Prediction and Distribution Analysis of Marcellus Shale Productive Facies in the Appalachian Basin, USA*

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Abstract

In hydrocarbon exploration and development of unconventional shale oil and gas reservoirs, the emphasis is often placed solely on organic content, but the productivity of shale reservoirs is also highly dependent on the ability of the rock to respond effectively to hydraulic stimulation. Considering the result of the typical extremely low-matrix permeability, higher potential gas productivity requires not only sufficient gas-in-place, but also a brittle mineralogy amenable to hydraulic fracturing (lower clay and higher carbonate and/or silica).We propose a quantitative method to characterize shale reservoirs in terms of both the organic richness and rock geomechanical properties. In the Marcellus Shale and related units of the Appalachian basin, we have identified and quantified seven shale lithofacies based on mineral composition, rock geomechanical properties, and organic-matter richness.

We develop an artificial neural network that uses a set of derived petrophysical parameters typical of shale analysis as input variables to calibrate and train conventional logs to predict previously defined shale lithofacies based on the integration of limited core data and pulsed neutron spectroscopy (PNS) log suites. Spatial geostatistical analysis is used to develop a series of experimental variogram models and vertical proportion of each lithofacies in order to construct a 3-D shale lithofacies realization and a final geocellular model for the Marcellus Shale across the Appalachian basin. The 3-D lithofacies geocellular model is used to map the organic-rich facies and brittle facies at both regional and local spatial scales and to examine individual wells. The most productive areas and horizons of Marcellus Shale are dominated by both organic-rich facies and brittle facies, which can be related to the regional and local geologic controls.

References Cited

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Jacobi, R.D., P.A. Agle, G.J. Smith, C. Lugert, J.L. Seever, G. Cross, and S. Loewenstein, 2008, Faulting and fracture heterogeneity in black shales of the Appalachian Basin of New York State: GSA Abstracts with Programs, v. 40/6, p. 233 p.

Jonk, R., K. Potma, M. Davie, and N. Austin, 2012, Mudstone lithofacies within a sequence stratigraphic framework: Key to mapping shale-gas rock properties in the Horn River basin, Canada (abstract): AAPG Search and Discovery Article #90142 (2012) (http://www.searchanddiscovery.com/abstracts/html/2012/90142ace/abstracts/jonk.htm?q=%2BtextStrip%3A90142+%2BtextStrip%3Ajonk).

Loucks, R.G., and S.C. Ruppel, 2007, Mississippian Barnett Shale: lithofacies and depositional setting of a deep-water shale-gas succession in the Fort Worth Basin, Texas: AAPG Bulletin, v. 91/ 4, p. 579-601.

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AAPG 2013 Annual Convention & Exhibition

Theme 1: Lower Paleozoic Unconventional Plays of the Northeast U.S. (EMD/AAPG)

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Outline

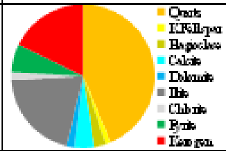
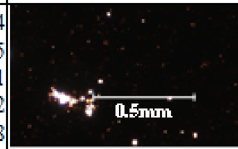
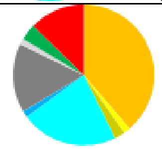
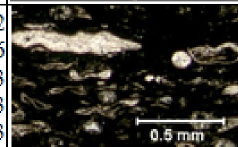
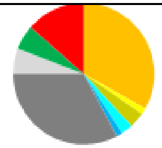
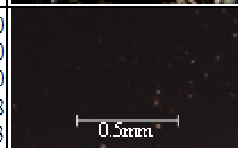
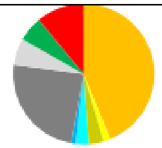
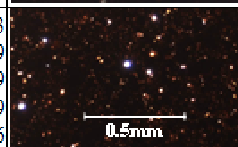
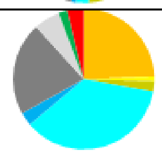
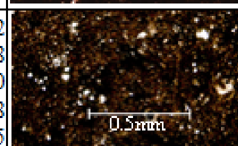
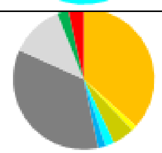
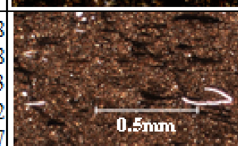
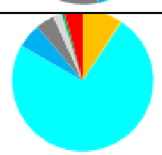
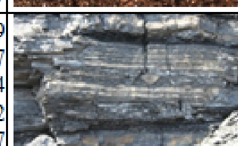
- **Black Shale Lithofacies**
- **Geologic Setting**
- **Lithofacies Identification**
  - **Core scale**
  - **Well scale : Neural Network & Statistical Reverse Model**
- **3-D Lithofacies Modeling**
  - **Structure Model**
  - **Geostatistic Modeling**
- **Productive Facies Distribution**
- **Conclusions**
- **Acknowledgements**

