Consortium, West Virginia University
[3]West Virginia Geological and Economic Survey
[4]Ohio Geologic Survey, Ohio Department of Natural Resources

BACKGROUND

- **Marcellus and Utica Shale Natural Gas Liquids (NGL's)** produced in the tri-state area of OH, PA and WV
- **NGL's** can support a global petrochemical industry
- **Strategic** location to plastics manufacturing centers
- **Regional cooperation agreement** signed in 2015
- **Subsurface storage** will be a necessary component
- **Appalachian Oil & Natural Gas Research Consortium** formed to evaluate subsurface storage potential

AREA OF INTEREST

- **Correlate stratigraphy**
- **Map thickness & structure**
- **Characterize the reservoir**
- Development and application of rating and ranking criteria

THREE OPTIONS FOR NGL STORAGE

- **Mined-rock caverns** (carbonate rock)
- **Solution-mined caverns** (bedded salt)
- **Depleted gas fields** (siliciclastic units)

GEOLOGIC INTERVALS

Mined-rock caverns

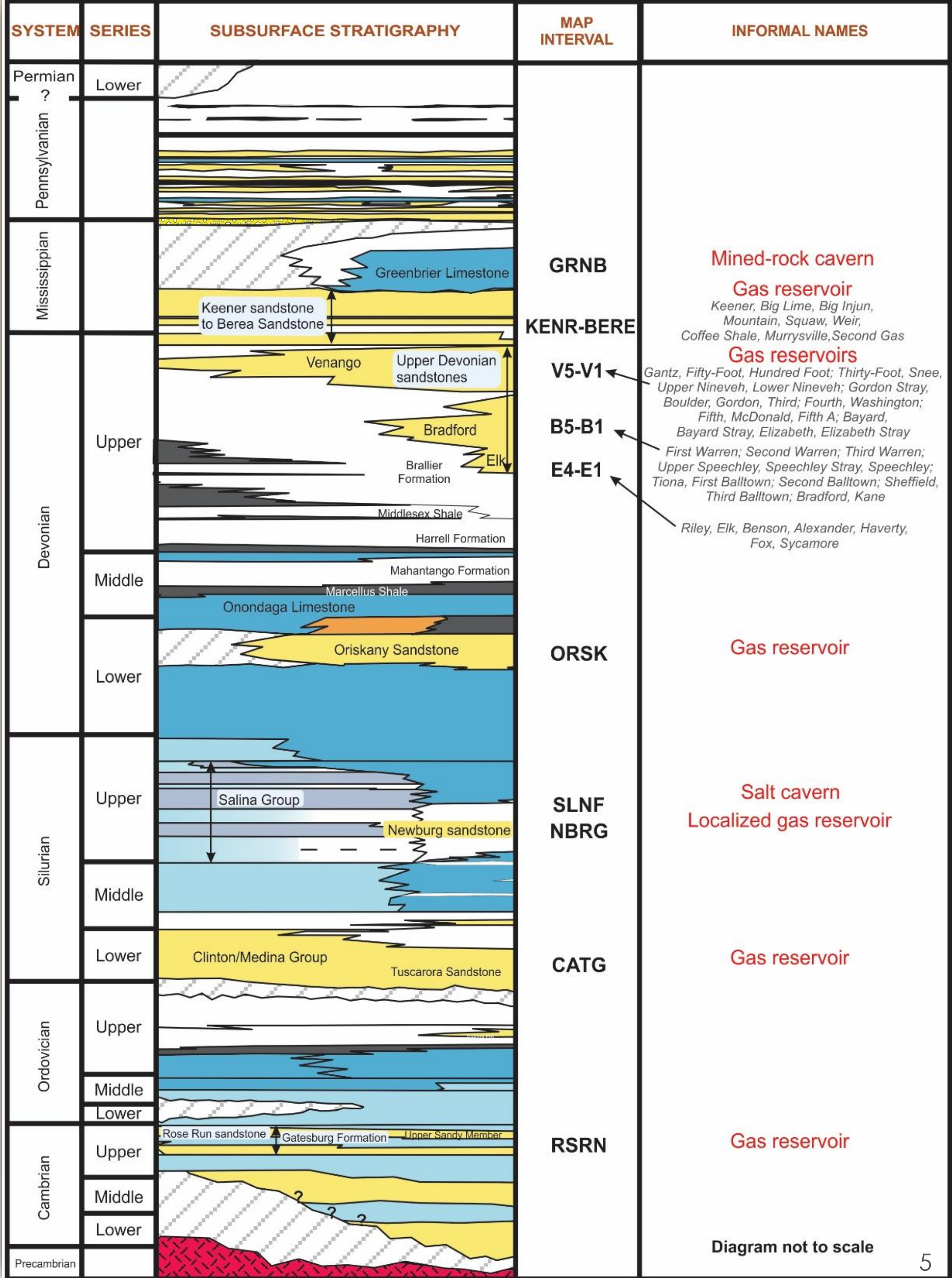
Greenbrier Limestone
(≥40 ft thick; 1,800 – 2000 ft deep)

Salt caverns

Salina Group salts (≥100 ft thick)

Depleted gas reservoirs or storage fields

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



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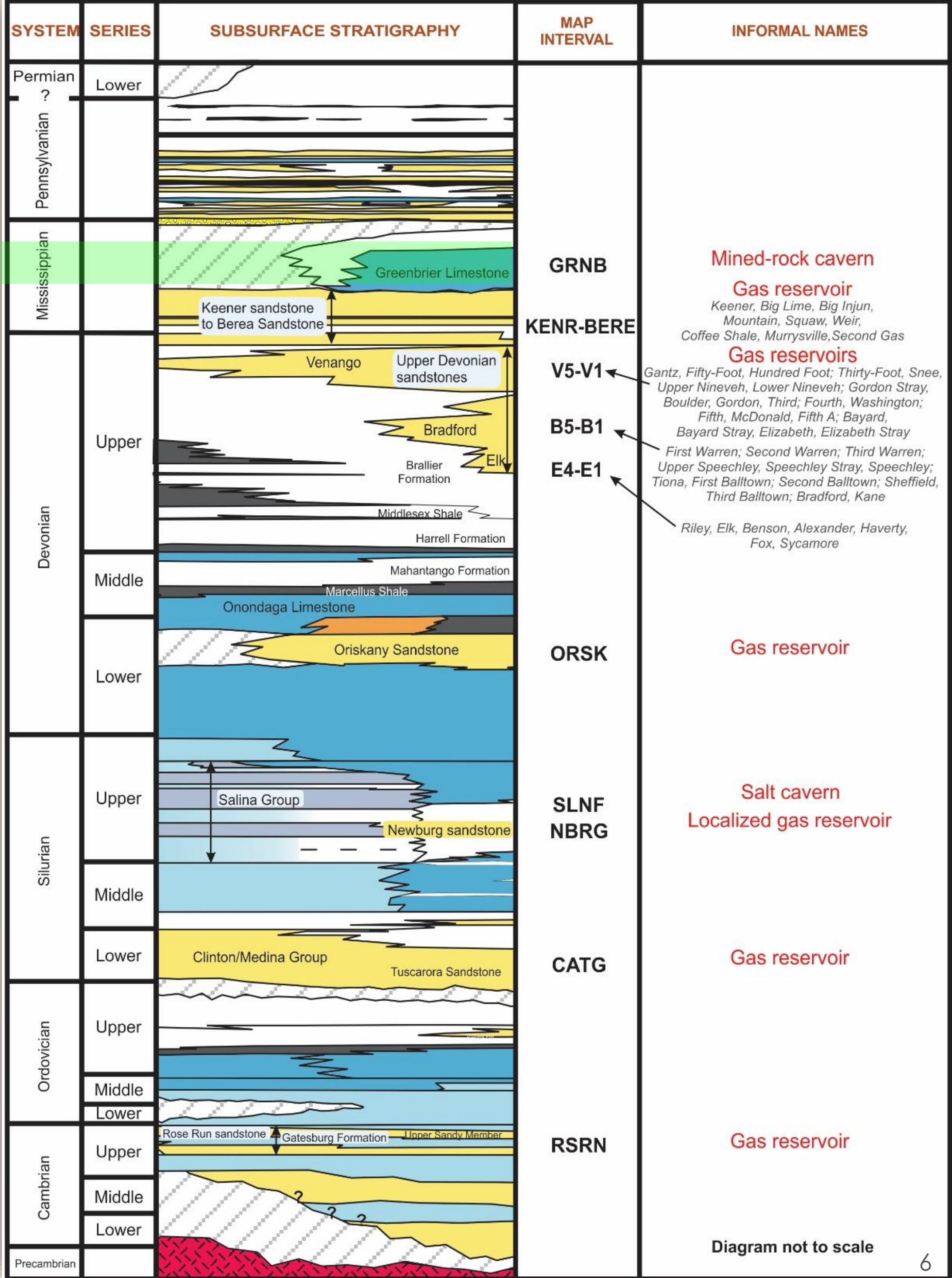

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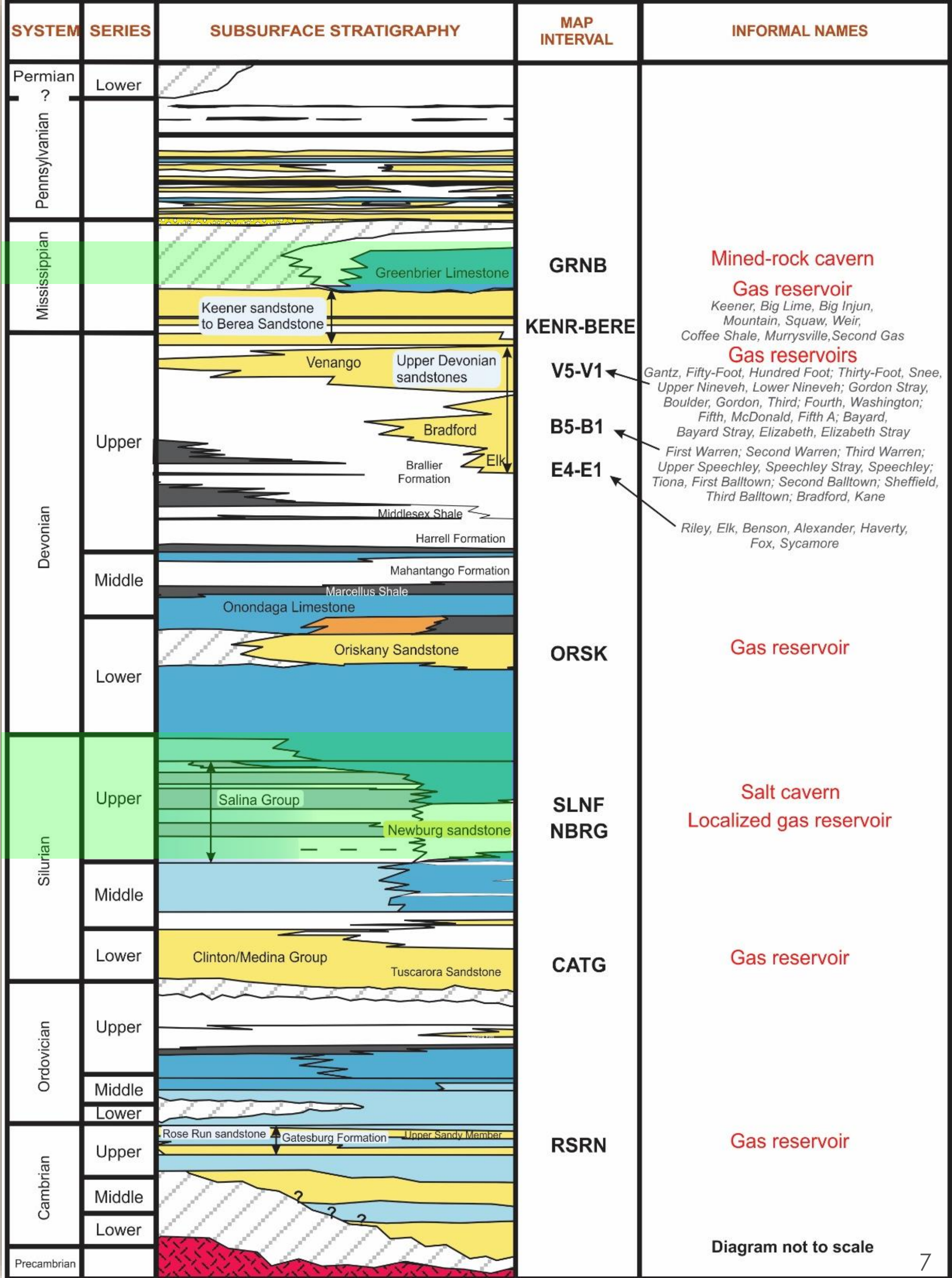

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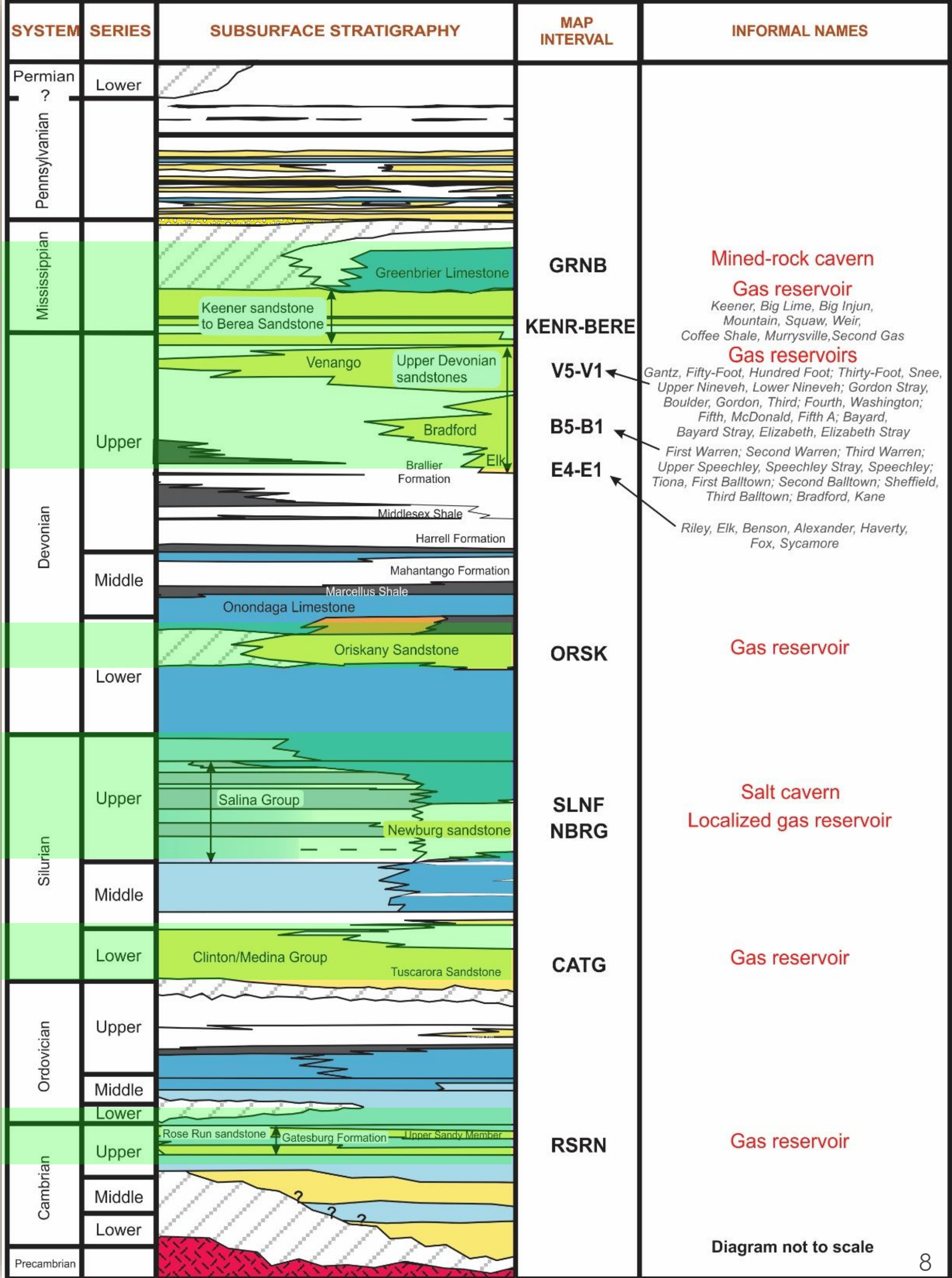

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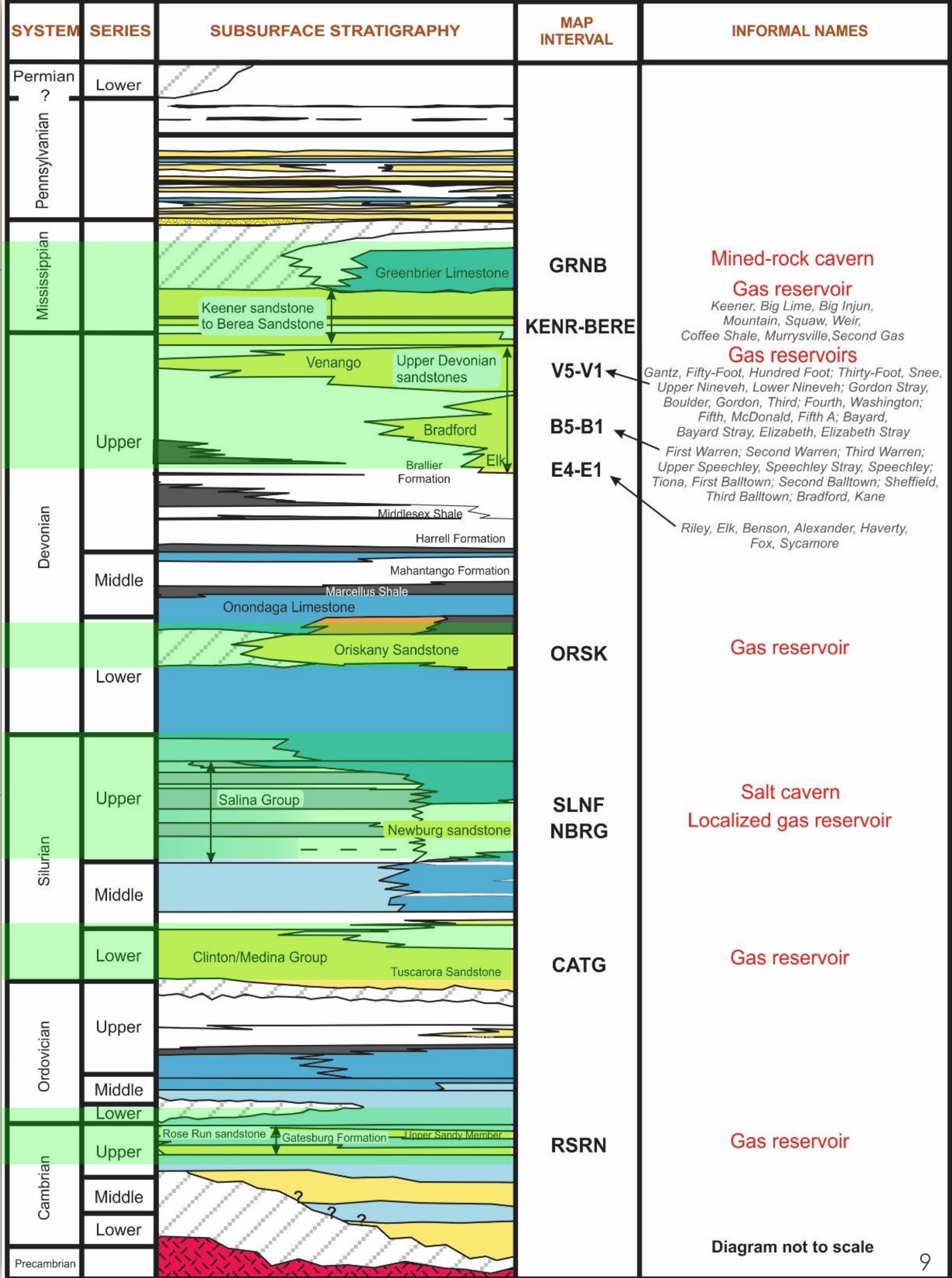
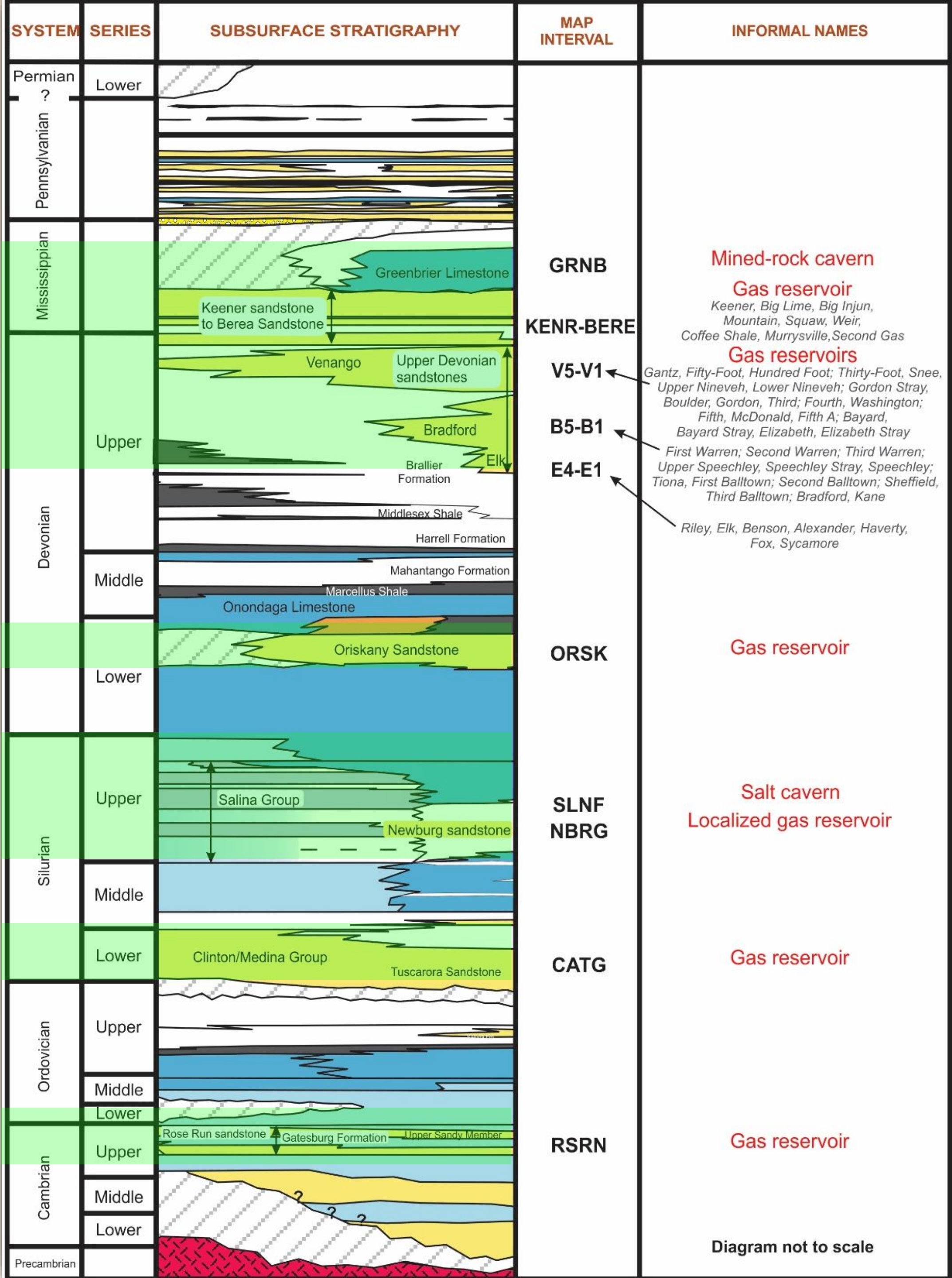
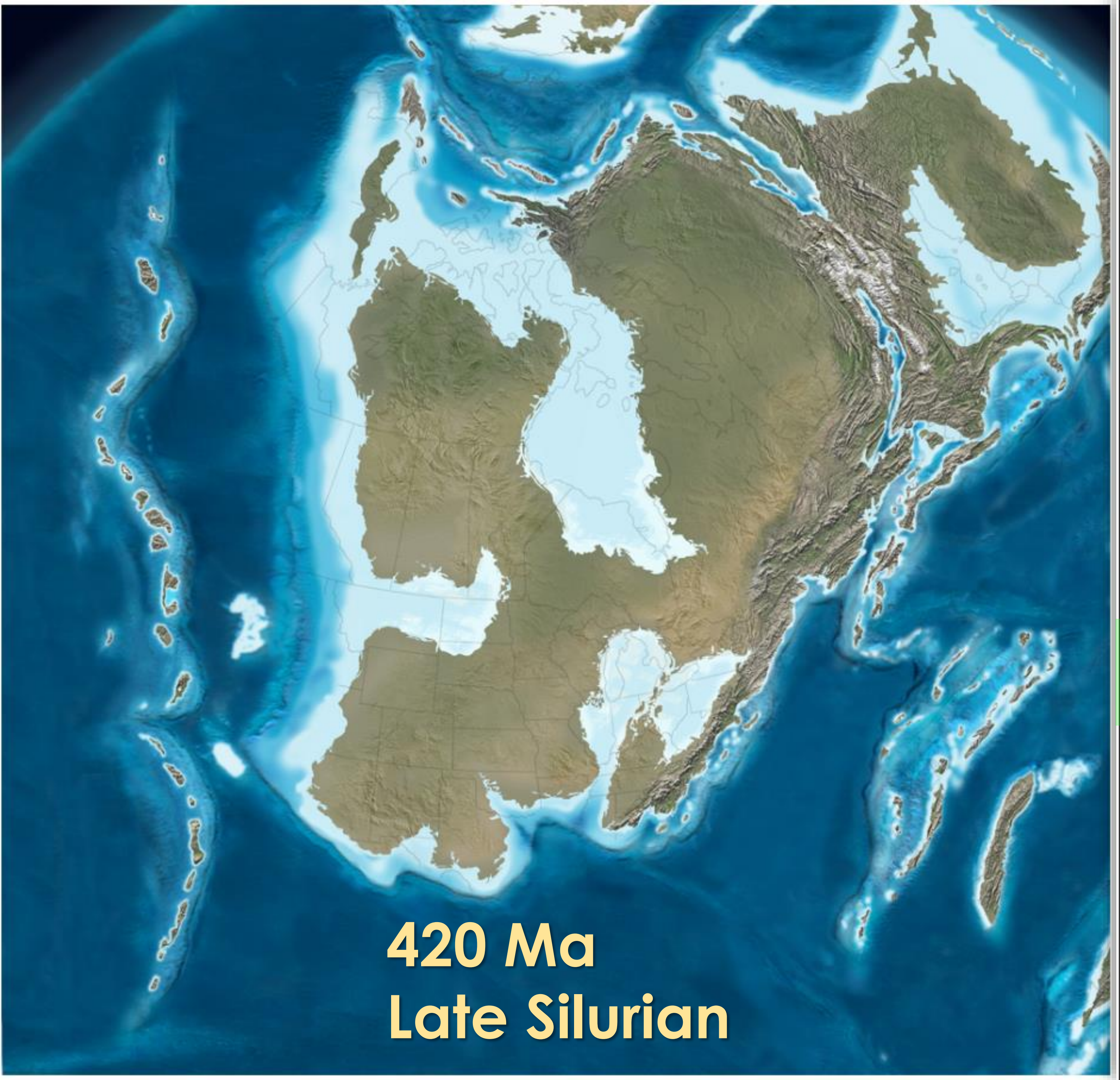
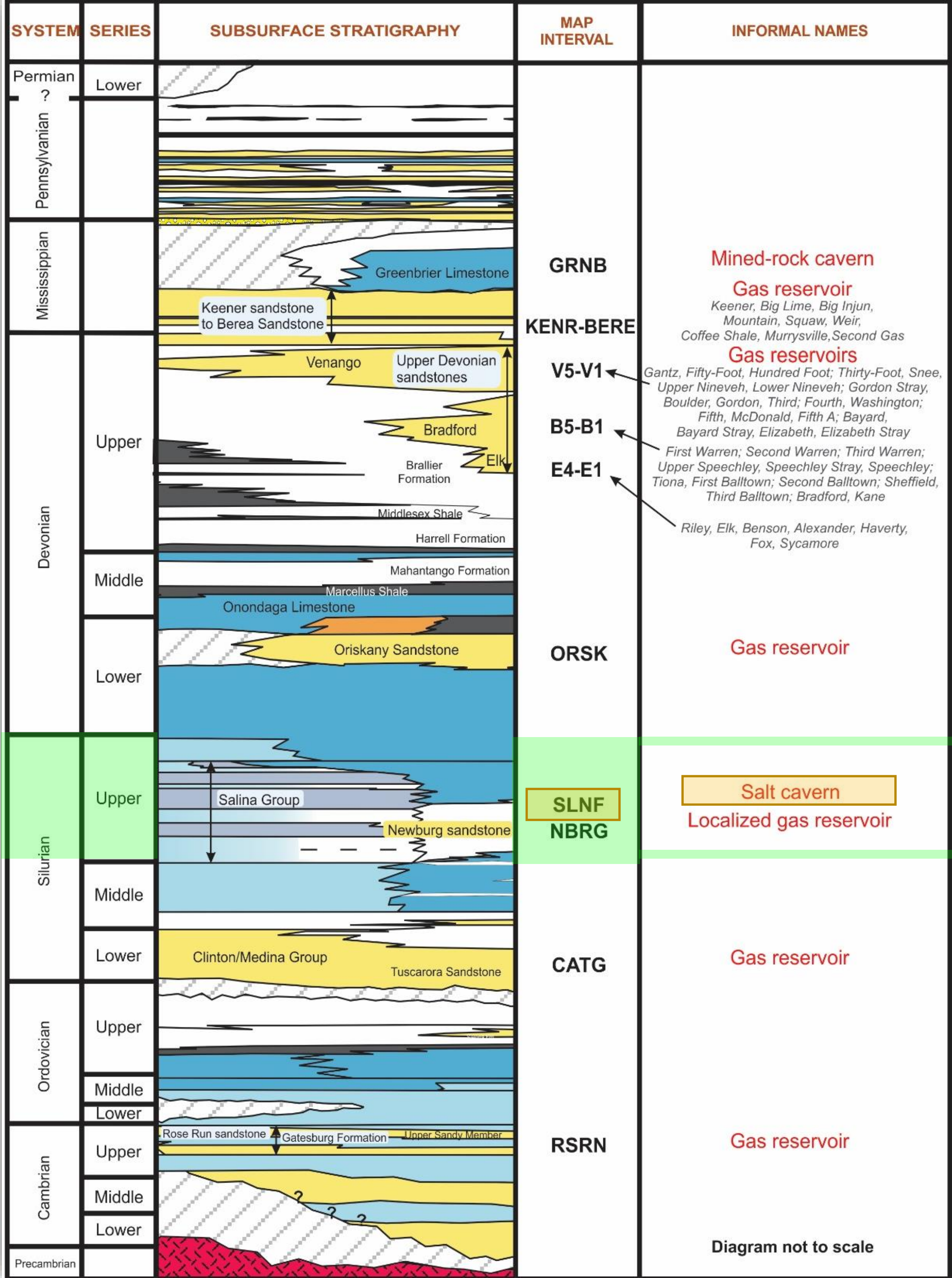