Black Shale Lithofacies

- Three common methods to define shale lithofacies
  - 1. Mineralogy, fabric, biota and texture
    - e.g., Loucks and Ruppel, 2007; Hickey and Henk, 2007
    - Laminated siliceous mudstone, skeletal argillaceous lime packstone
  - 2. Petrophysical and geomechanical properties
    - e.g., Jacobi et al., 2008;
    - Organic-rich shale, siliceous mudstone, carbonate mudstone
  - 3. Mineral composition and organic matter richness
    - e.g., Wang and Carr, 2012; Jonk et al., 2012
- Two significant factors in recognizing good shale-gas reservoirs
  - 1. Total Organic Carbon (TOC): related to gas content
  - 2. Mineral Composition: related to shale brittleness
- One key job for shale-gas reservoir characterization
  - 1. Find zones with high TOC and brittle

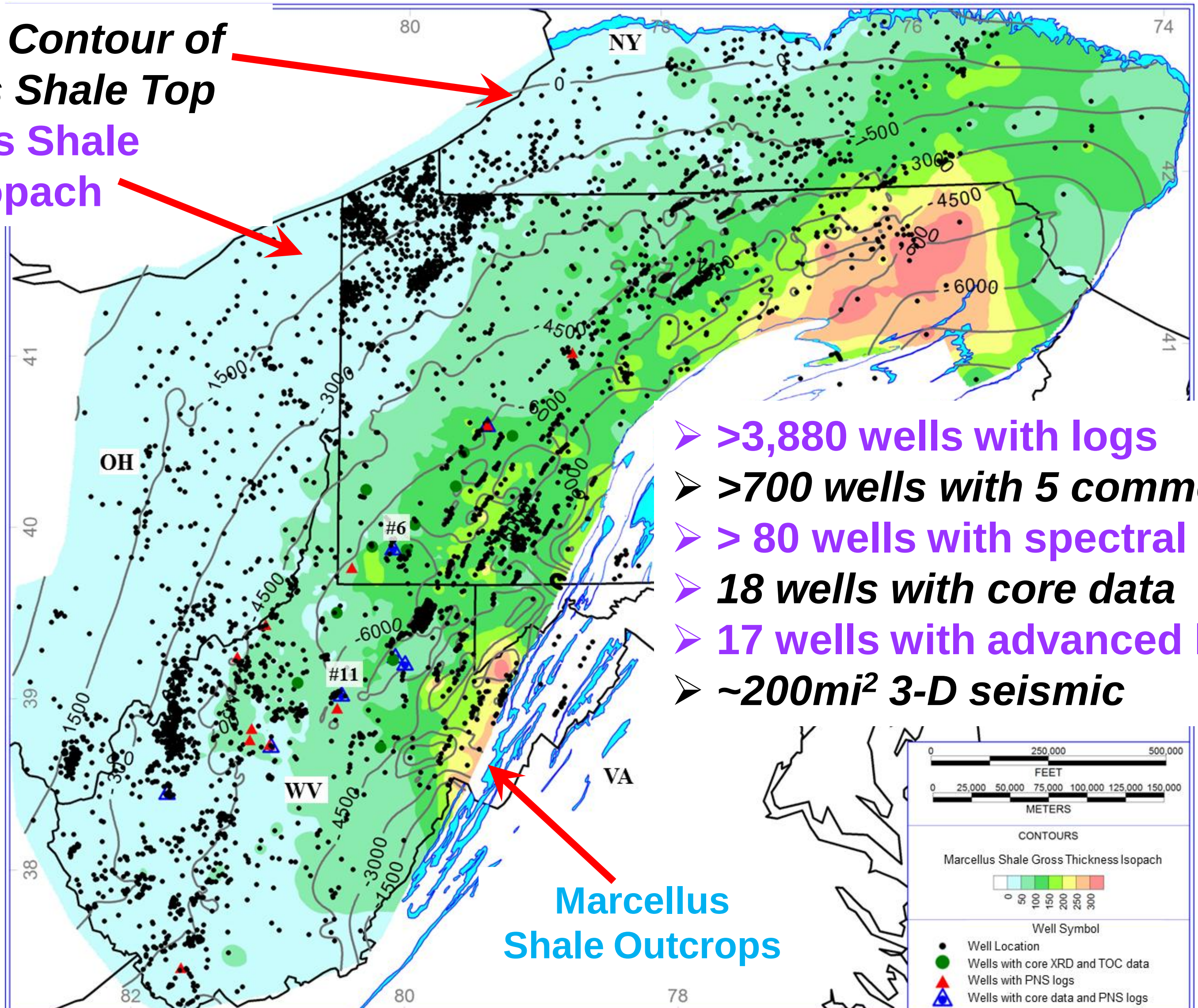
A shale lithofacies is a laterally and vertically continuous zone that possesses similar mineral composition, geomechanical properties and organic-matter richness