RESERVOIR CHARACTERIZATION

- **Unique characterization**
  each type of storage container
  - ➢ **Depth** – structure maps
  - ➢ **Thickness** – isopach maps
  - ➢ **Extent** – facies evaluation
  - ➢ **Preliminary assessment** – Environments of deposition, post-depositional processes




420 Ma
Late Silurian


SYSTEM
SERIES
SUBSURFACE STRATIGRAPHY
MAP INTERVAL
INFORMAL NAMES
Permian
?
Lower
Pennsylvanian
Mississippian
Devonian
Upper
Middle
Lower
Silurian
Upper
Middle
Lower
Ordovician
Upper
Middle
Lower
Cambrian
Upper
Middle
Lower
Precambrian
Greenbrier Limestone
Keener sandstone to Berea Sandstone
Venango
Upper Devonian sandstones
Bradford
Brallier Formation
Elk
Middlesex Shale
Harrell Formation
Mahantango Formation
Marcellus Shale
Onondaga Limestone
Oriskany Sandstone
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Tuscarora Sandstone
Rose Run sandstone
Gatesburg Formation
Upper Sandy Member
?
?
?
GRNB
KENR-BERE
V5-V1
B5-B1
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ORSK
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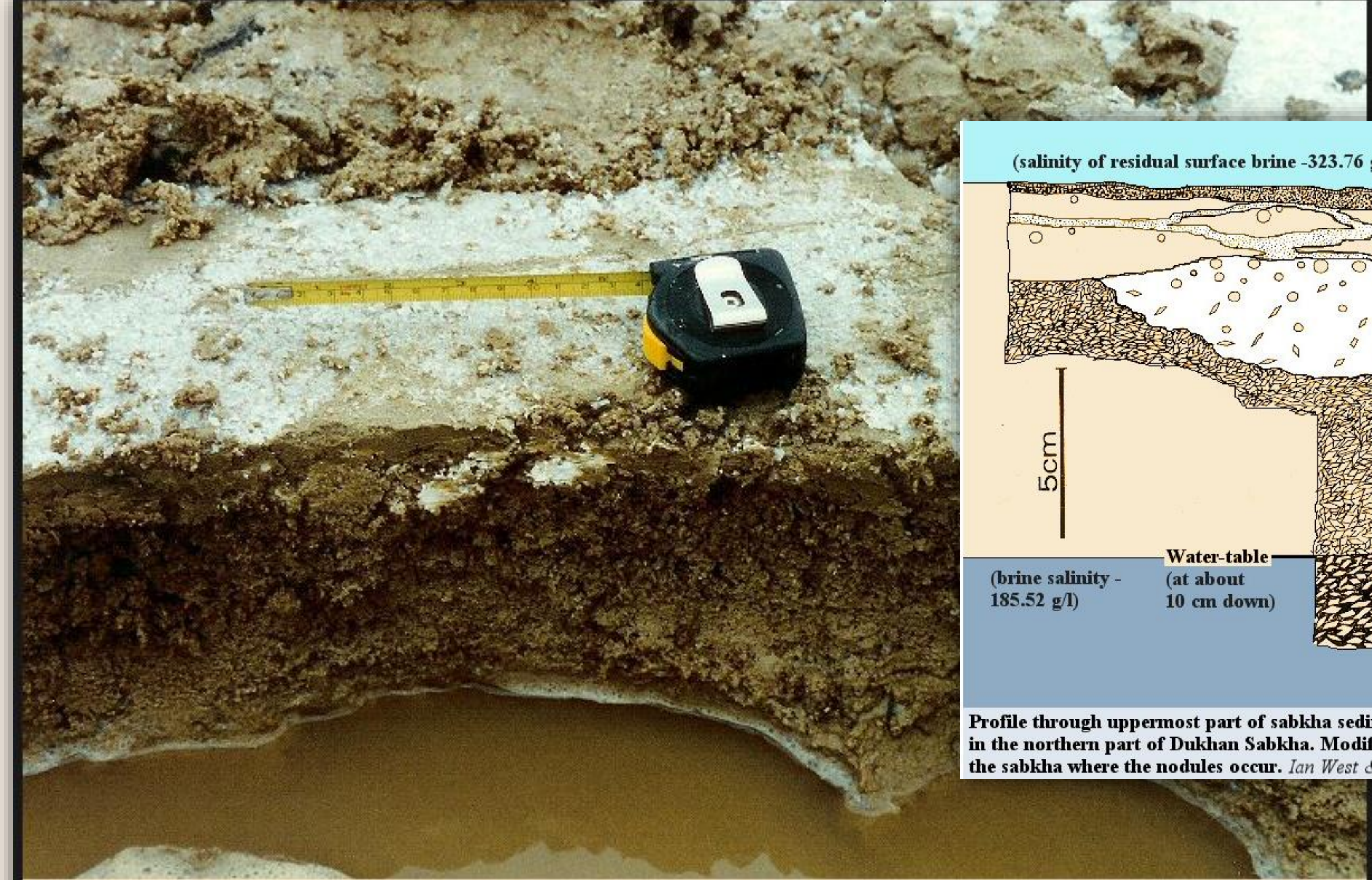
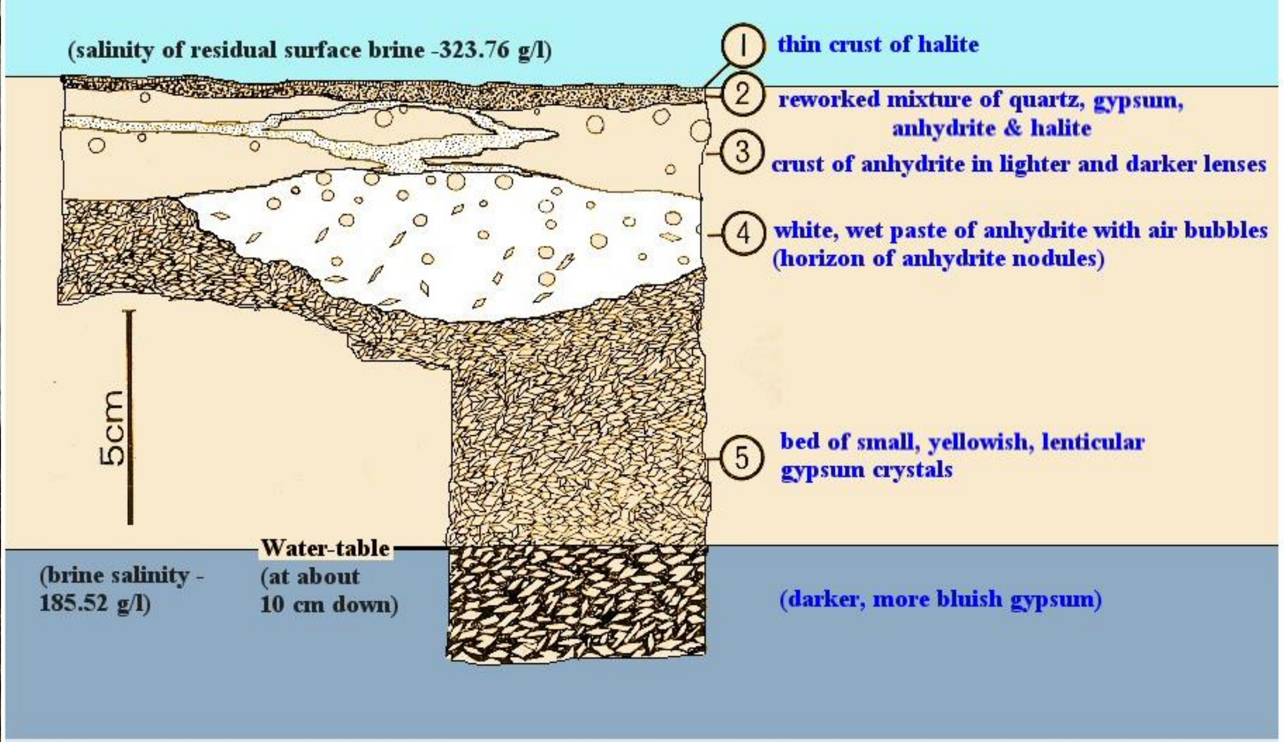
CATG
RSRN
Mined-rock cavern
Gas reservoir
Keener, Big Lime, Big Injun, Mountain, Squaw, Weir, Coffee Shale, Murrysville, Second Gas
Gas reservoirs
Gantz, Fifty-Foot, Hundred Foot; Thirty-Foot, Snee, Upper Nineveh, Lower Nineveh; Gordon Stray, Boulder, Gordon, Third; Fourth, Washington; Fifth, McDonald, Fifth A; Bayard, Bayard Stray, Elizabeth, Elizabeth Stray
First Warren; Second Warren; Third Warren; Upper Speechley, Speechley Stray, Speechley; Tiona, First Balltown; Second Balltown; Sheffield, Third Balltown; Bradford, Kane
Riley, Elk, Benson, Alexander, Haverty, Fox, Sycamore
Gas reservoir
Salt cavern
Localized gas reservoir
Gas reservoir
Gas reservoir
Diagram not to scale

Modern Analog: Persian Gulf Sabkha



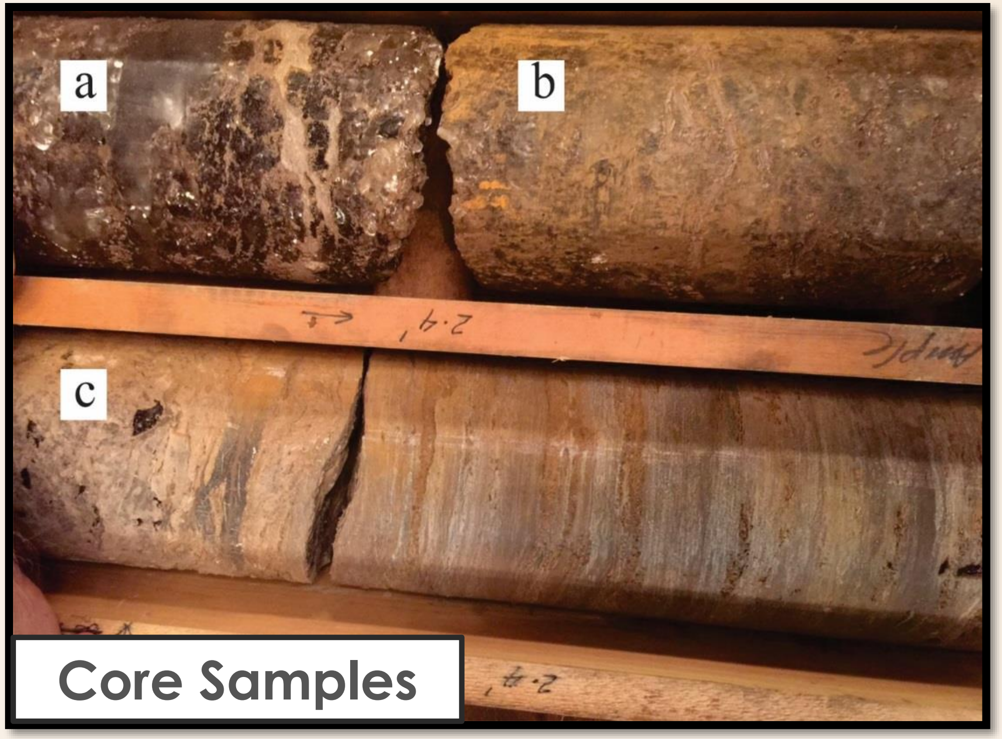
Pit through a marginal part of Dukhan Sabkha near the salt lake. White anhydrite occurs a few cm beneath the surface. The level of the gypsum-saturated brine is about 10 or 15 cm beneath the halite encrusted surface. Compare with profile of Perthuisot (1977). *Ian West & Tonya West (c) 2006.*



Profile through uppermost part of sabkha sediments about 50 metres from the margin of the salt crust (salt lake) in the northern part of Dukhan Sabkha. Modified after Perthuisot (1977). Compare with later photograph of pit in the sabkha where the nodules occur. *Ian West & Tonya West (c) 2006.*

http://www.southampton.ac.uk/~imw/Sabkhas-Bibliography.htm

The Salina is a **bedded** salt

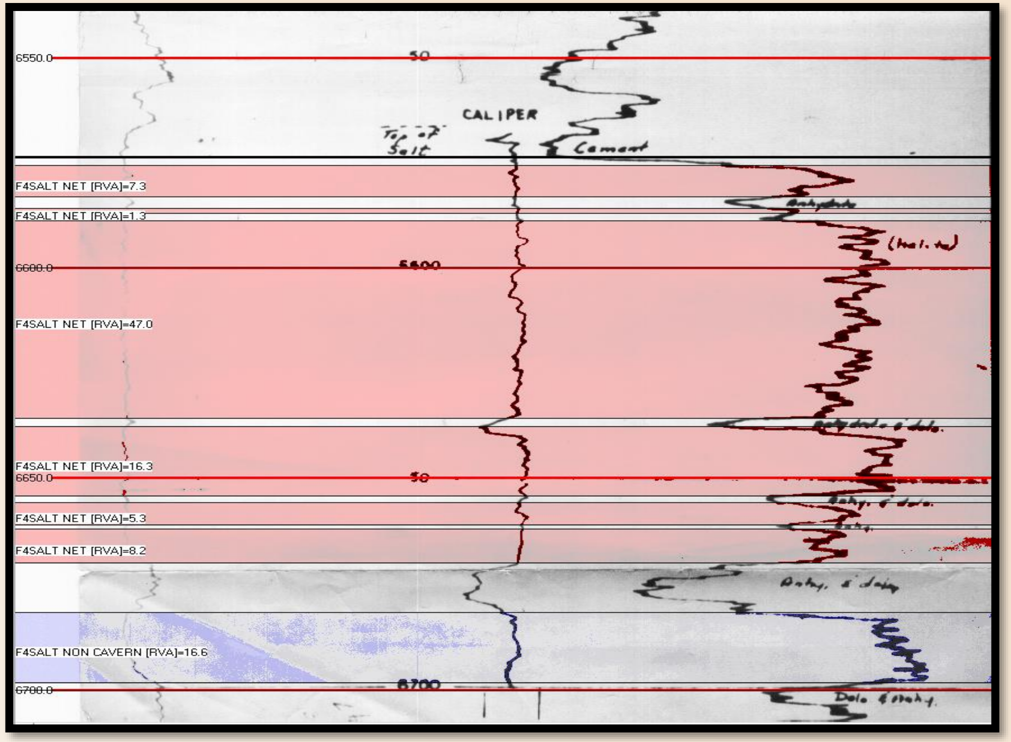


Core Samples

a: Coarse halite crystals with evenly disseminated black anhydrite pieces that give the sample a dark gray color;

b: post-lithification fracture includes some salt crystals along the fracture zone;

c: brown-gray calcareous shale, thinly laminated, sometimes wavy, partially replaced by salt & pepper carbonate(?)-anhydrite mixture. The shale is interbedded with the carbonate-anhydrite beds.

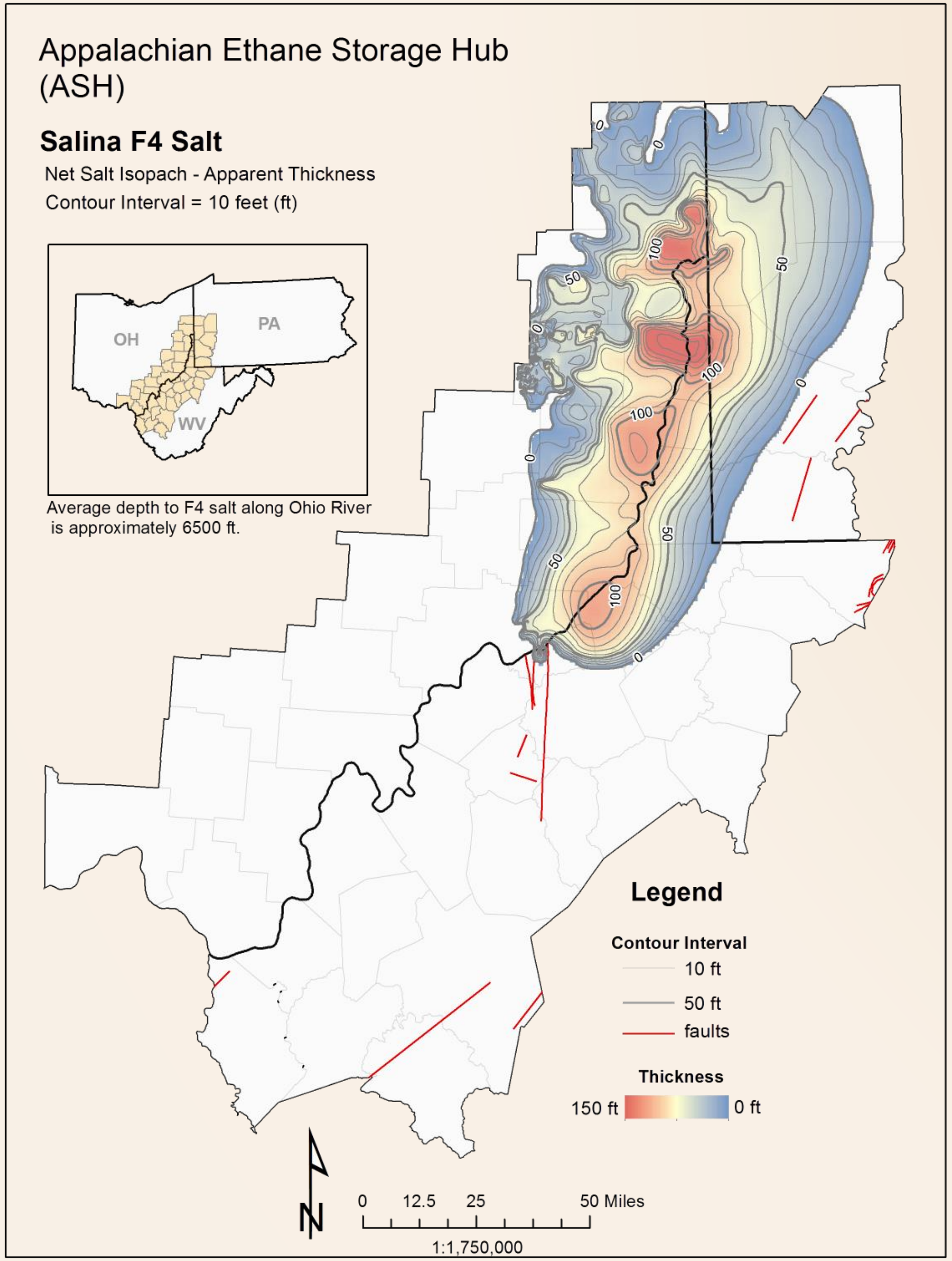


Geophysical Logs

Well penetrating the F4 Salt, where lithologies tied into the geophysical log identify zones of anhydrite and dolomite.

SOLUTION-MINED CAVERNS
SALINA SALT

- Cavern size limited by salt thickness
- Salt itself forms sealing mechanism for this type of container
- Need thick intervals of pure salt
- Need large area to create cavern with buffer zone between cavern and edge of salt
- Thickness, purity and extent are key factors



SALINA F4 SALT THICKNESS

- **Only Salina salt deposit likely to occur in thicknesses ≥ 100 ft.**
- **Four areas with net thickness ≥ 100 ft.**

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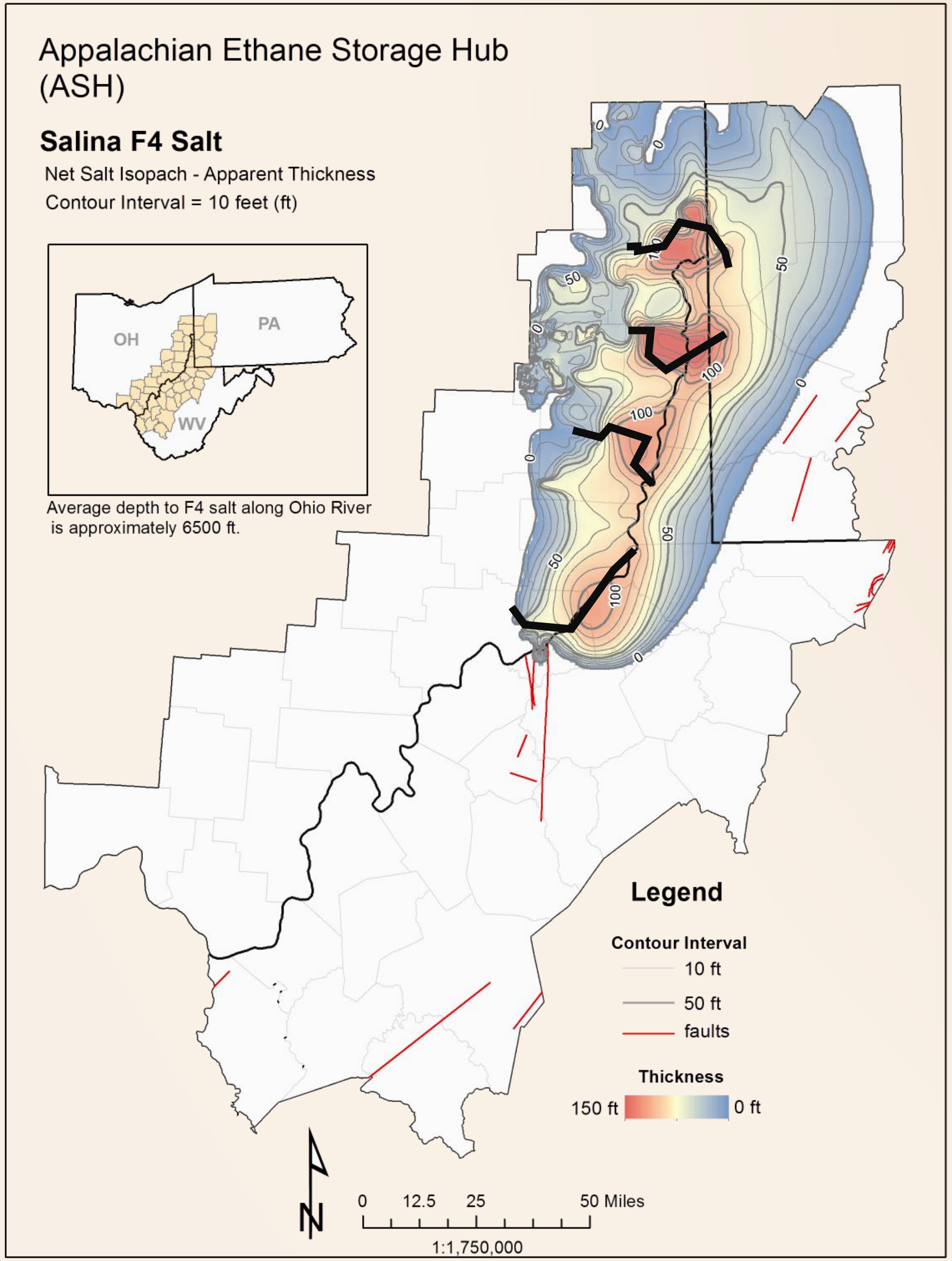

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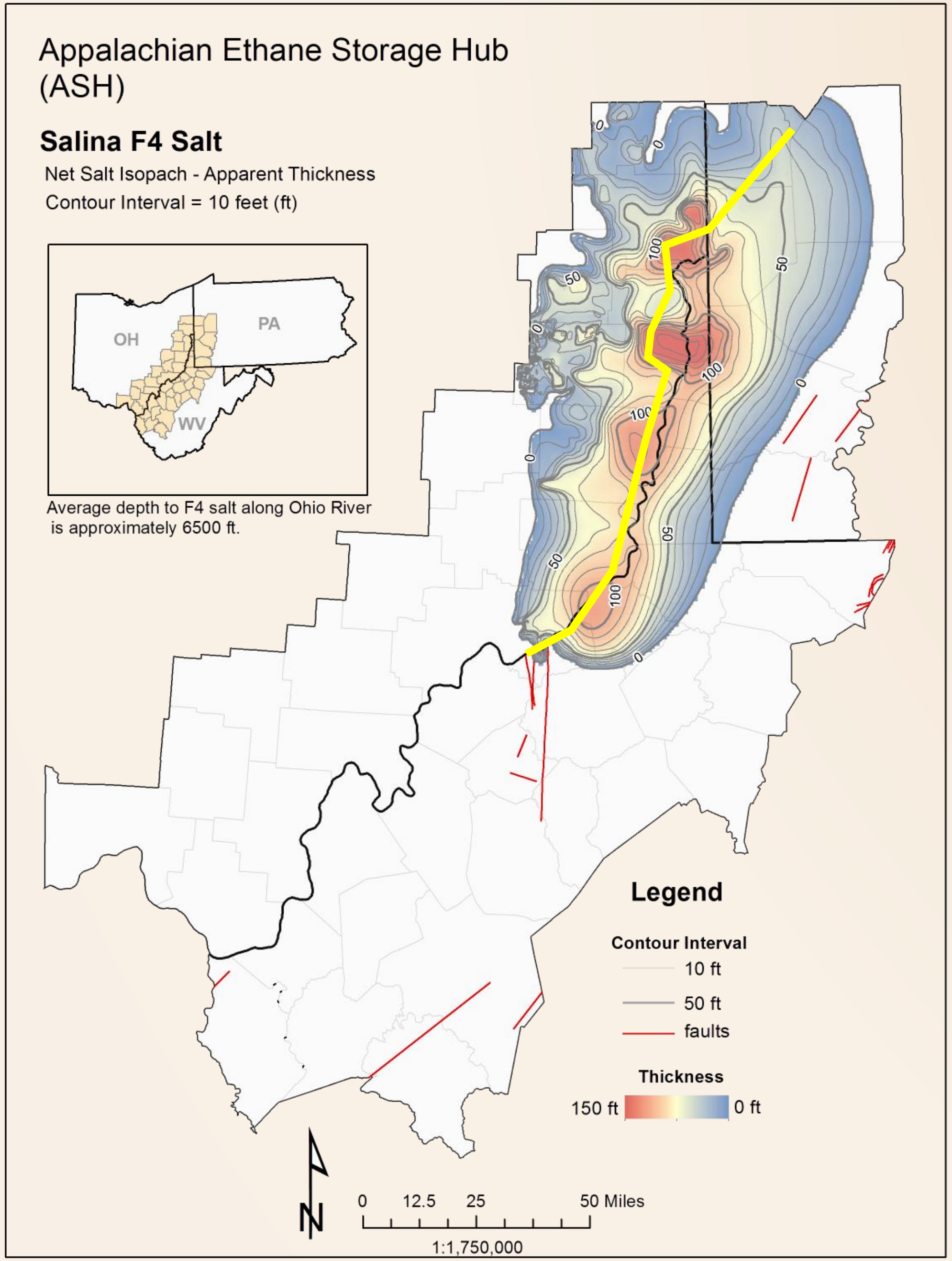

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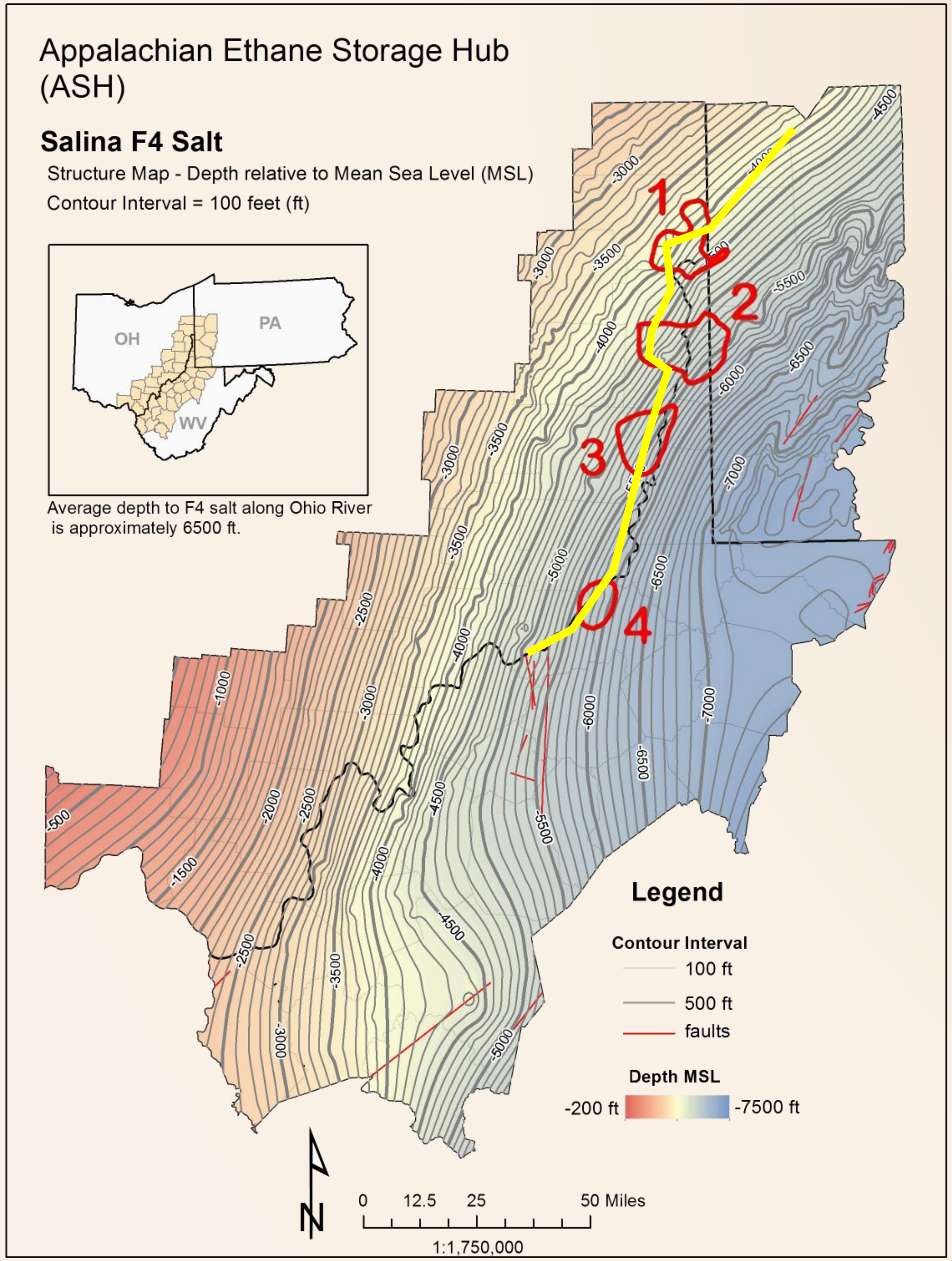


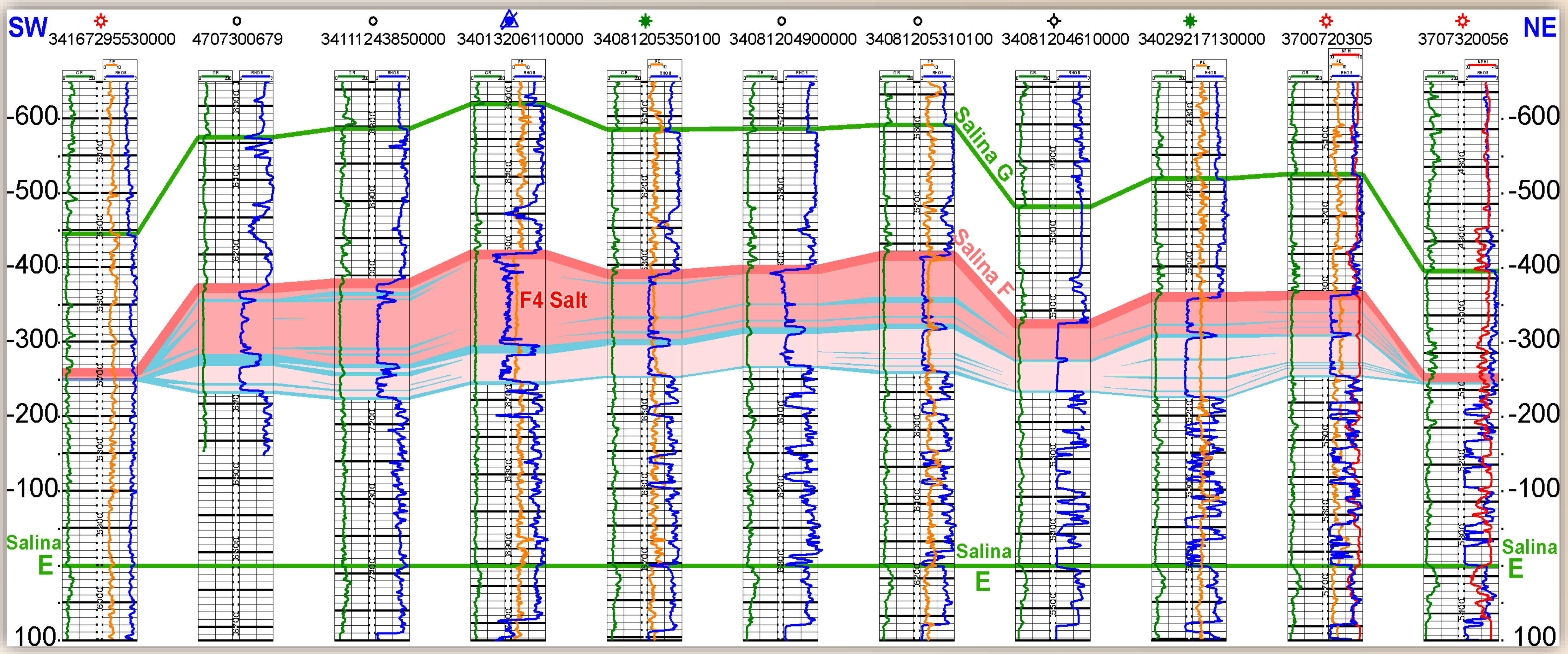
SALINA F4 SALT DEPTH

- **Below deepest occurrence of fresh drinking water**
- **Few gas wells penetrate salt, so limits vertical migration routes**
- **Increase in salt plasticity limits lower cavern depth to <7,000'**

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

Depths to top of F4 Salt relative to Mean Sea Level (MSL) range from -3,700 to -6,000 feet

SW-NE CROSS SECTION ALONG STRIKE



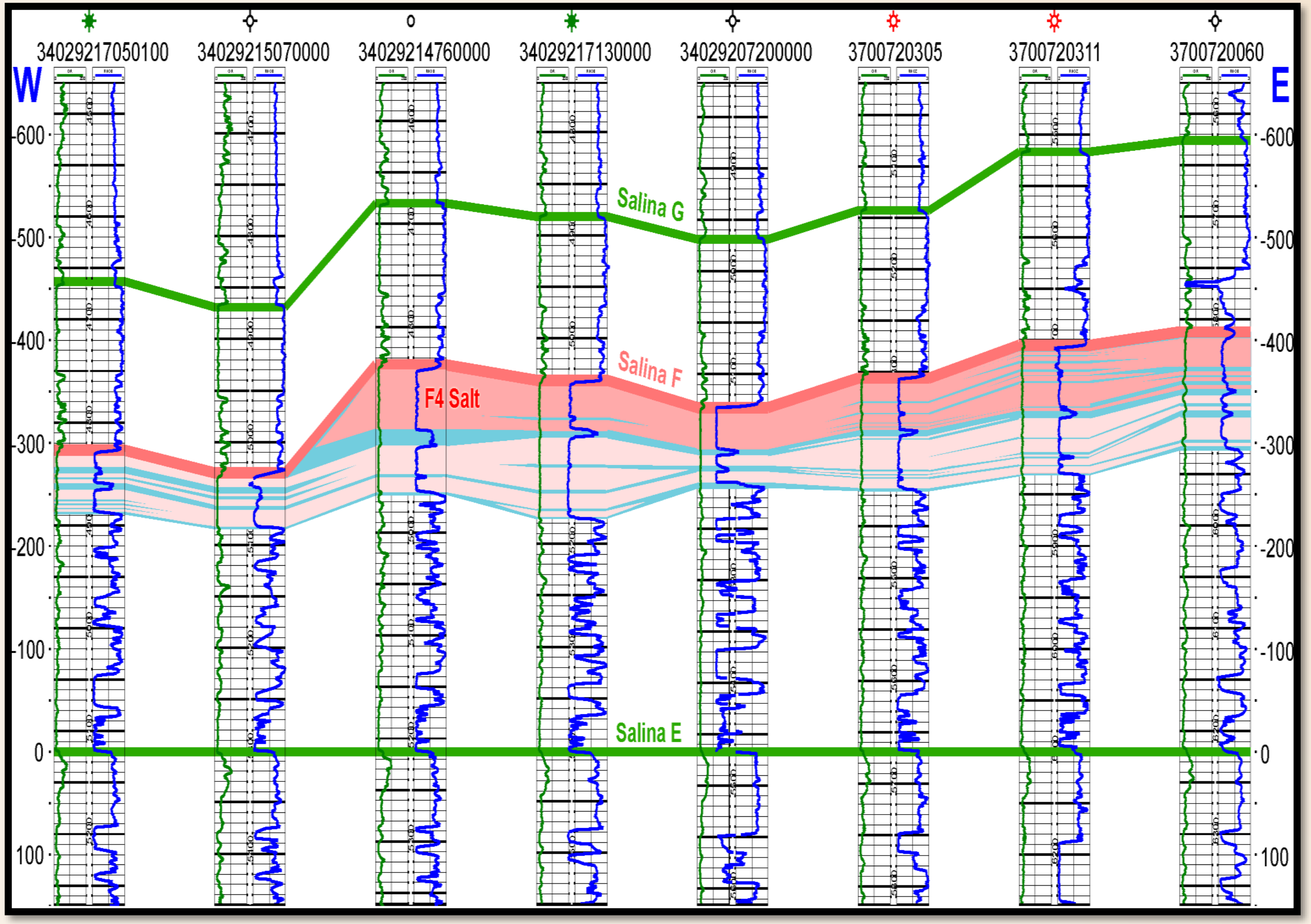
F4 Salt

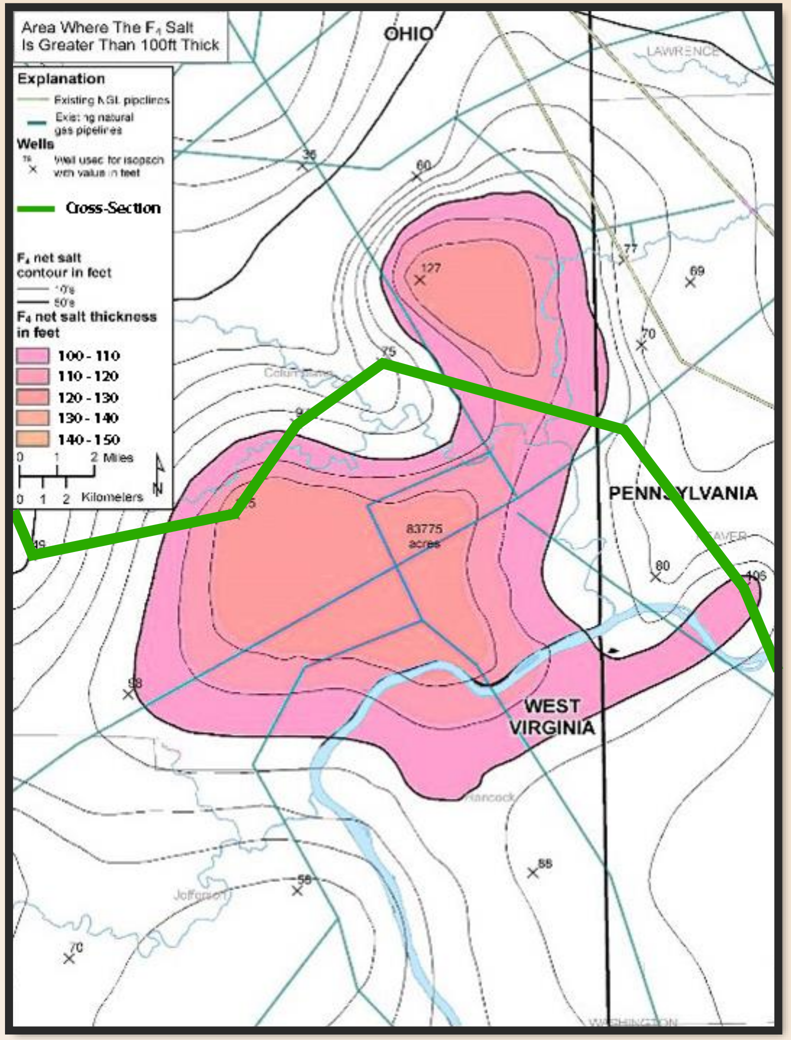
Salt

Interbedded dolomite and anhydrite

Cross Section

AREA 1





Isopach

F4 Salt

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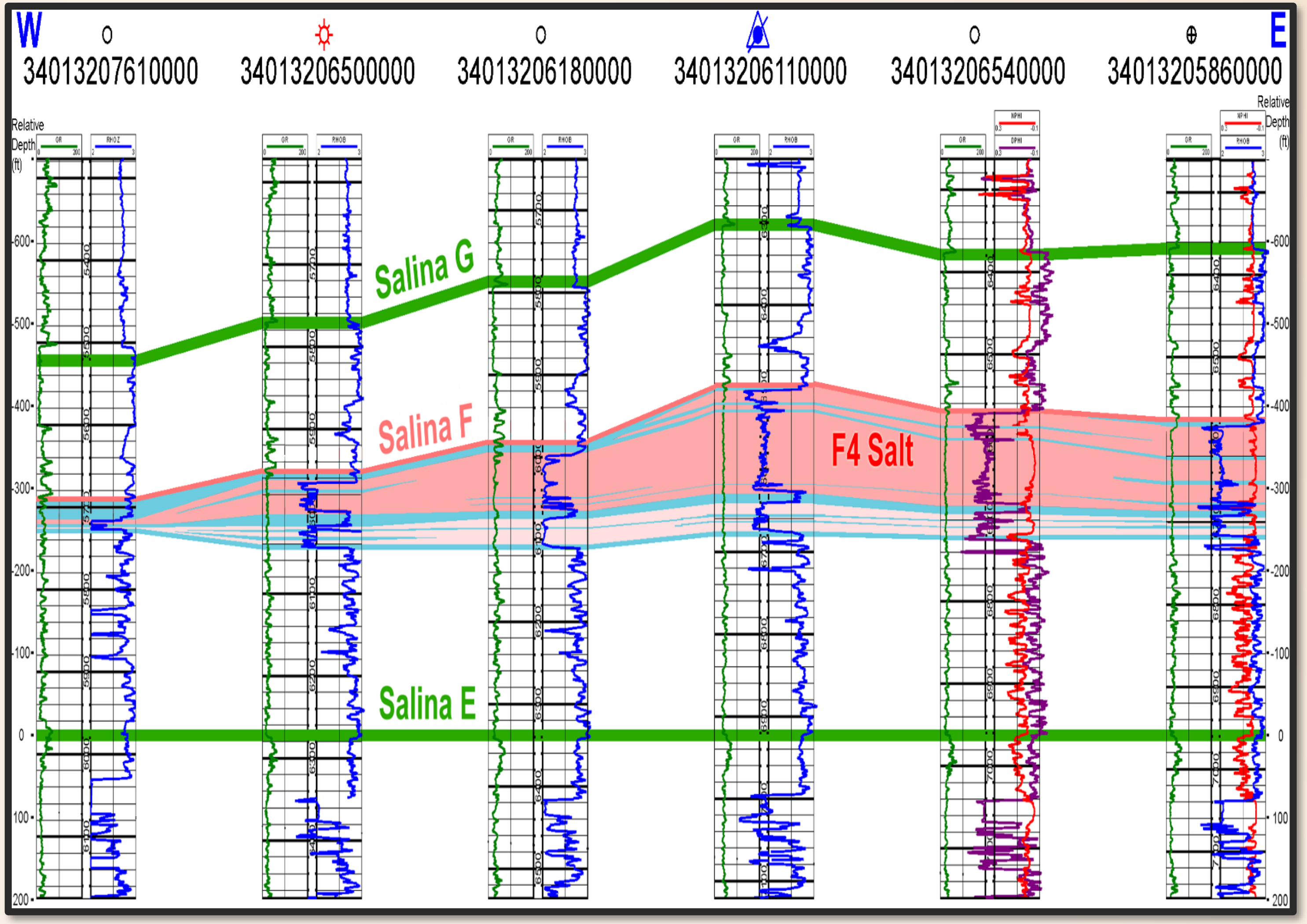
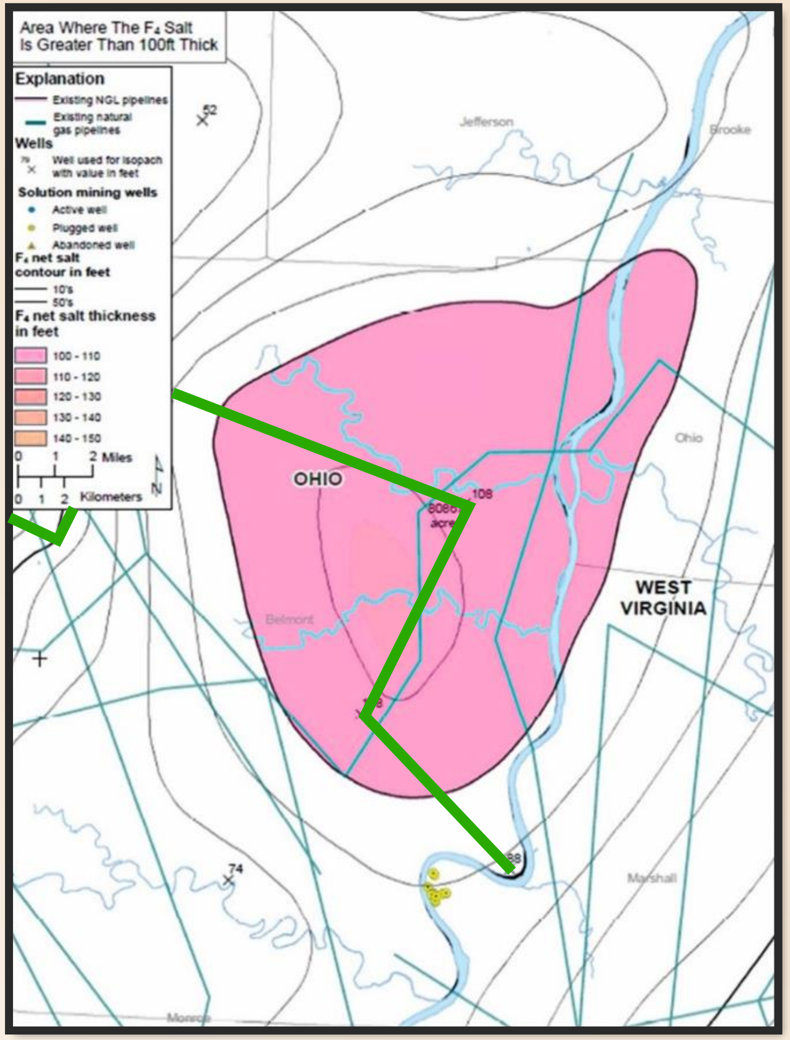
Cross Section