Black Shale Lithofacies

Lithofacies	Mineral and Organic Matter Features			Comments	Conventional Logs Statistics					
	Pie Plot	Average Volume (%)	Thin Section*		GR (API)	RHOB (g/cm^3)	NEU (%)	ILD (ohmm)	PE (B/E)	URAN (ppm)
Organic Siliceous Shale (OSS)		Quartz: 62.04 Carb: 8.25 Clay: 29.71 RQC: 7.52 TOC: 10.38		Brittle; High Quartz; High TOC; High RFAG	278~785 449	2.1~2.48 2.39	18.0~30.4 24.1	152~2505 854	2.7~7.9 3.5	20~80 40
Organic Mixed Shale (OMS)		Quartz: 50.12 Carb: 28.96 Clay: 20.93 RQC: 1.73 TOC: 7.93		Brittle; High Carb.; High TOC; High RFAG	242~628 424	2.3~2.59 2.47	13.3~27.5 20.3	95~1475 450	3.3~6.3 4.3	18~73 34
Organic Mudstone (OMD)		Quartz: 46.30 Carb: 5.10 Clay: 48.60 RQC: 9.08 TOC: 7.13		Ductile; High Clay; High TOC; Low RFAG	315~793 491	2.4~2.64 2.53	21.8~29.7 25.7	26~414 164	3.4~7.0 4.4	17~74 36
Gray Siliceous Shale (GSS)		Quartz: 57.83 Carb: 4.99 Clay: 37.19 RQC: 11.59 TOC: 4.66		Brittle; High Quartz; Low TOC; High RFAG	115~277 193	2.4~2.62 2.59	15.5~24.1 19.8	20~241 94	2.8~4.8 3.5	2~14 8
Gray Mixed Shale (GMS)		Quartz: 28.72 Carb: 41.98 Clay: 29.30 RQC: 0.68 TOC: 2.05		Brittle; High Carb.; Low TOC; High RFAG	87~178 131	2.5~2.75 2.66	6.3~23.4 14.4	24~282 103	3.5~5.1 4.2	1.5~12 5.4
Gray Mudstone (GMD)		Quartz: 44.98 Carb: 4.08 Clay: 50.93 RQC: 11.02 TOC: 2.17		Ductile; High Clay; Low TOC; Low RFAG	139~229 209	2.4~2.70 2.60	17.2~27.7 22.6	19~121 56	3.3~5.5 3.8	2~15 8.1
Carbonate (CARB)		Quartz: 9.69 Carb: 83.67 Clay: 6.64 RQC: 0.12 TOC: 1.77		Very hard; Fracturing boundary; Shale gas migration	24~135 82	2.6~2.75 2.69	1.8~15.2 6.2	61~1432 636	3.9~5.1 4.7	0~7.7 3.1