AREA 3



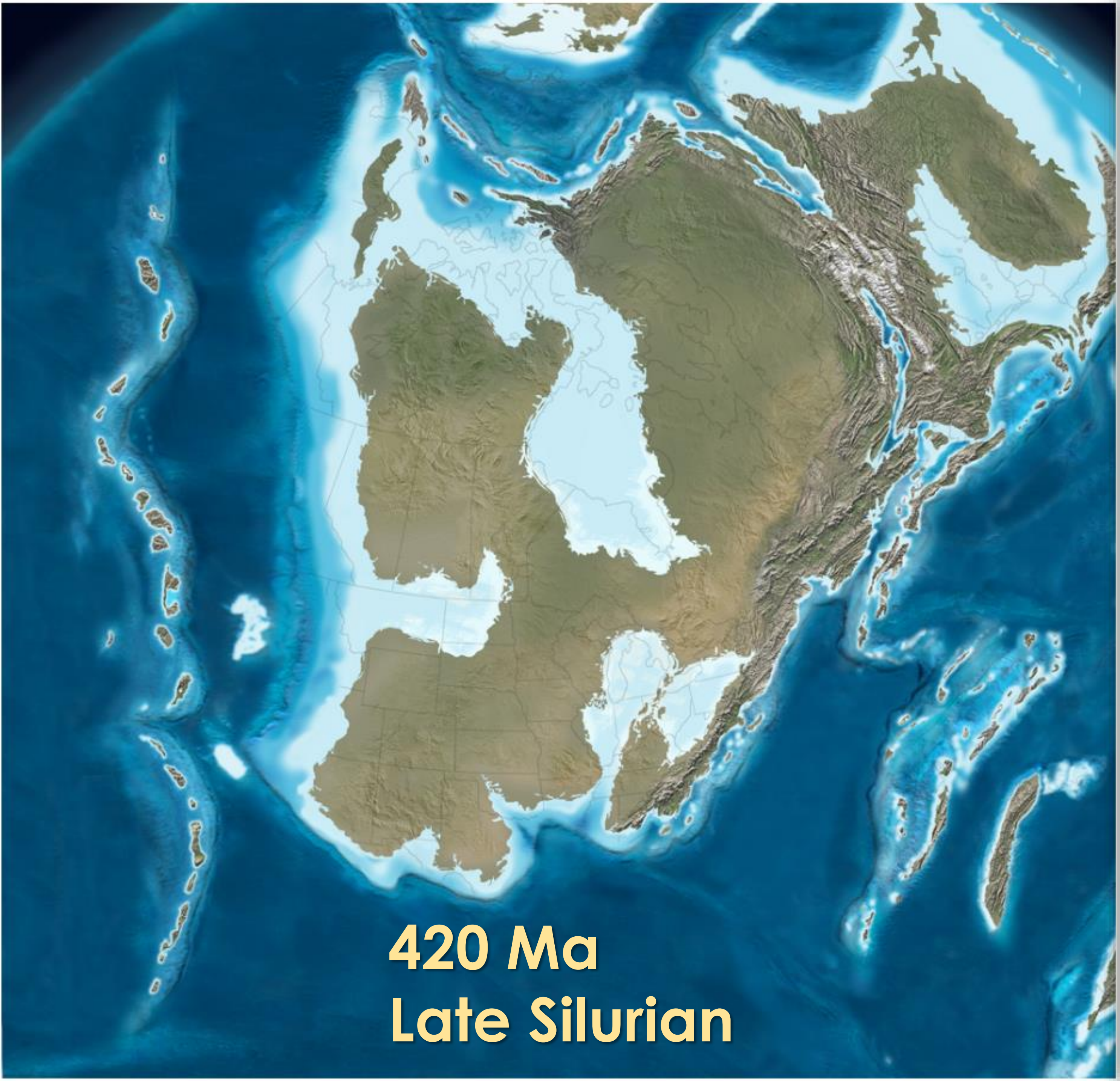


F4 Salt | Salt | Interbedded dolomite and anhydrite

Isopach

SALINA SALT CAVERNS

- Mapped net thickness of upper F4 salt (conservative approach)
- Identified four areas where upper F4 salt >100 ft
- Salt thickness changes abruptly east and west of the main trend
- Anhydrite and dolomite increases outside the 100 ft. footprint
- 20-25 foot lower salt present below the persistent dolomite anhydrite layer
- Important to leave buffer zone between caverns and edge of salt basin
- Pressure, temperature, and cavern shape affect cavern stability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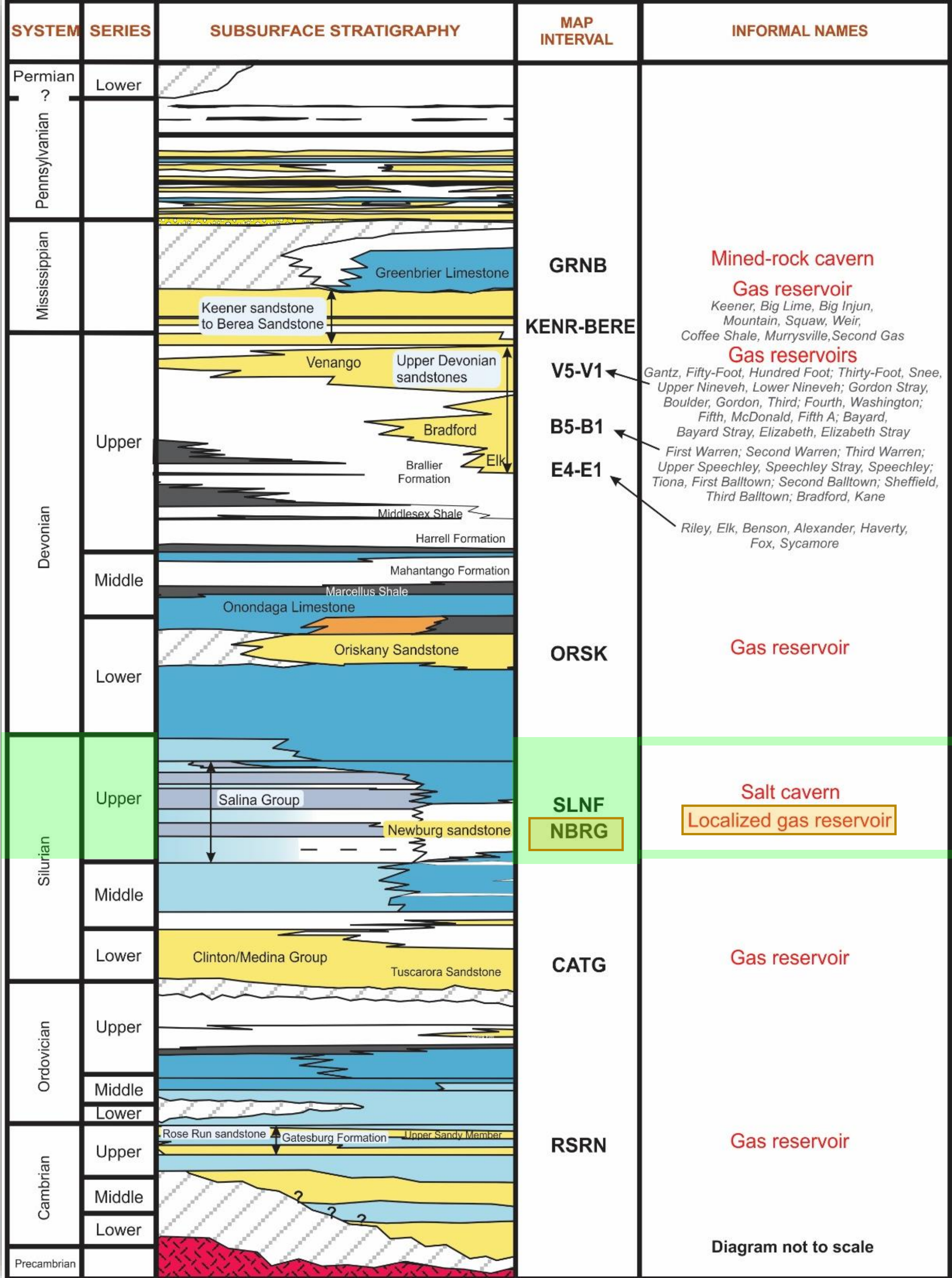
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Lower
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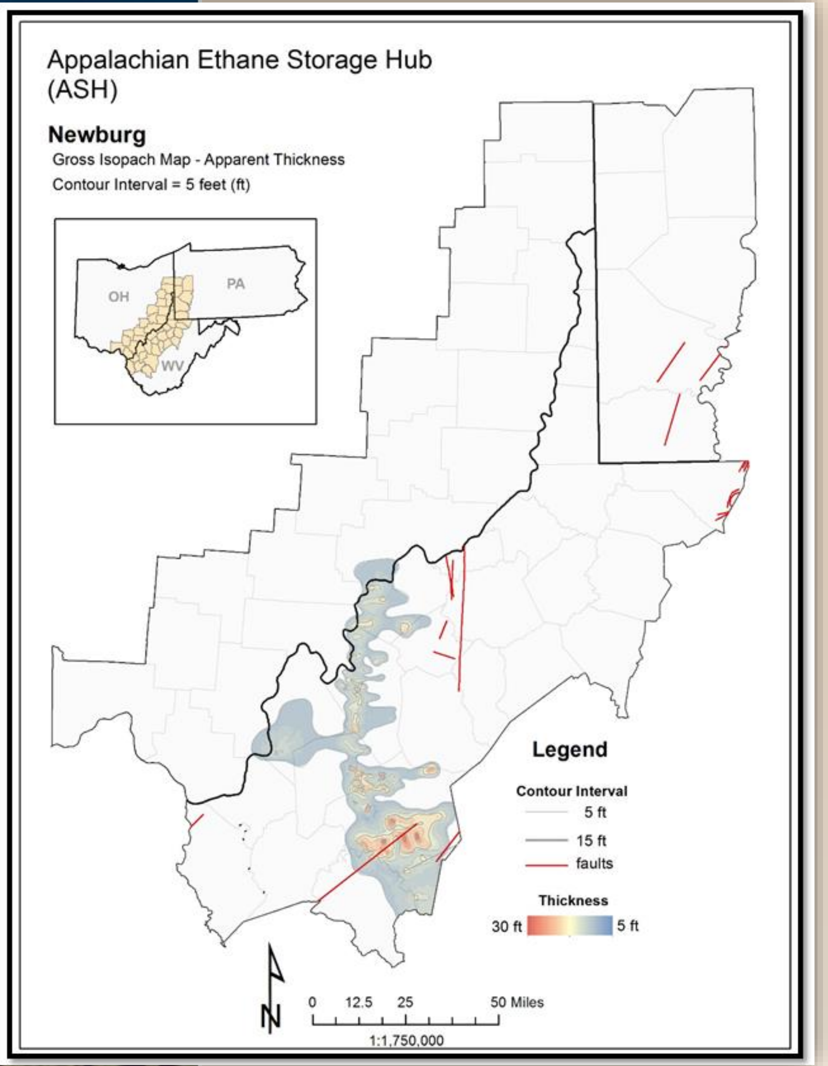
Diagram not to scale

NEWBURG

Modern Analog: U.S. East Coast (Massachusetts) Coastal Sand Bodies



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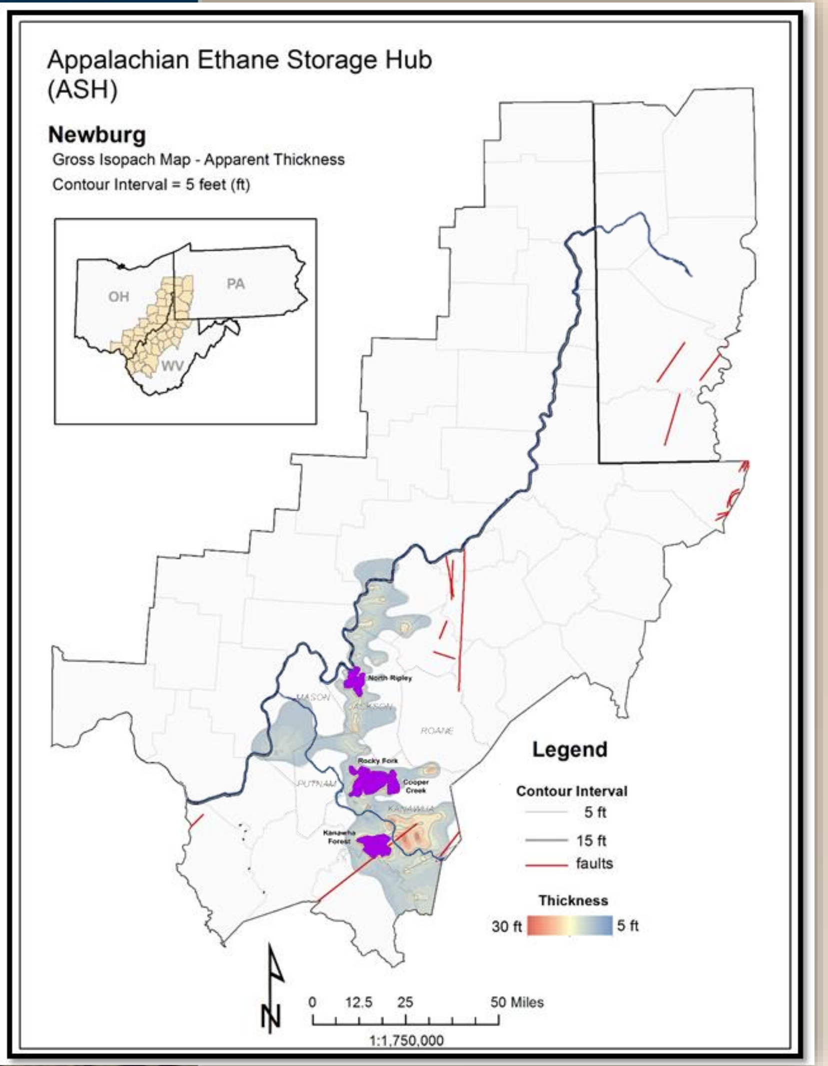

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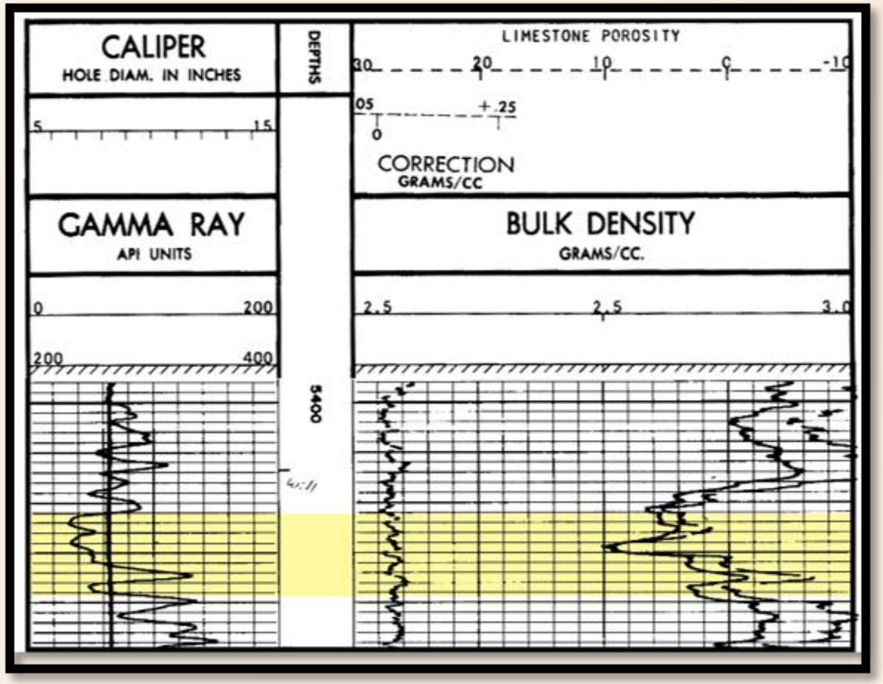
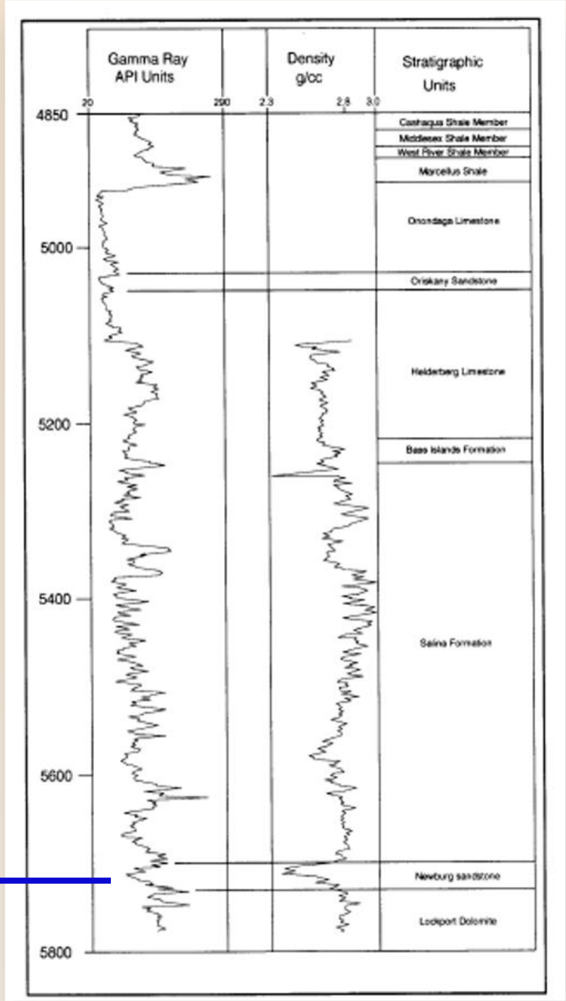
NEWBURG: example of depleted gas fields in a sandstone reservoir

- Porosity / permeability
- Geophysical logs





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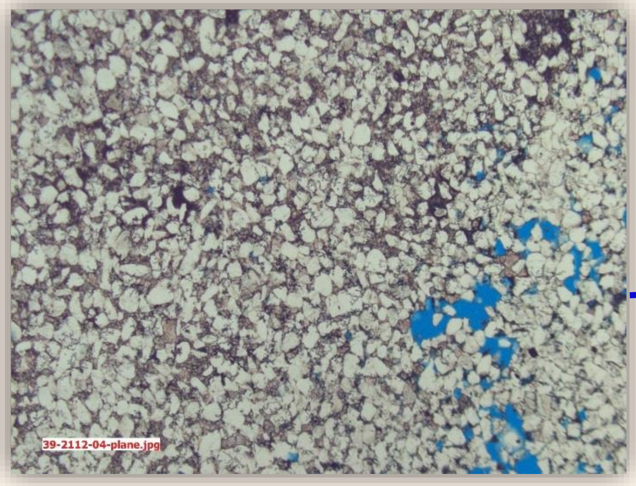
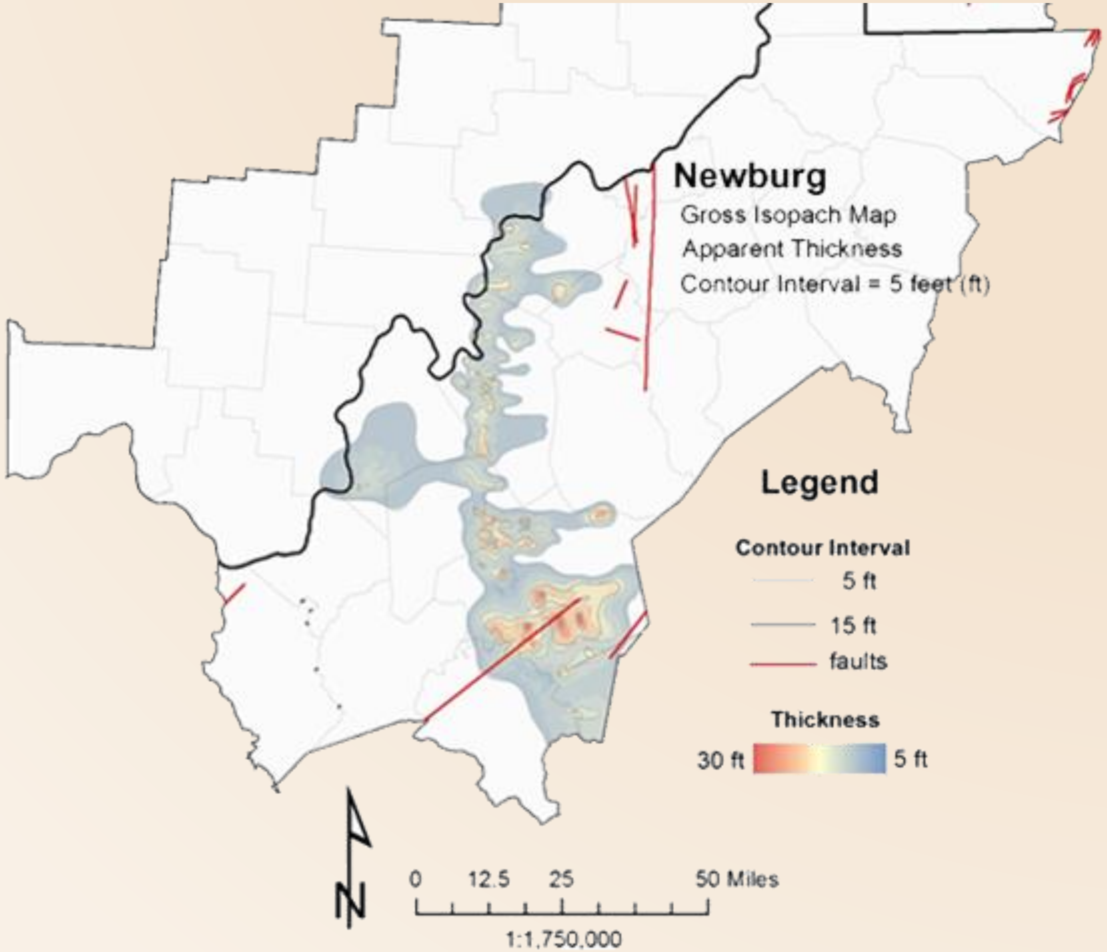
- Thin-section analyses



NEWBURG: example of depleted gas fields in a sandstone reservoir

- Thickness (gross isopach map)
- Areal extent (updip dry holes & wells with salt water downdip delineate container extents)
- Close to pipeline infrastructure
- Seals (upper, lower and lateral)



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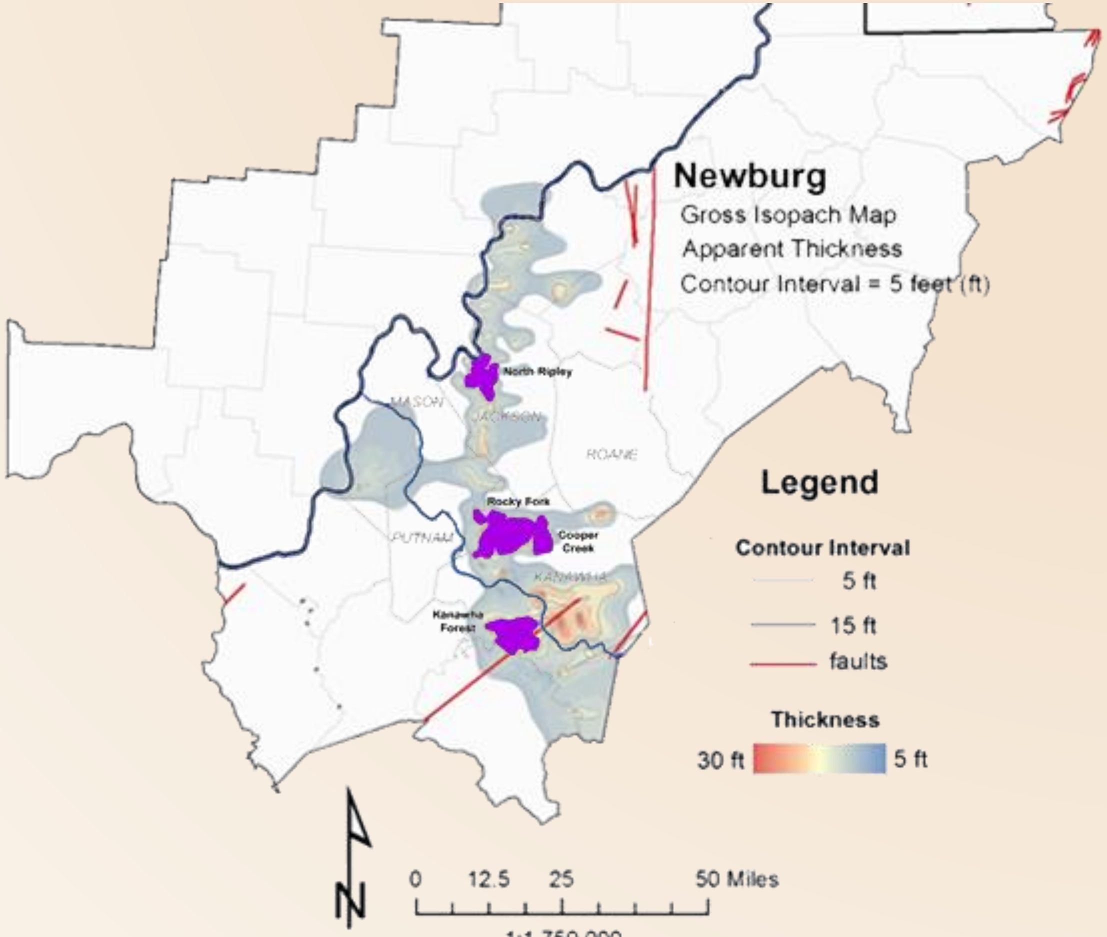

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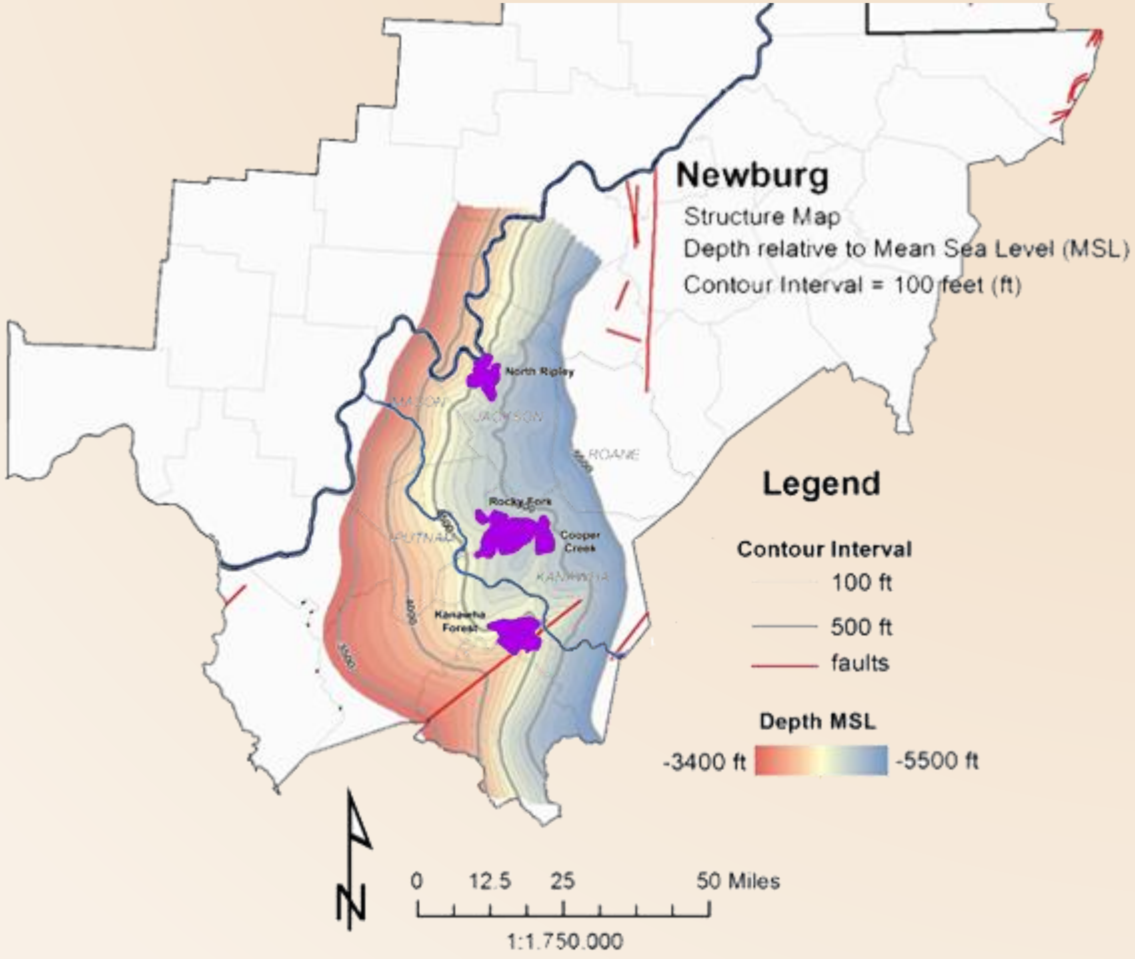

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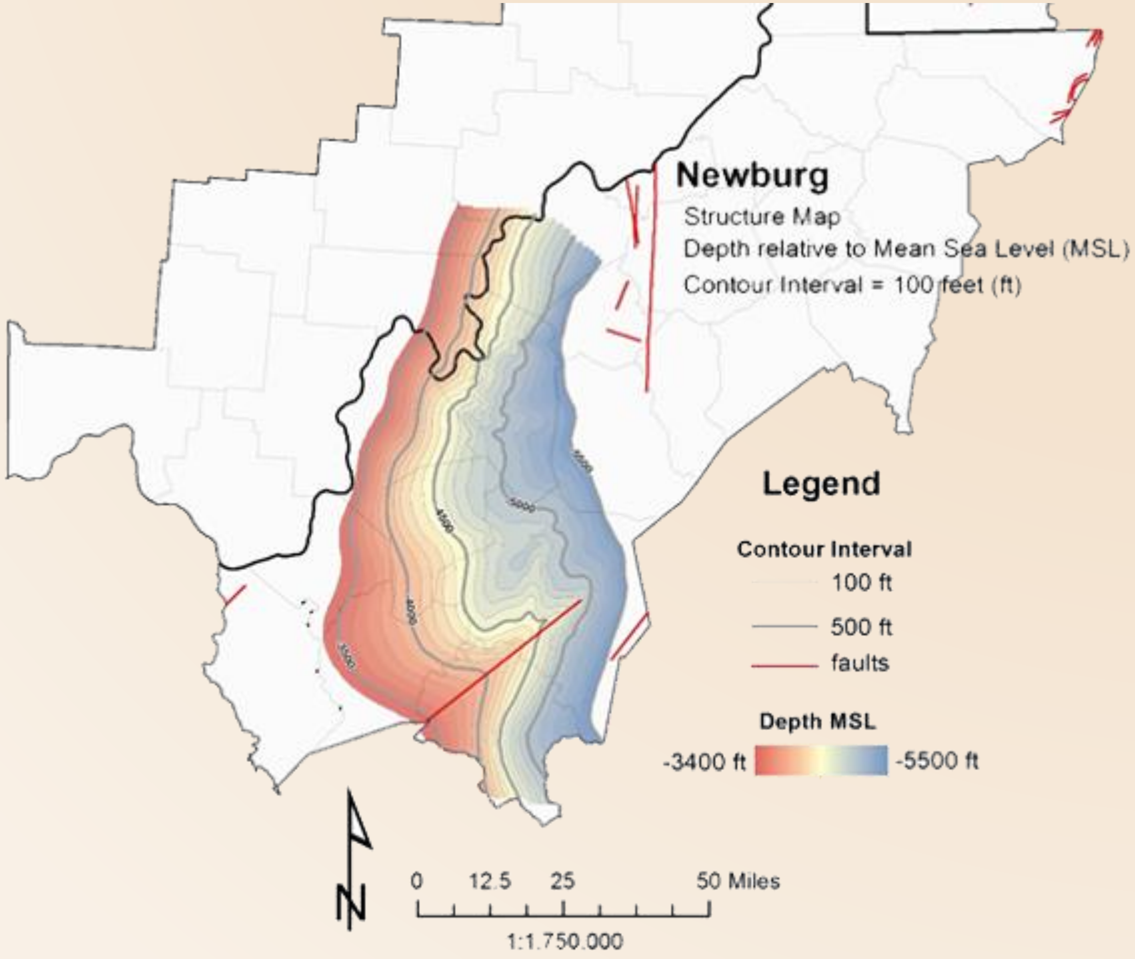
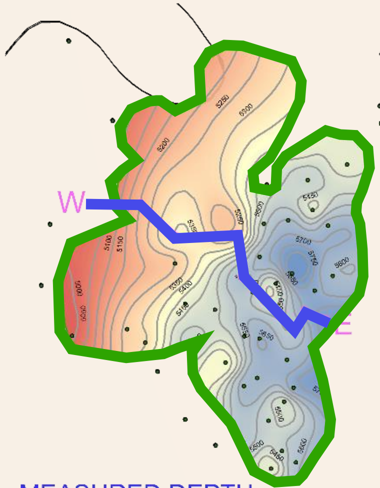
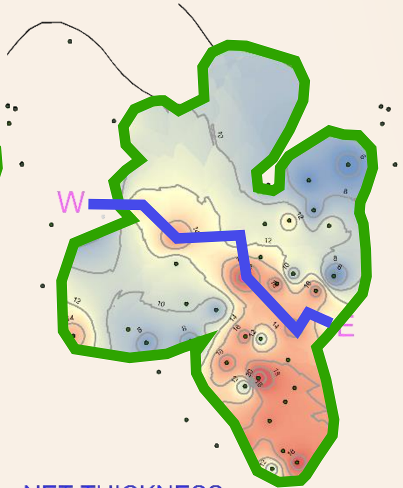


NEWBURG: W-E Cross-Section

North Ripley Field



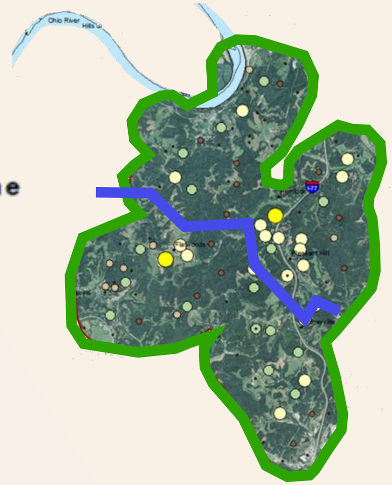
MEASURED DEPTH

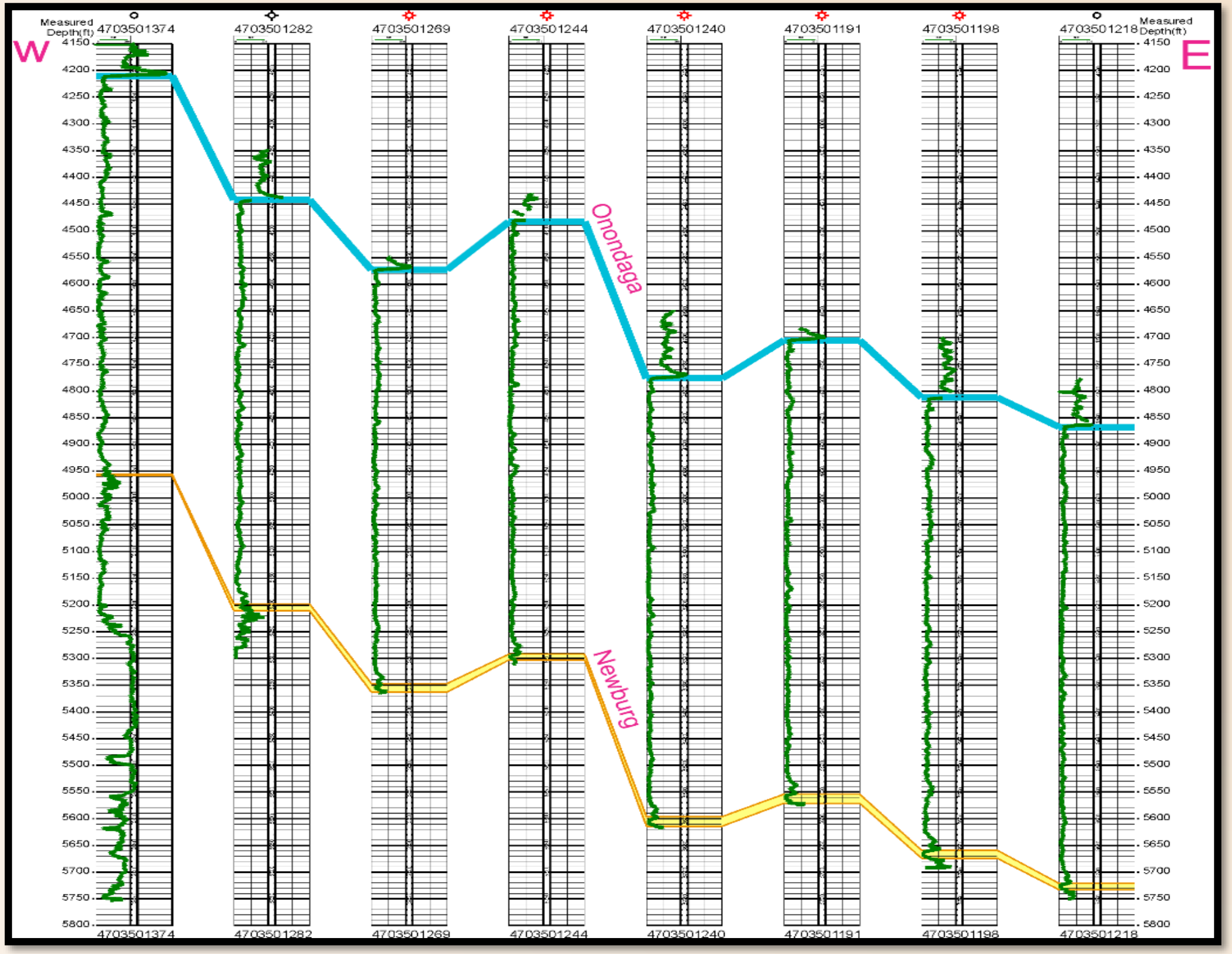


NET THICKNESS

Initial Production Volume (mcf; post-stimulation)

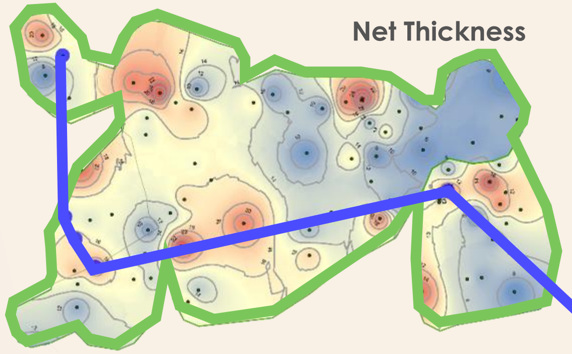
- 0 - 2,500
- 2,500 - 10,000
- 10,000 - 25000
- 25,000 - 50,000
- 50,000 - 100,000
- 100,000 - 170,000