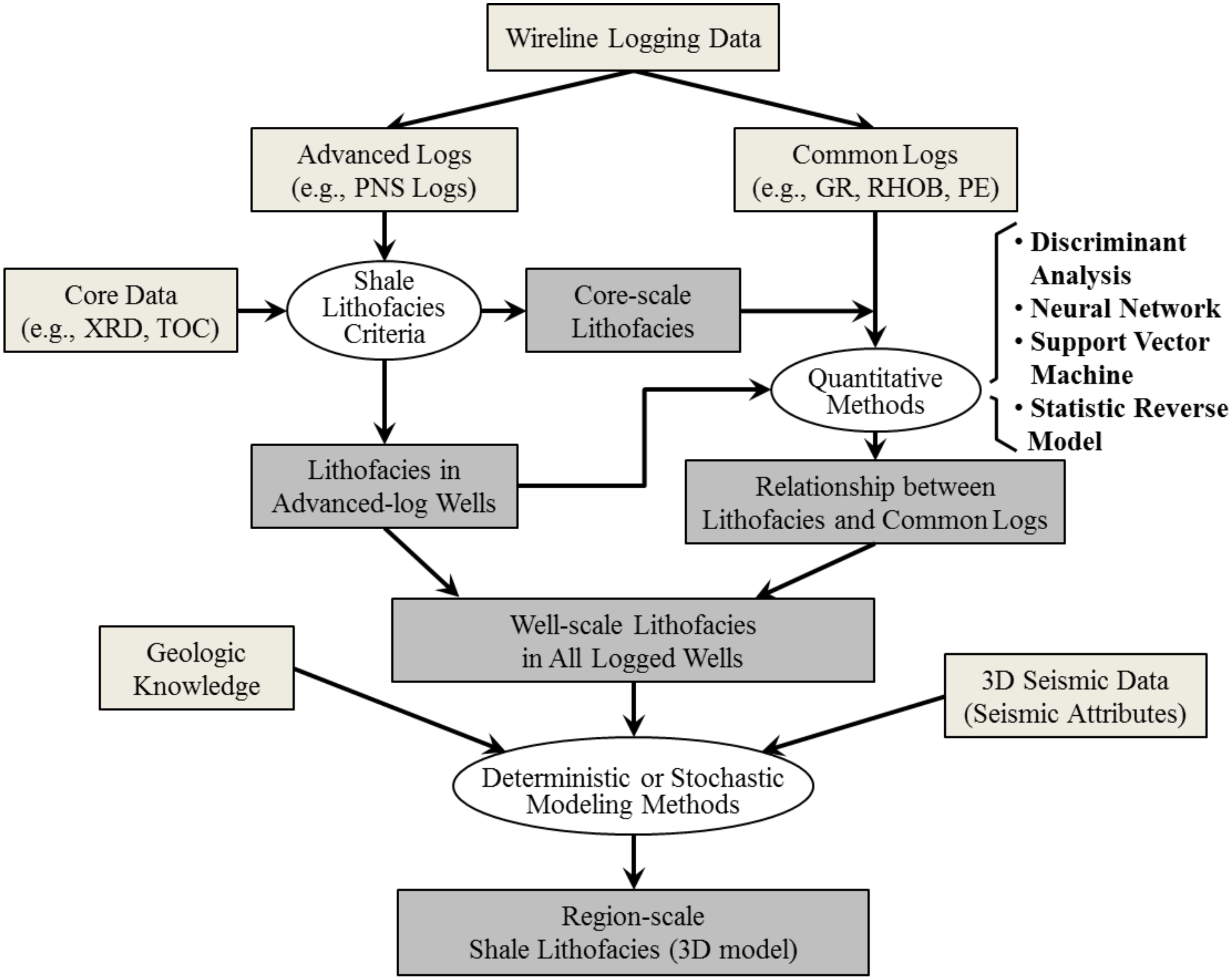
Geologic Setting and Database

- ***Structure Contour of Marcellus Shale Top***
- **Marcellus Shale Gross Isopach**



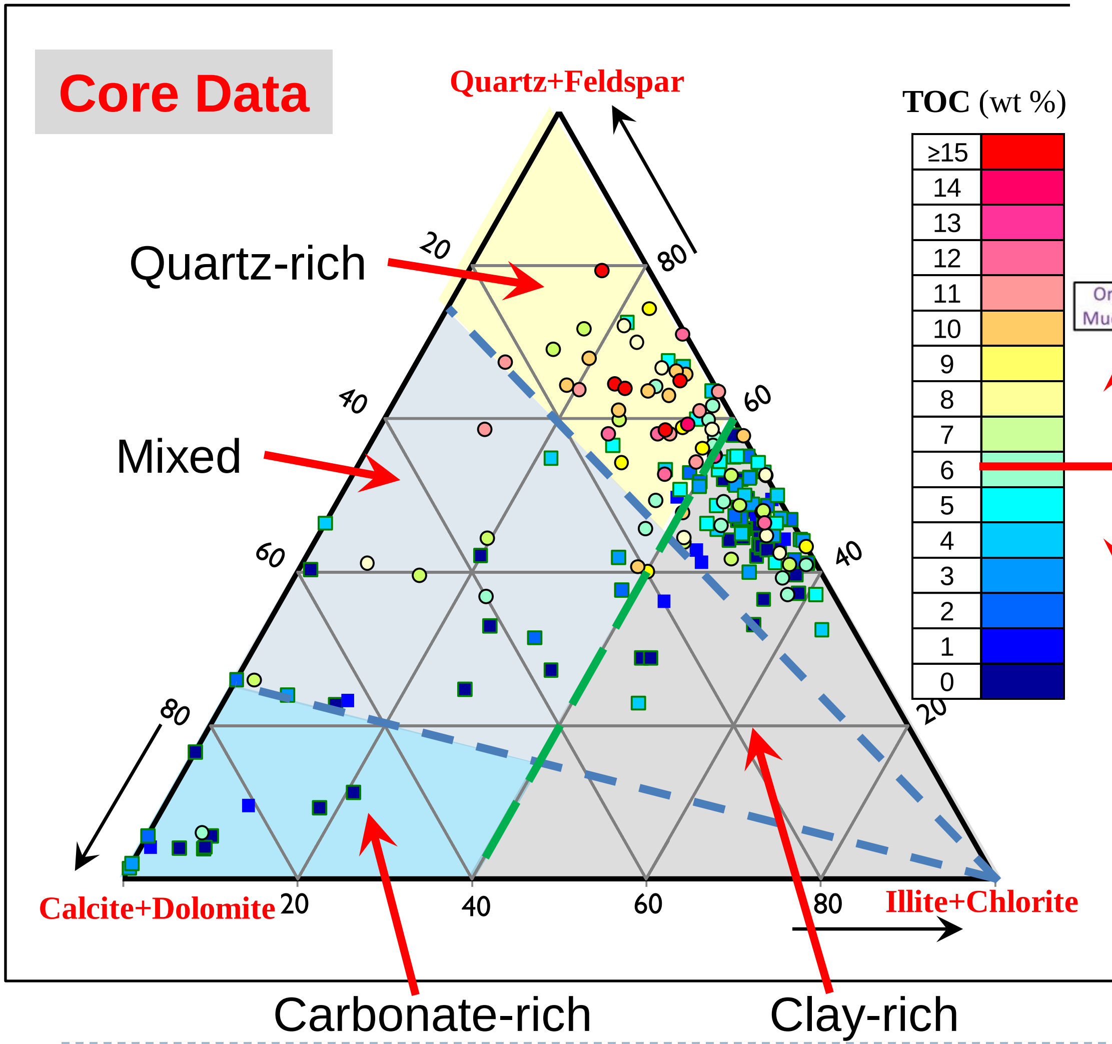
- **>3,880 wells with logs**
- ***>700 wells with 5 common logs***
- **> 80 wells with spectral GR**
- ***18 wells with core data***
- **17 wells with advanced logs**
- ***~200mi^2 3-D seismic***