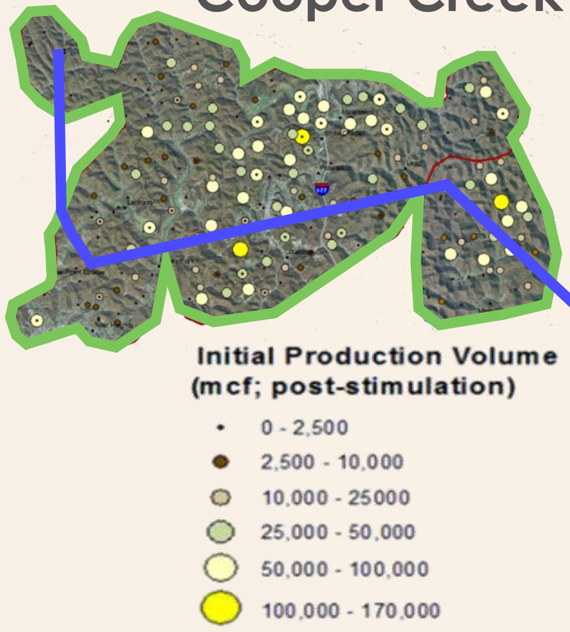


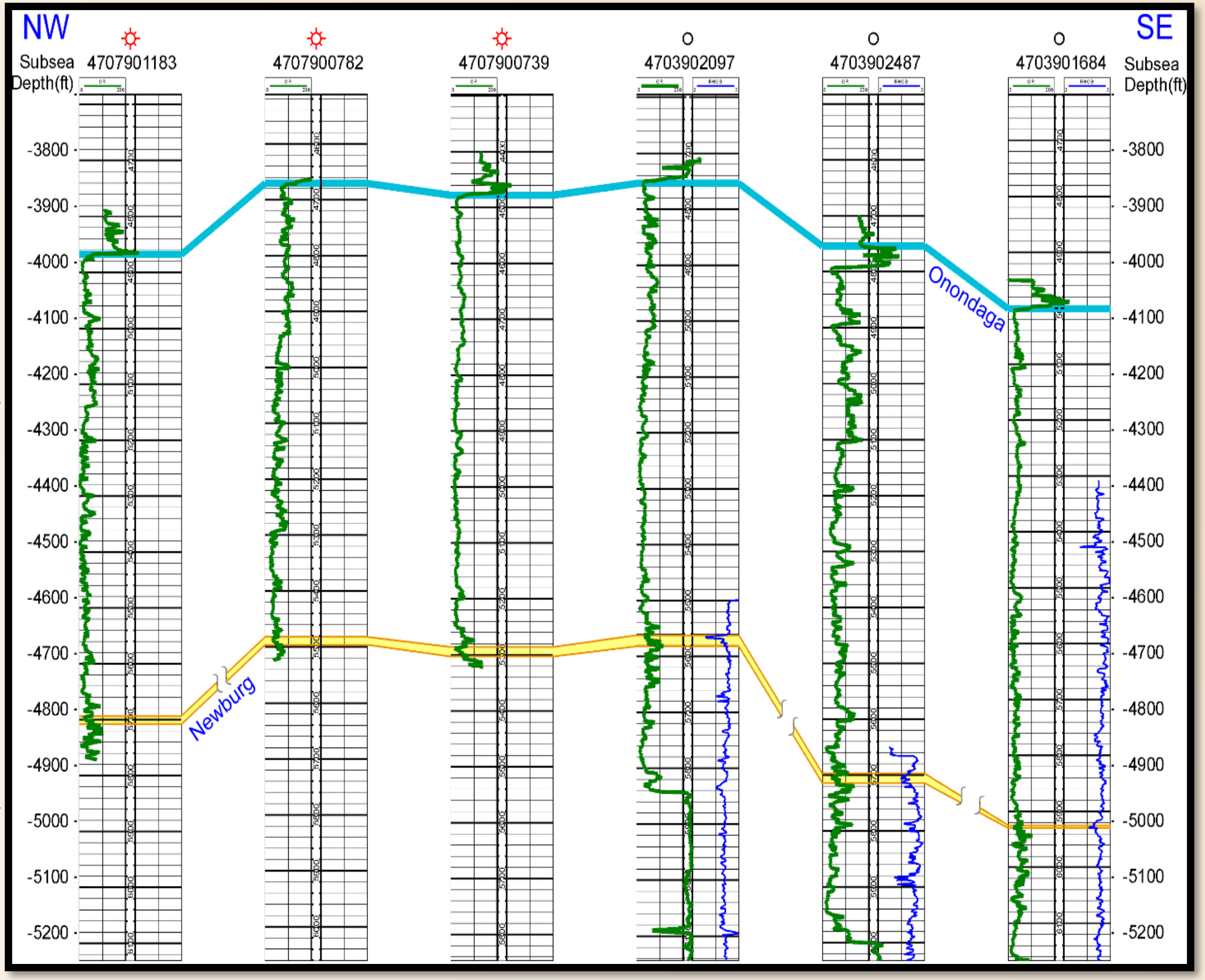
Newburg Sandstone

NEWBURG: NW-SE Cross-Section



Rocky Fork and Cooper Creek





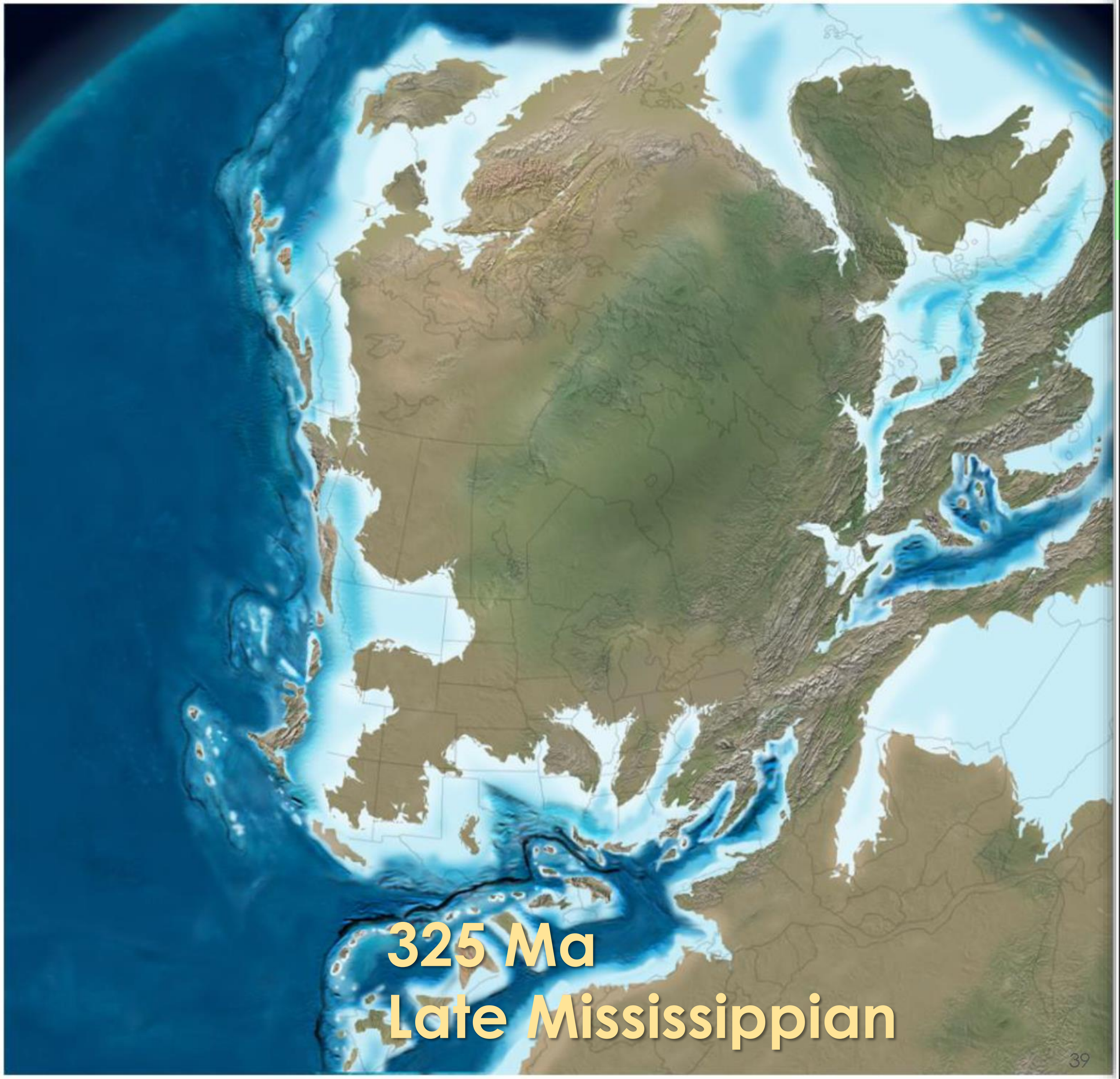
Newburg Sandstone

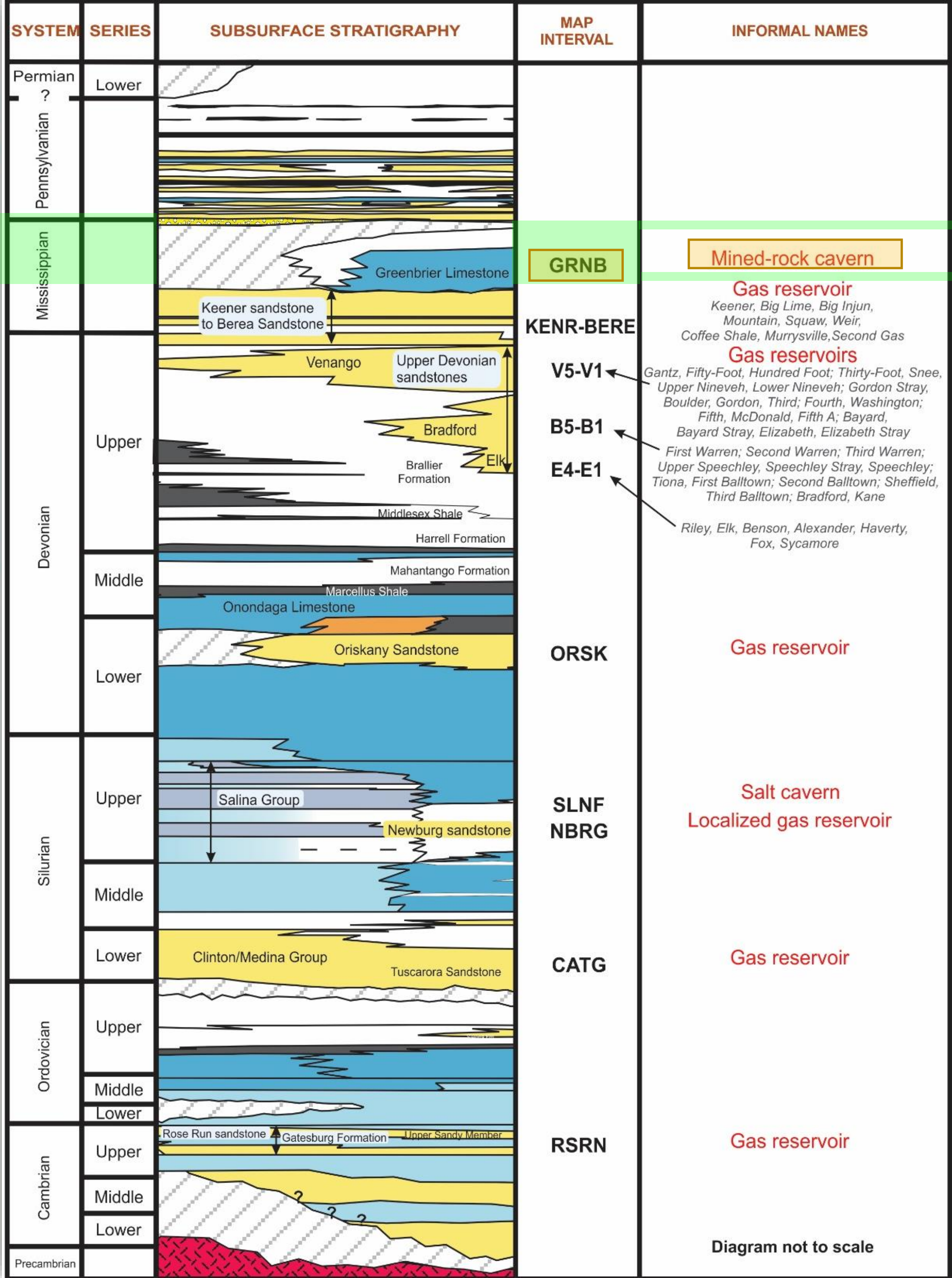
NEWBURG:
Depleted Sandstone Reservoirs

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

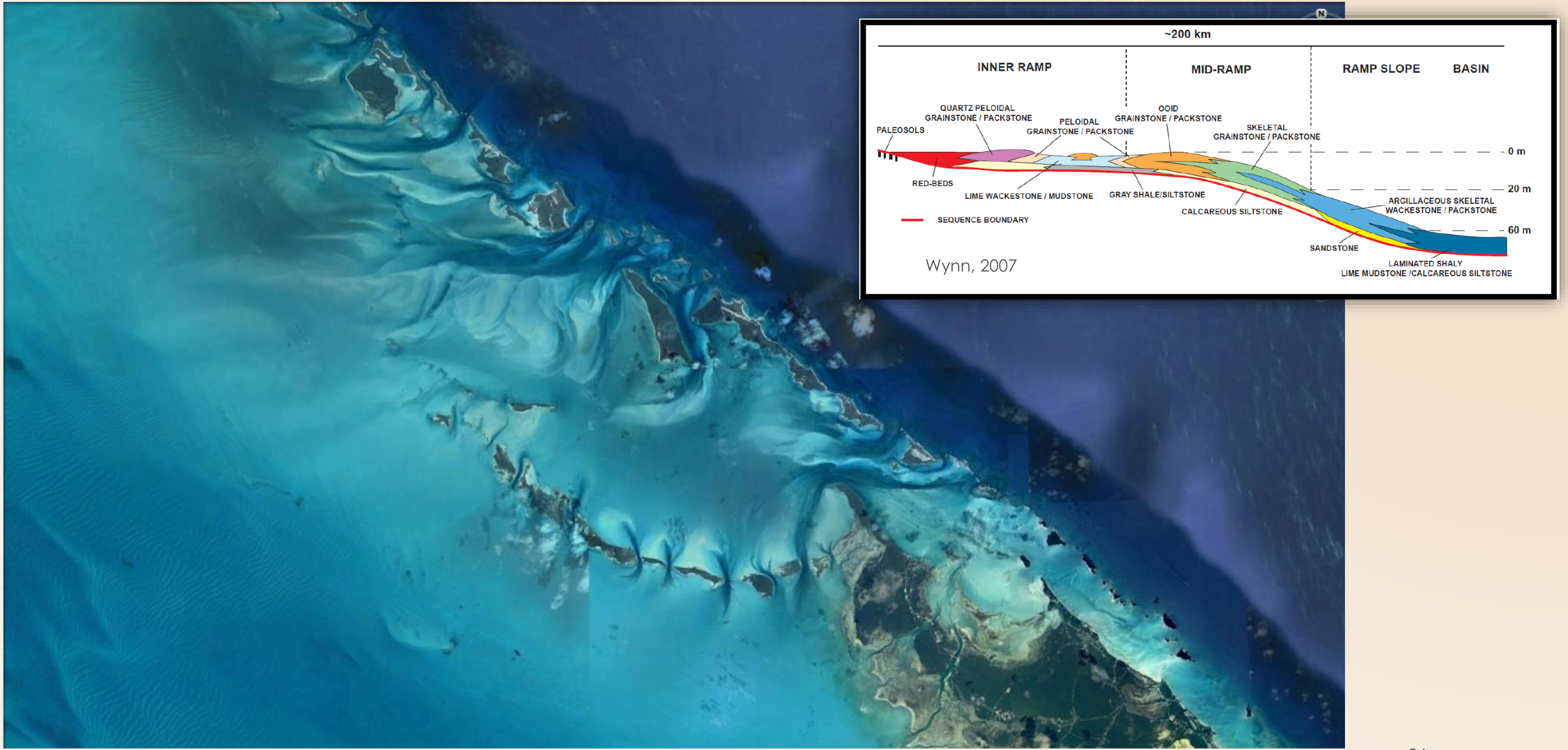
*from Patchen (1996)

- Good peak storage: High porosity and permeability in thin sandstone reservoir yields small container with high deliverability
- Updip dry holes (sand pinchout) & wells with salt water downdip structurally delineate lateral container extents
- Evaporites and carbonates make good vertical seals
- Close to pipeline infrastructure


325 Ma
Late Mississippian


SYSTEM
SERIES
SUBSURFACE STRATIGRAPHY
MAP INTERVAL
INFORMAL NAMES
Permian
?
Lower
Pennsylvanian
Mississippian
Greenbrier Limestone
GRNB
Mined-rock cavern
Keener sandstone to Berea Sandstone
KENR-BERE
Gas reservoir
Keener, Big Lime, Big Injun, Mountain, Squaw, Weir, Coffee Shale, Murrysville, Second Gas
Devonian
Upper
Venango
Upper Devonian sandstones
V5-V1
Gas reservoirs
Gantz, Fifty-Foot, Hundred Foot; Thirty-Foot, Snee, Upper Nineveh, Lower Nineveh; Gordon Stray, Boulder, Gordon, Third; Fourth, Washington; Fifth, McDonald, Fifth A; Bayard, Bayard Stray, Elizabeth, Elizabeth Stray
Bradford
B5-B1
First Warren; Second Warren; Third Warren; Upper Speechley, Speechley Stray, Speechley; Tiona, First Balltown; Second Balltown; Sheffield, Third Balltown; Bradford, Kane
Brallier Formation
Elk
E4-E1
Riley, Elk, Benson, Alexander, Haverty, Fox, Sycamore
Middlesex Shale
Harrell Formation
Middle
Mahantango Formation
Marcellus Shale
Onondaga Limestone
Lower
Oriskany Sandstone
ORSK
Gas reservoir
Silurian
Upper
Salina Group
Newburg sandstone
SLNF
NBRG
Salt cavern
Localized gas reservoir
Middle
Lower
Clinton/Medina Group
Tuscarora Sandstone
CATG
Gas reservoir
Ordovician
Upper
Middle
Lower
Cambrian
Upper
Rose Run sandstone
Gatesburg Formation
Upper Sandy Member
RSRN
Gas reservoir
Middle
Lower
Precambrian
Diagram not to scale

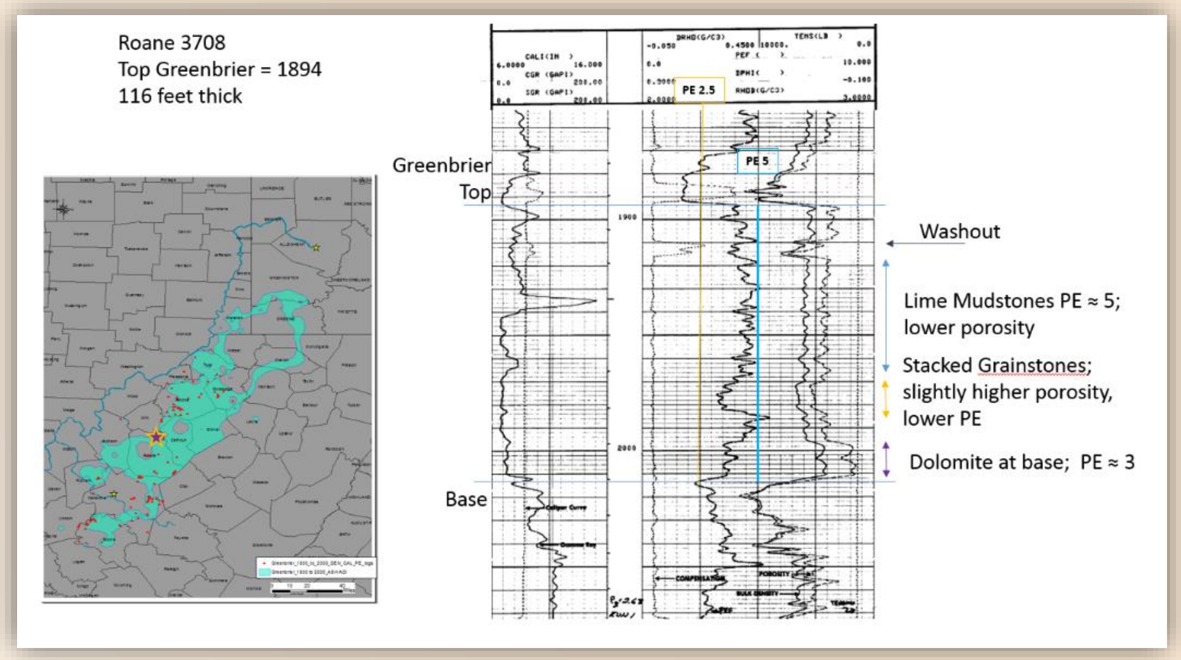
Modern Analog: Bahama Banks Carbonate Platform

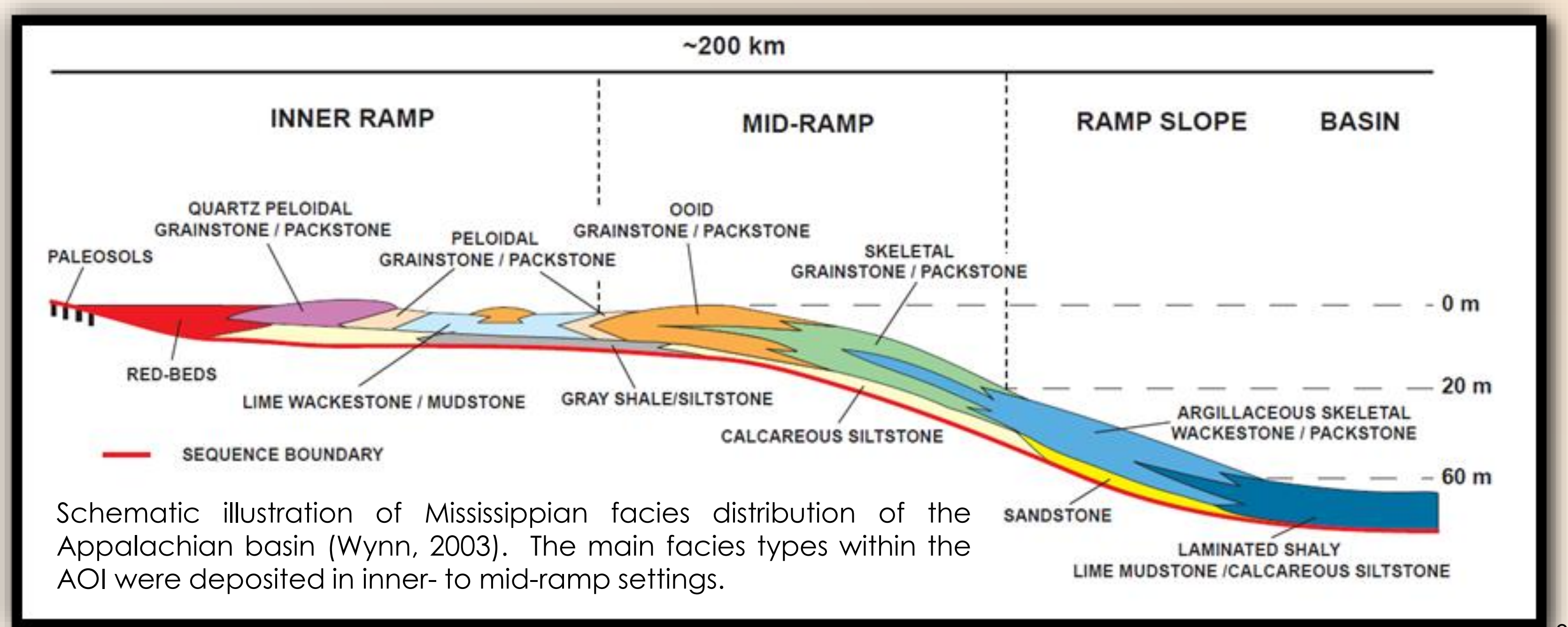


Wynn, 2007

GREENBRIER LIMESTONE (MINED-ROCK CAVERNS)

- Characterize facies using geophysical logs (RHOB, DPHI, PE) and drillers' descriptions
- Carbonate ramp environment of deposition

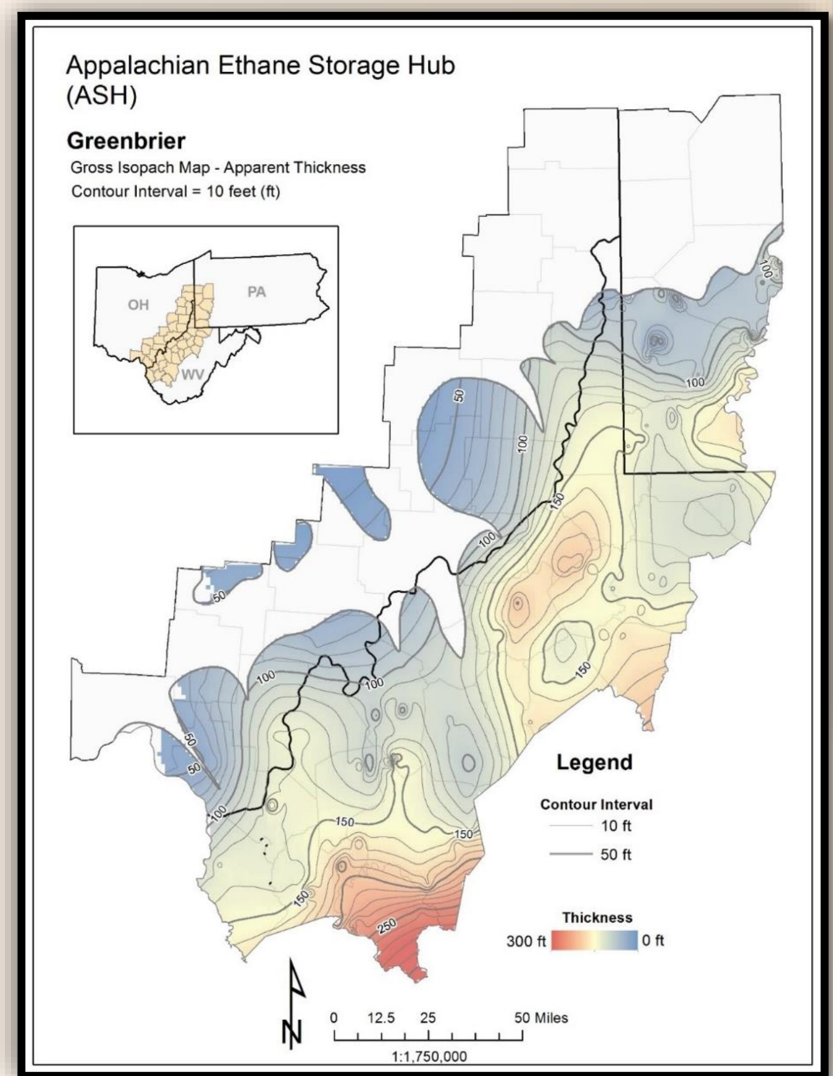


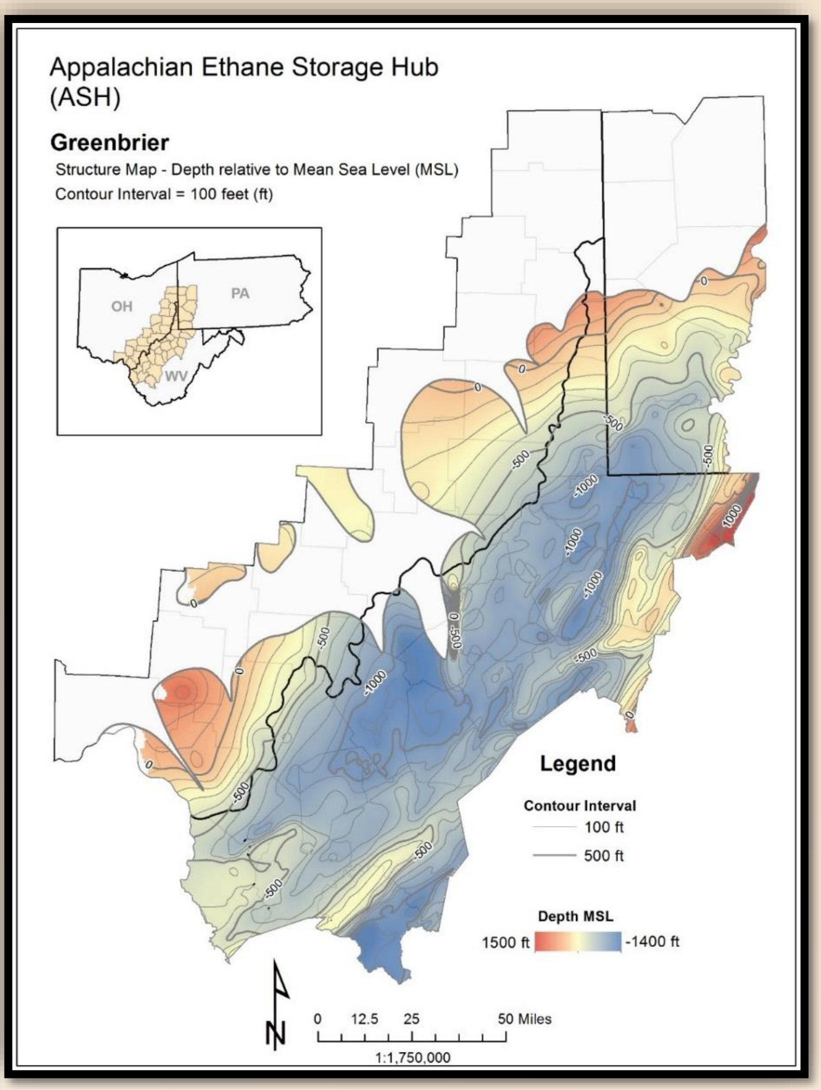


Schematic illustration of Mississippian facies distribution of the Appalachian basin (Wynn, 2003). The main facies types within the AOI were deposited in inner- to mid-ramp settings.