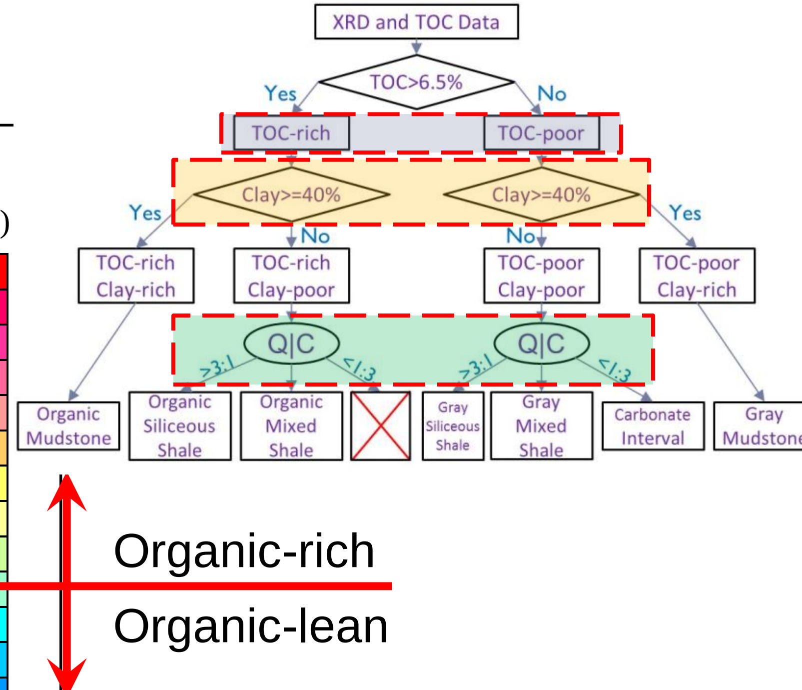
Lithofacies Identification-Methodology



Lithofacies Identification-Core Scale

Shale lithofacies should focus primarily on organic-matter richness

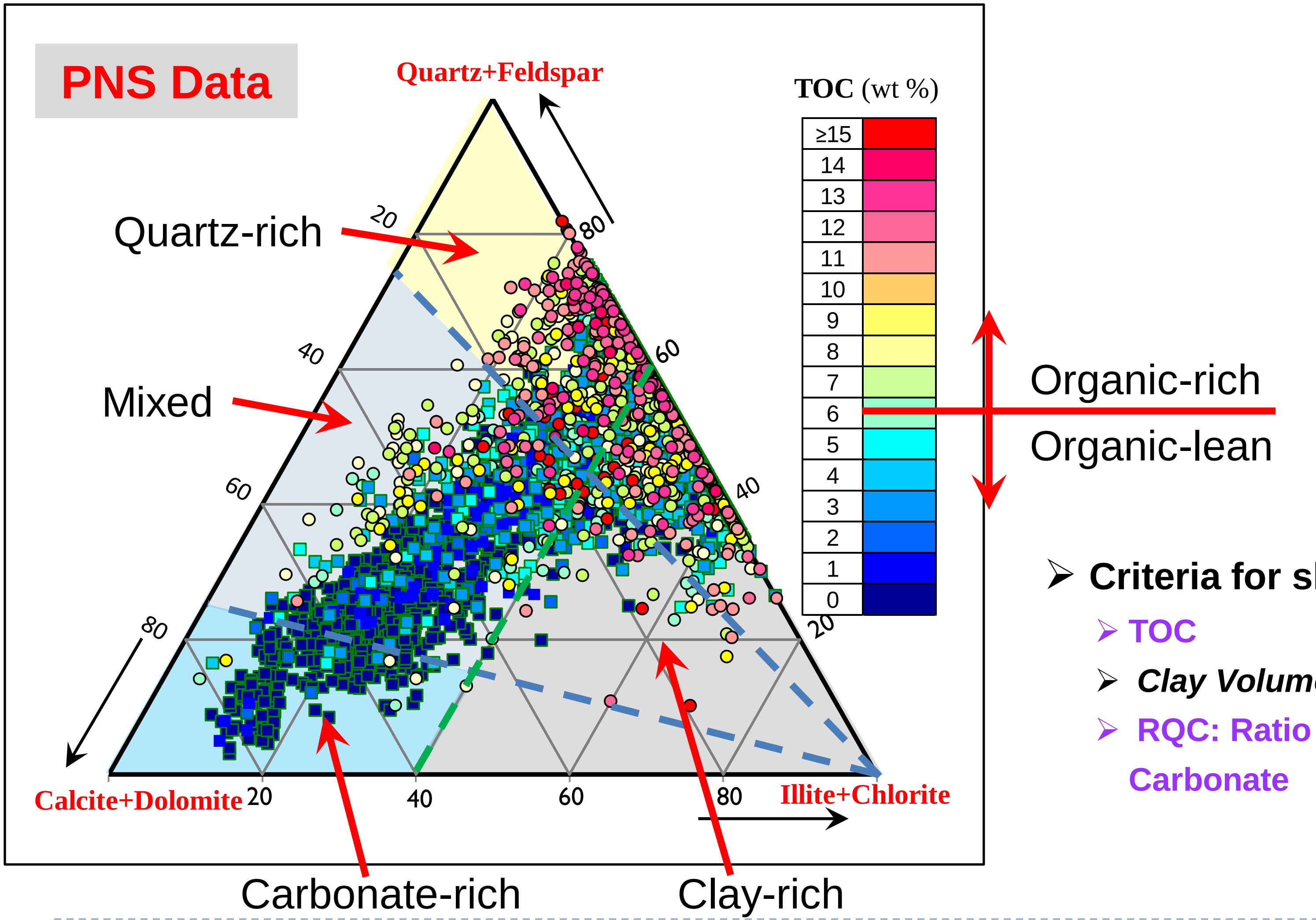




- **Criteria for shale lithofaices**
  - **TOC: 6.5% (wt)**
  - ***Clay Percentage: 40% (vl)***
  - **Ratio of Quartz to Carbonate: 3 & 1/3**

Lithofacies Identification-Well Scale

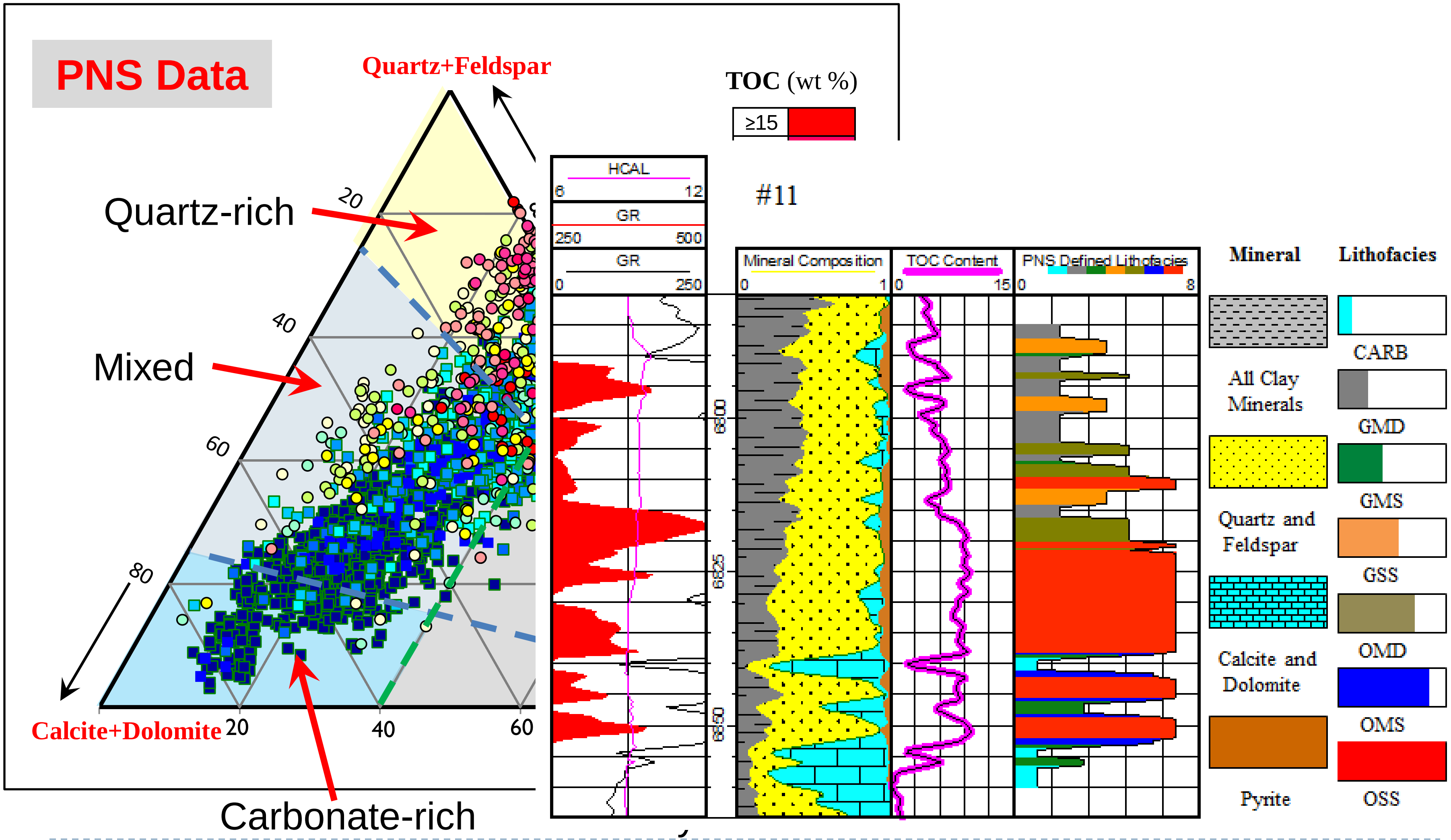
Pulsed Neutron Spectroscopy Log Suite (PNS Log)