GREENBRIER LIMESTONE (MINED-ROCK CAVERNS)

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





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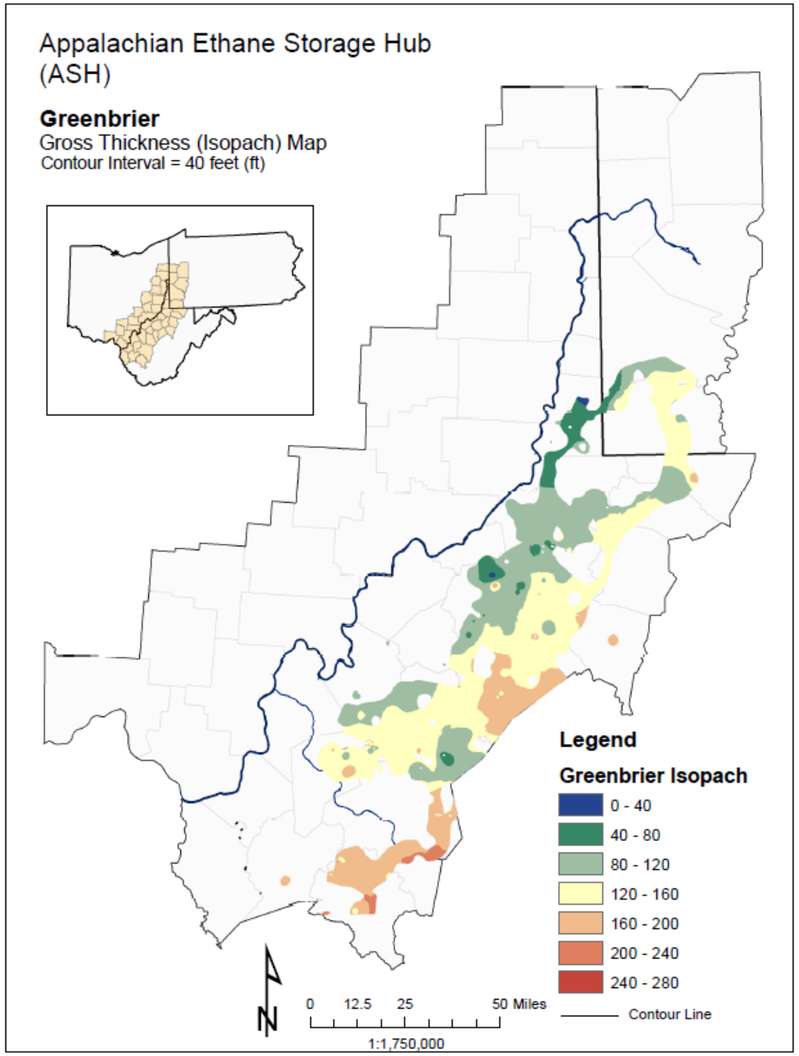
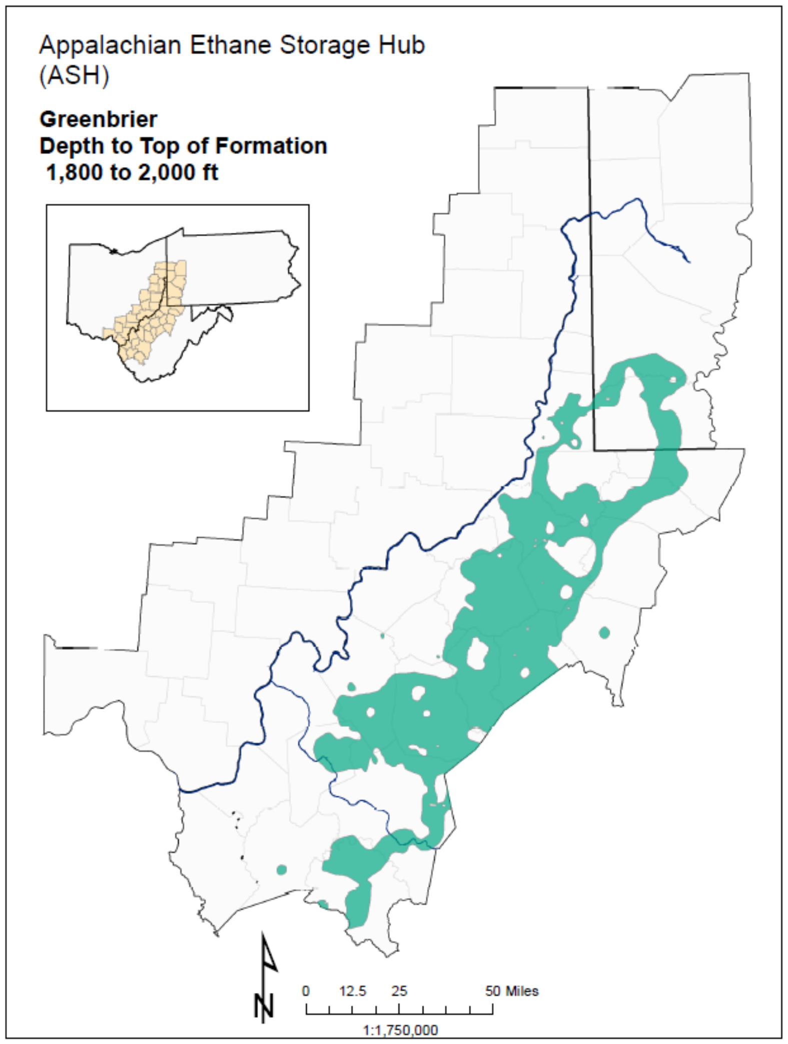
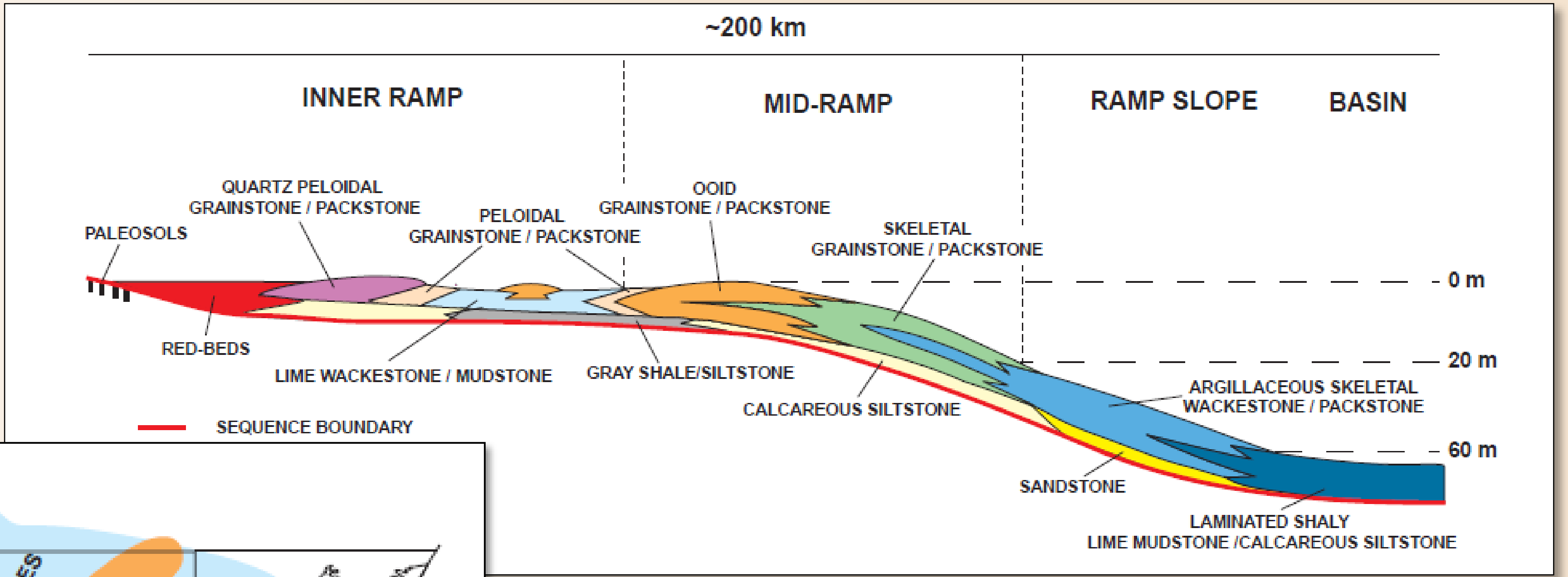
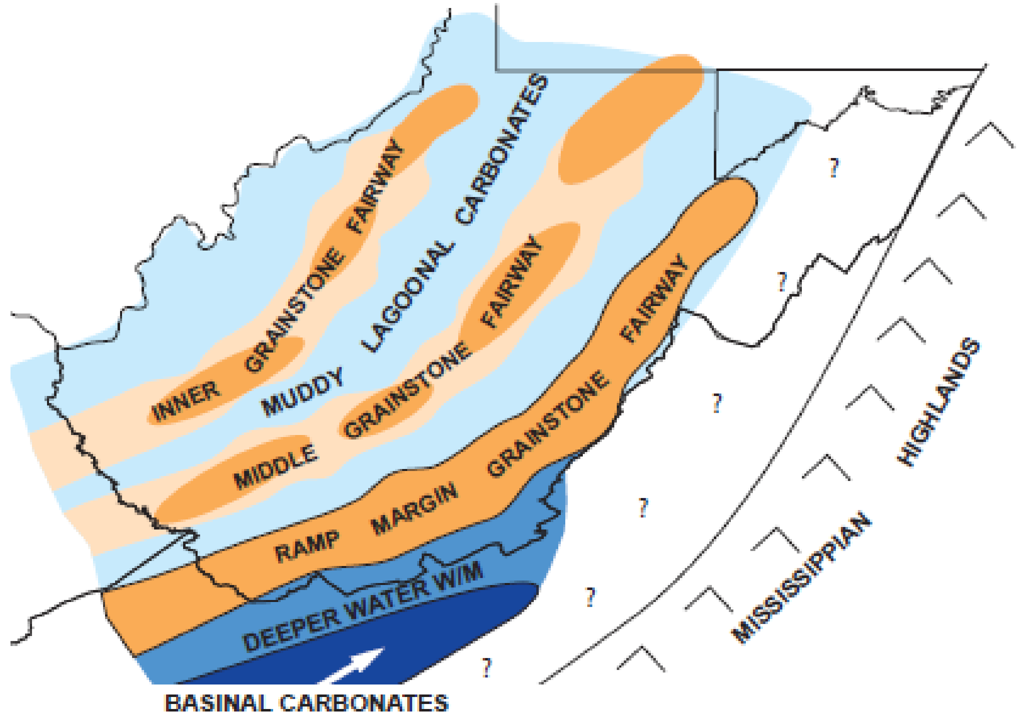
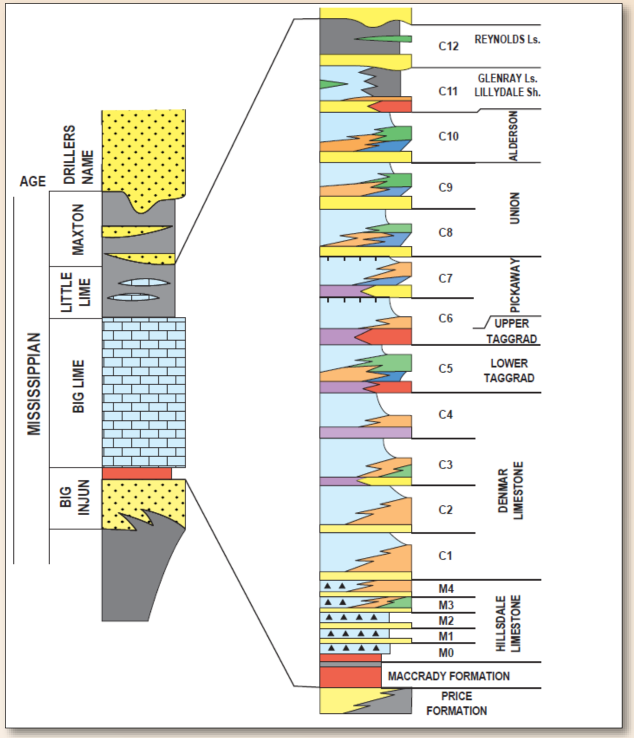








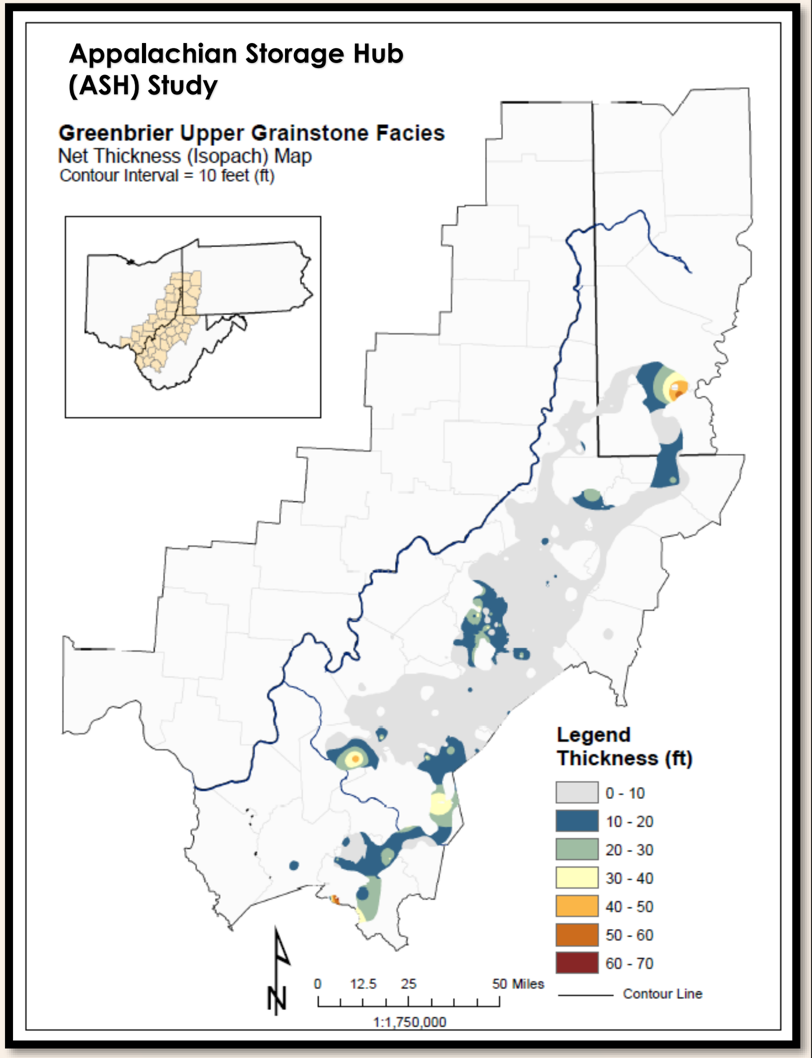
Facies Model for Highstand System

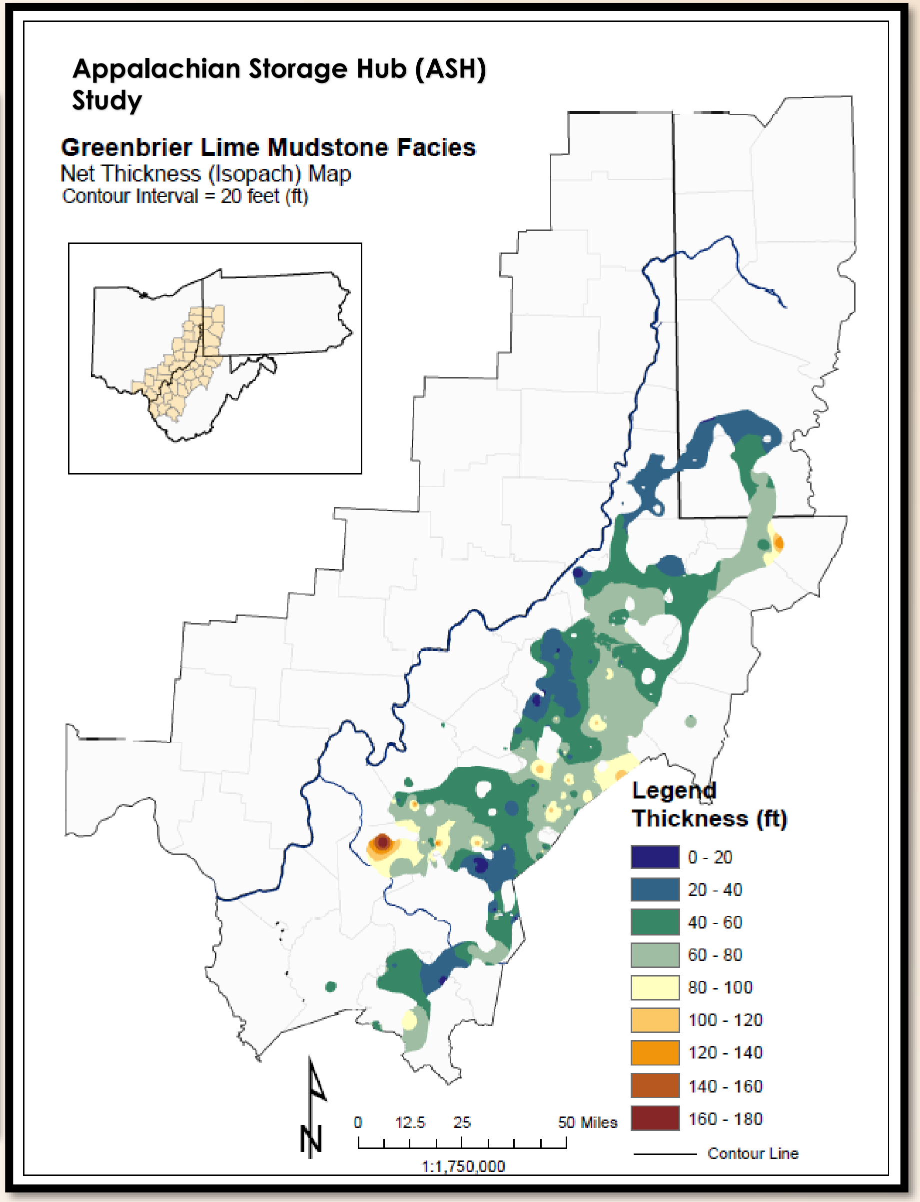


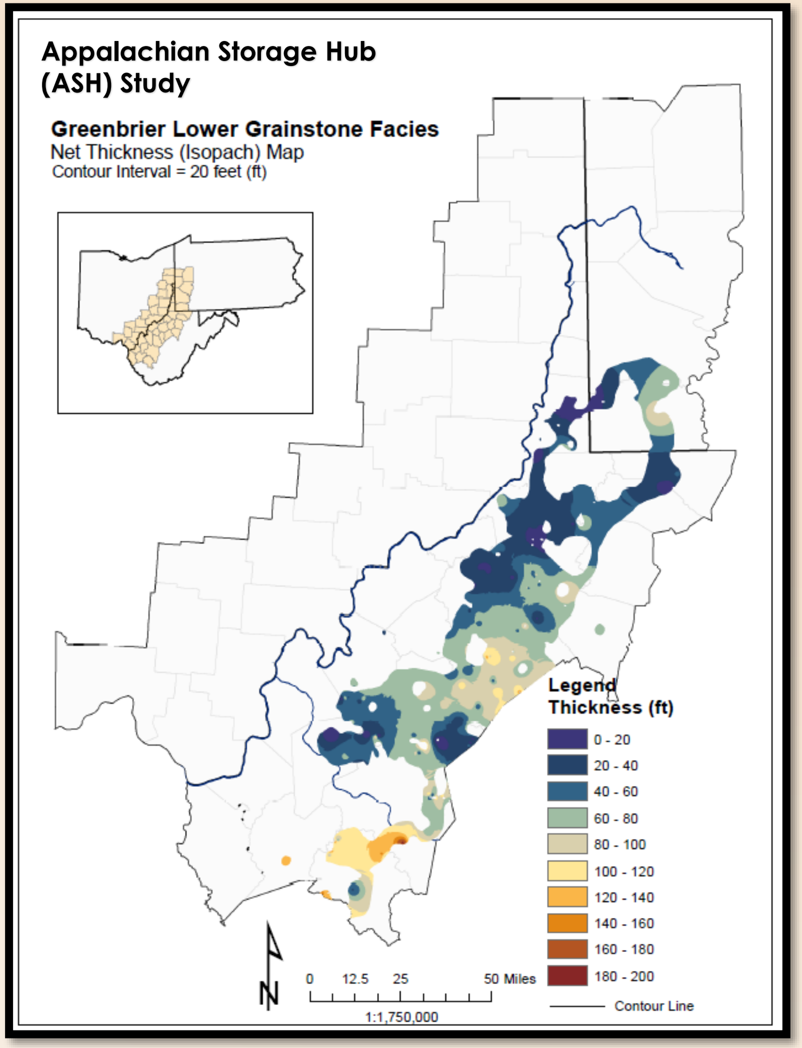
GREENBRIER MINED-ROCK CAVERNS

- Identified three main facies; mapped net thickness of each
  - Upper grainstone (top seal)
  - Lime mudstone (mine)
  - Lower grainstone (bottom seal)

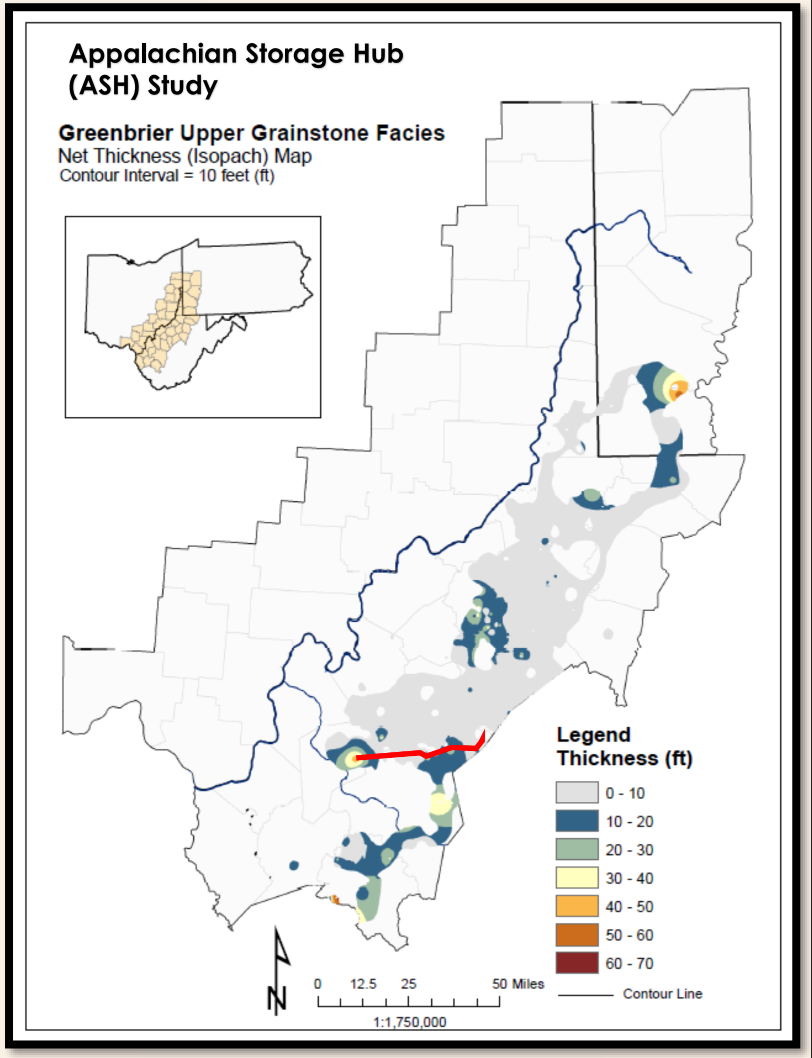
GREENBRIER LIMESTONE – THREE FACIES

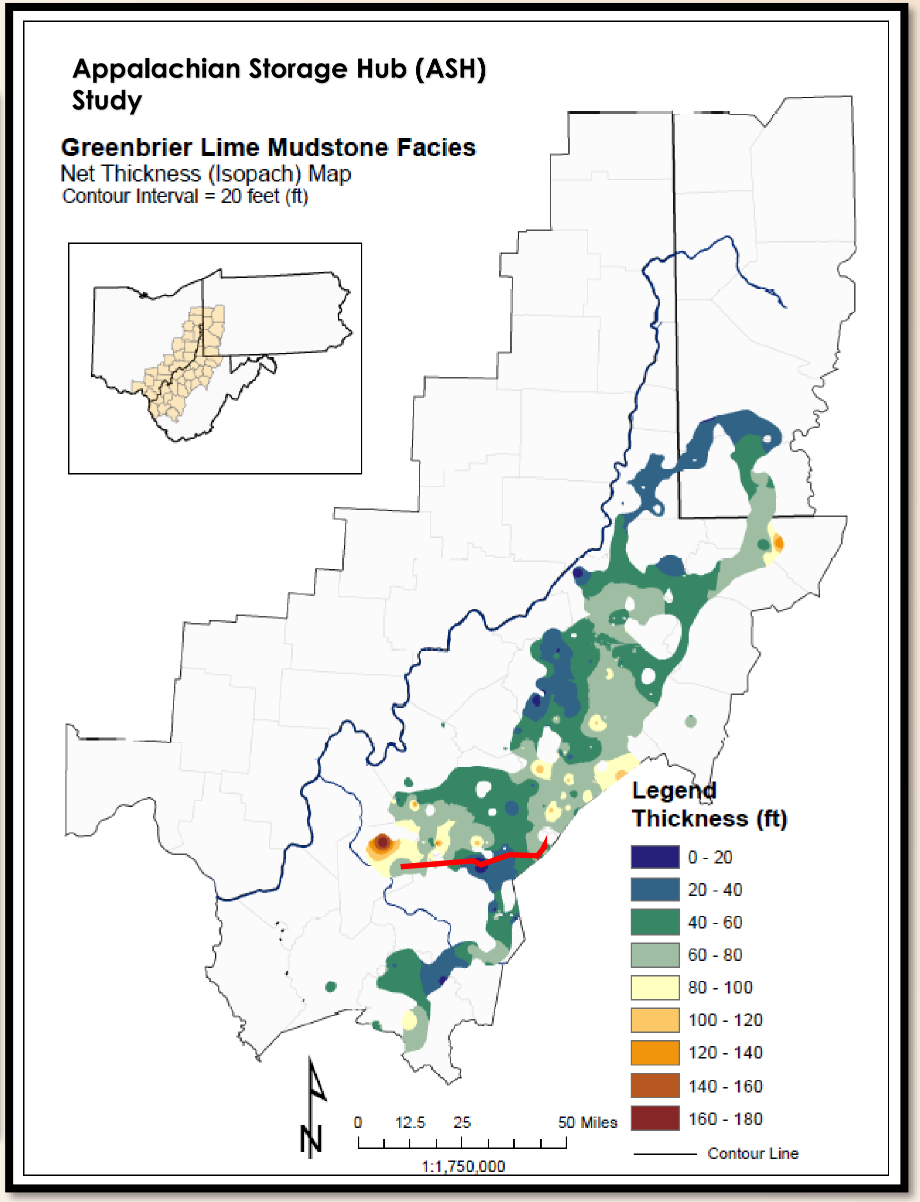


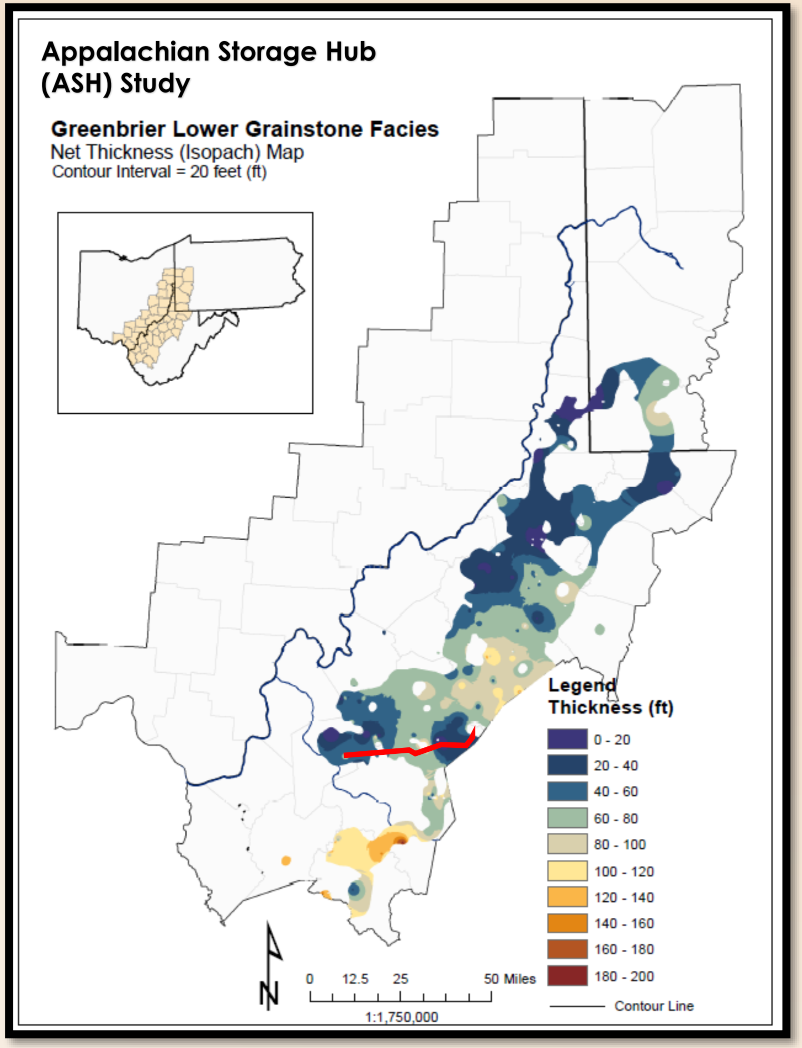




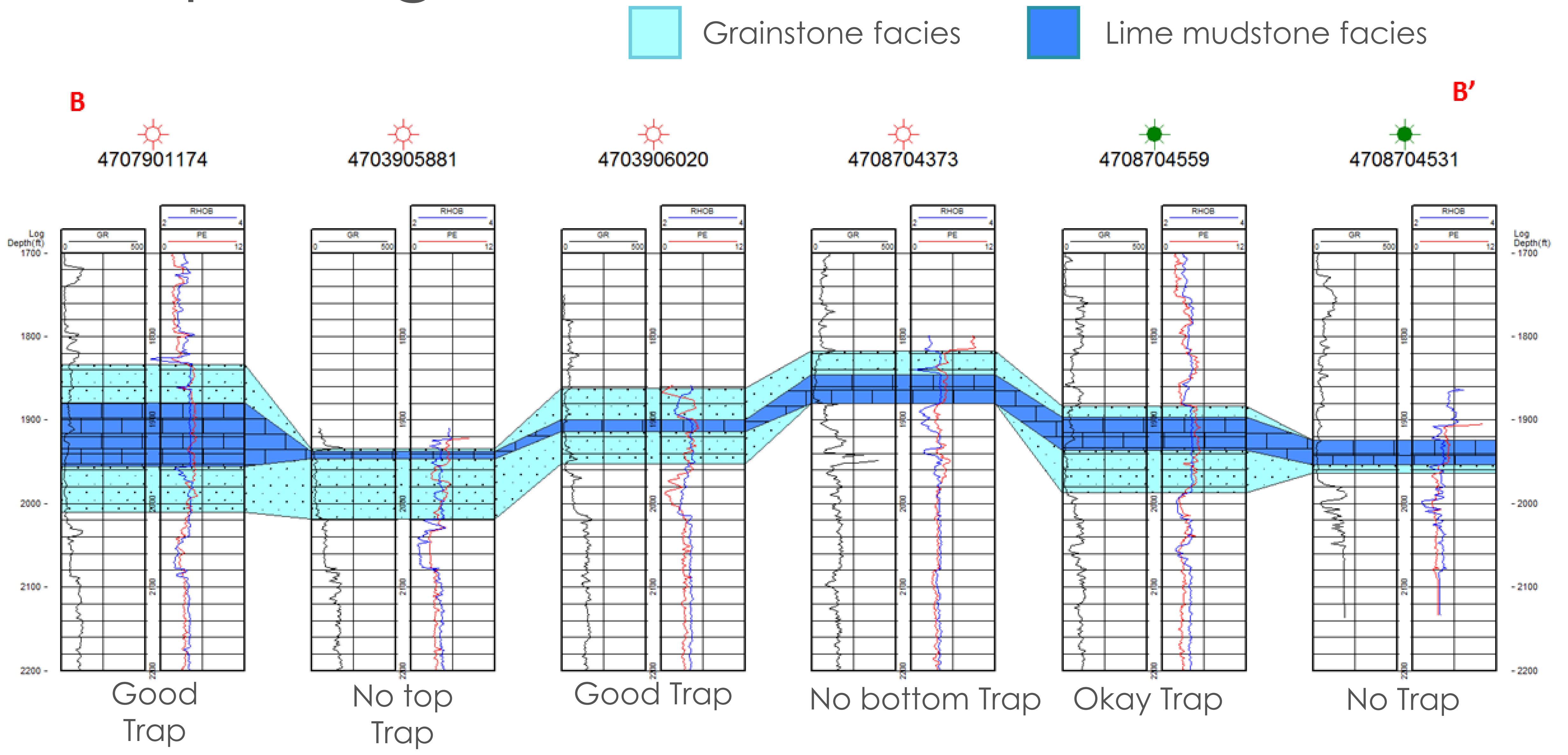
GREENBRIER LIMESTONE – THREE FACIES







Trap integrities of Mined Rock Fields



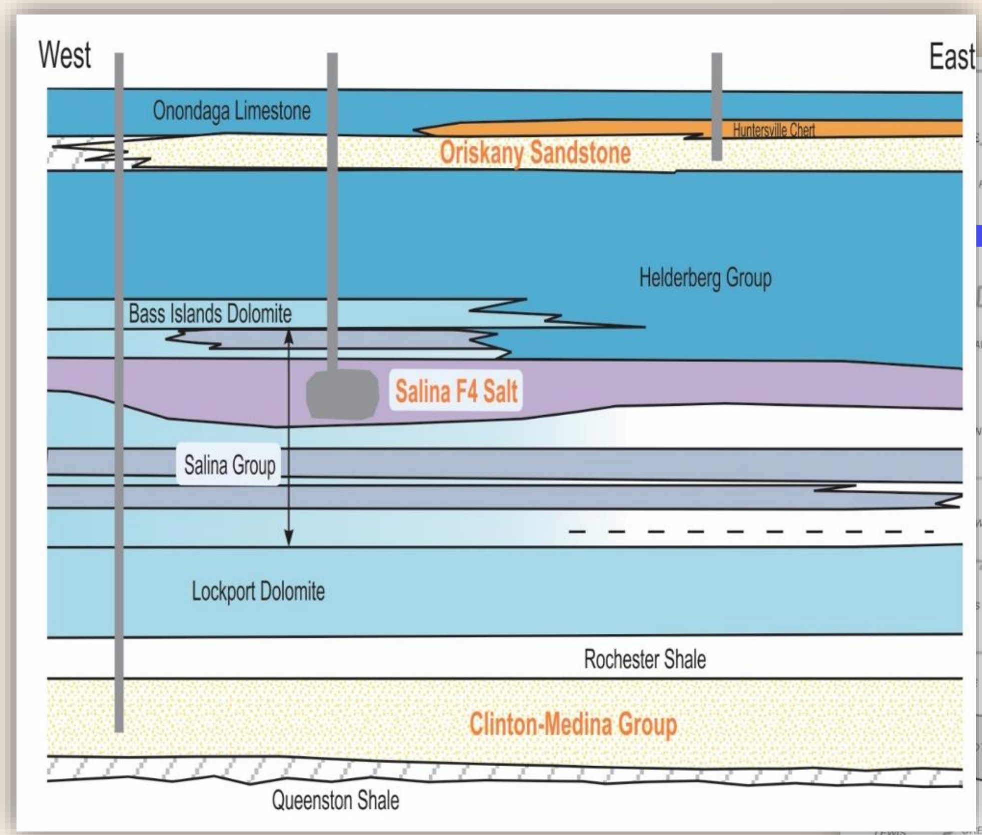
MINED-ROCK CAVERNS: GREENBRIER LIMESTONE

- Not all limestones are the same
- They differ in grain size, pore space, etc. due to variations in where and how they were deposited
- Our goal was to find the best type of limestone for storage – lithology is important!
- A mined-rock cavern needs a good seal, so overlying/underlying unit properties are also important

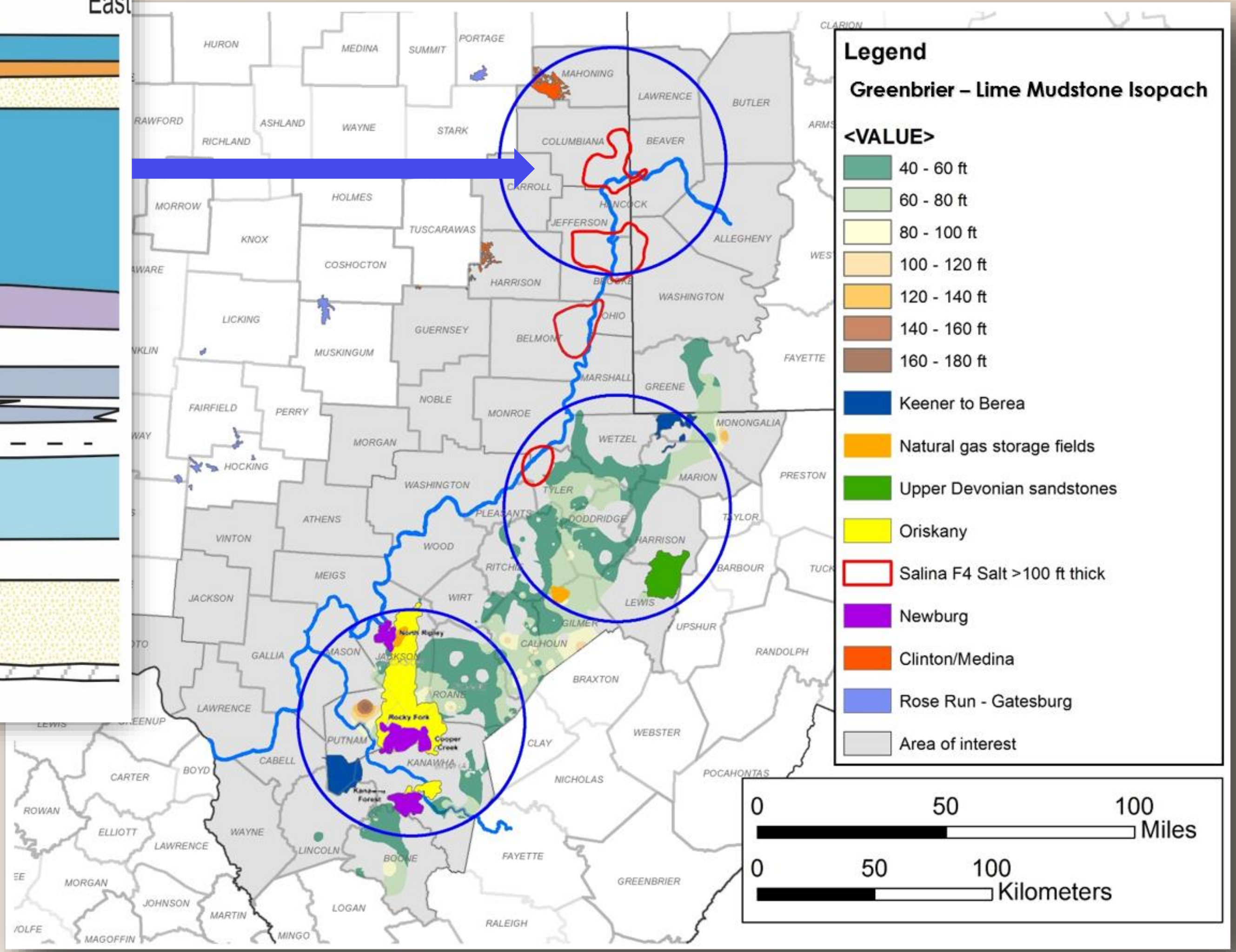
SUMMARY - POINTS TO CONSIDER

- Examined three categories of storage options, mined caverns, solution caverns, depleted siliclastic reservoirs
- 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
- Optimal reservoir types may (or may not) be co-located above or below one another

CORRELATION DIAGRAM



AREA OF INTEREST



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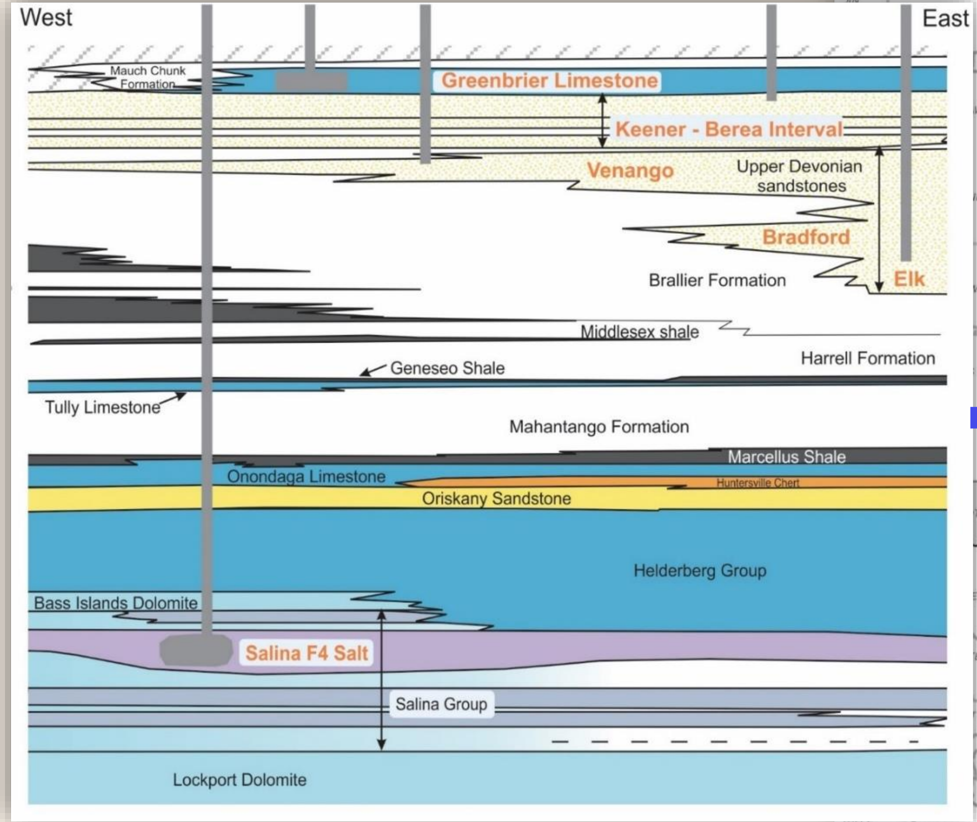

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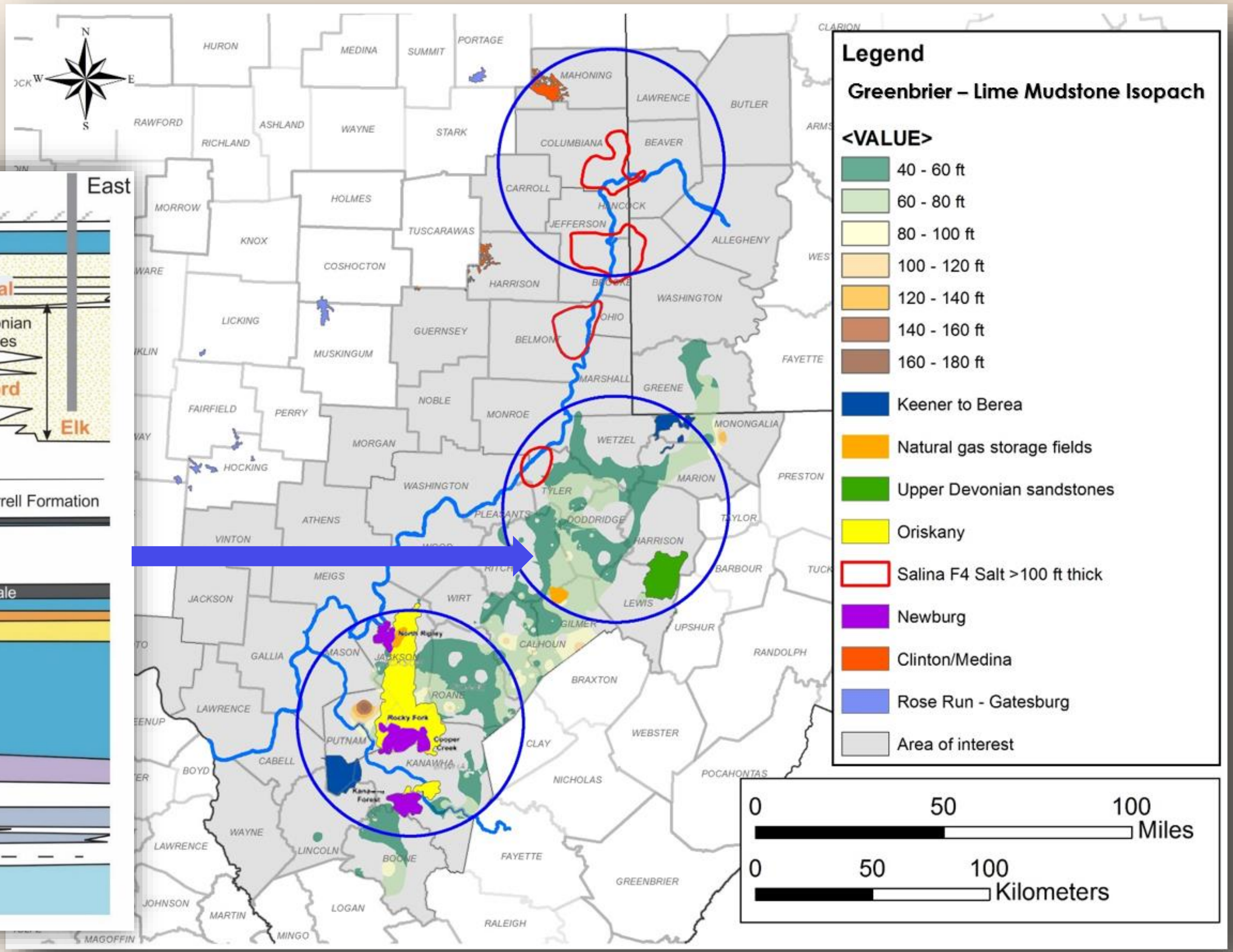

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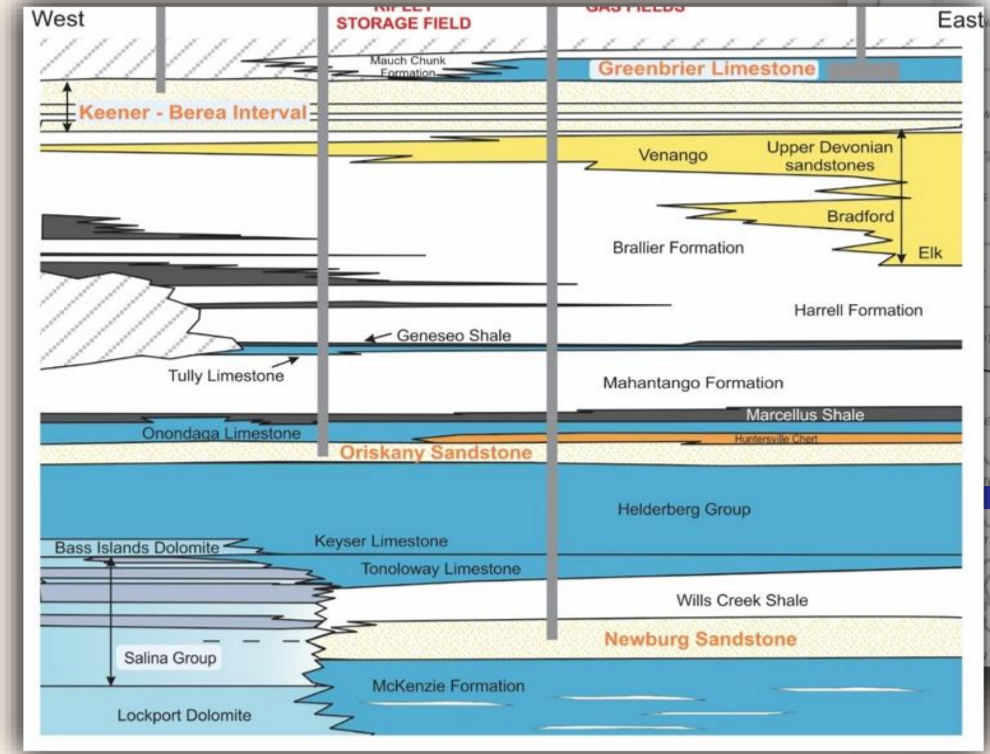

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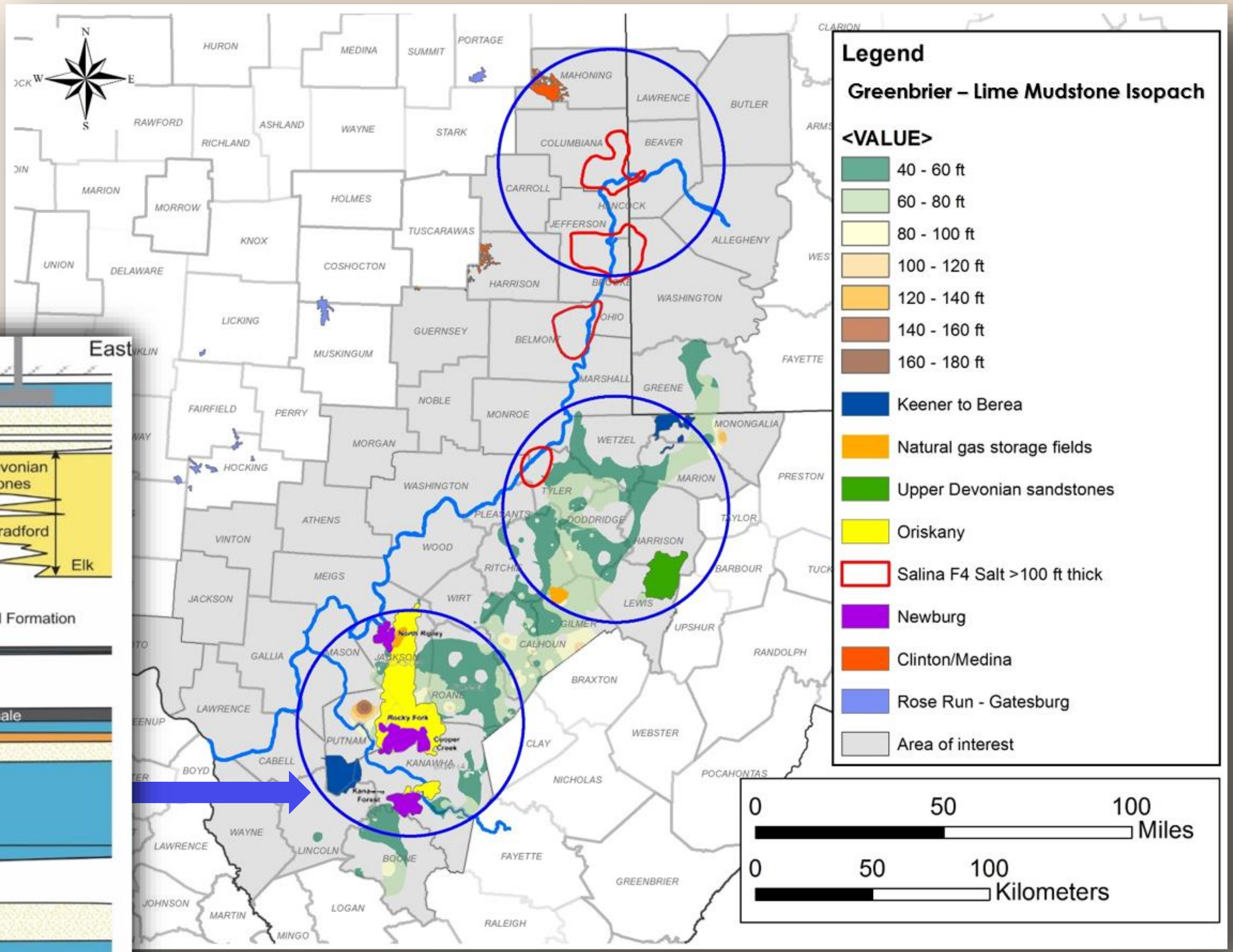

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Benedum Foundation

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West Virginia University – WVU Foundation, WVU Research Corporation, National Research Center for Coal and Energy and WVU Corporate Relations Office

Advisory Group

THANK YOU!

Project website available at www.wvgs.wvnet.edu

Robin Anthony – Geoscientist (robanthony@pa.gov)
Pennsylvania Geological Survey (Pittsburgh, PA)