- **Criteria for shale lithofaices**
  - **TOC**
  - ***Clay Volume***
  - **RQC: Ratio of Quartz to Carbonate**

Lithofacies Identification-Well Scale

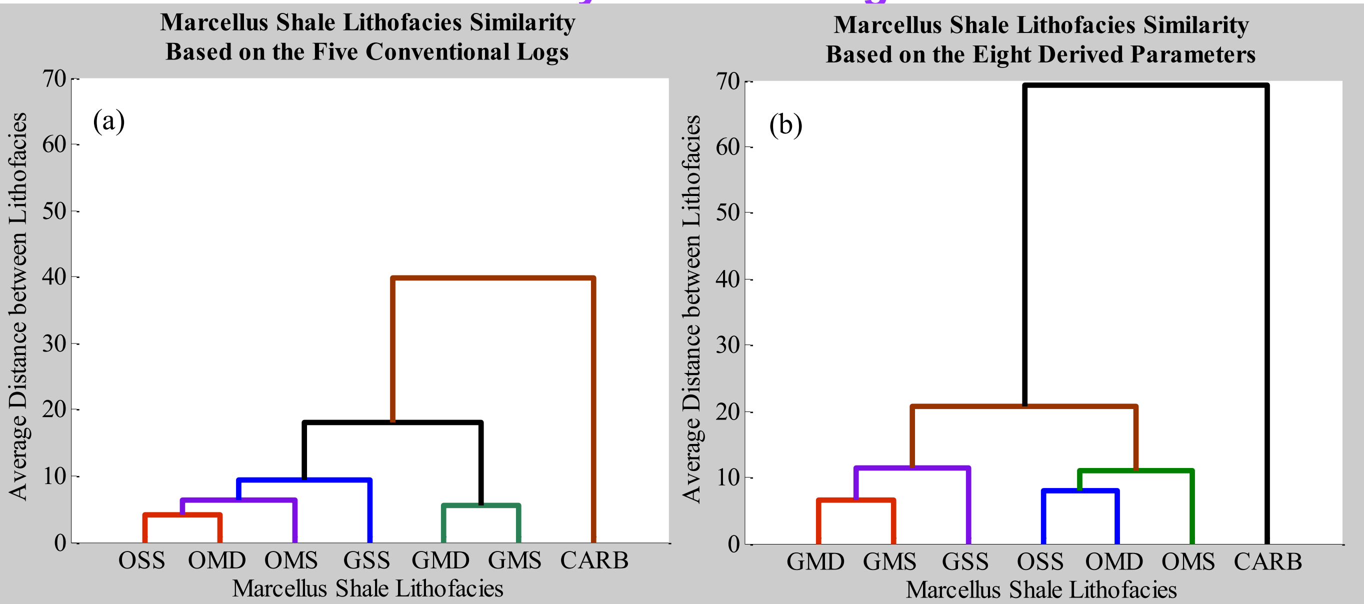
Pulsed Neutron Spectroscopy Log Suite (PNS Log)



Lithofacies Identification-Well Scale

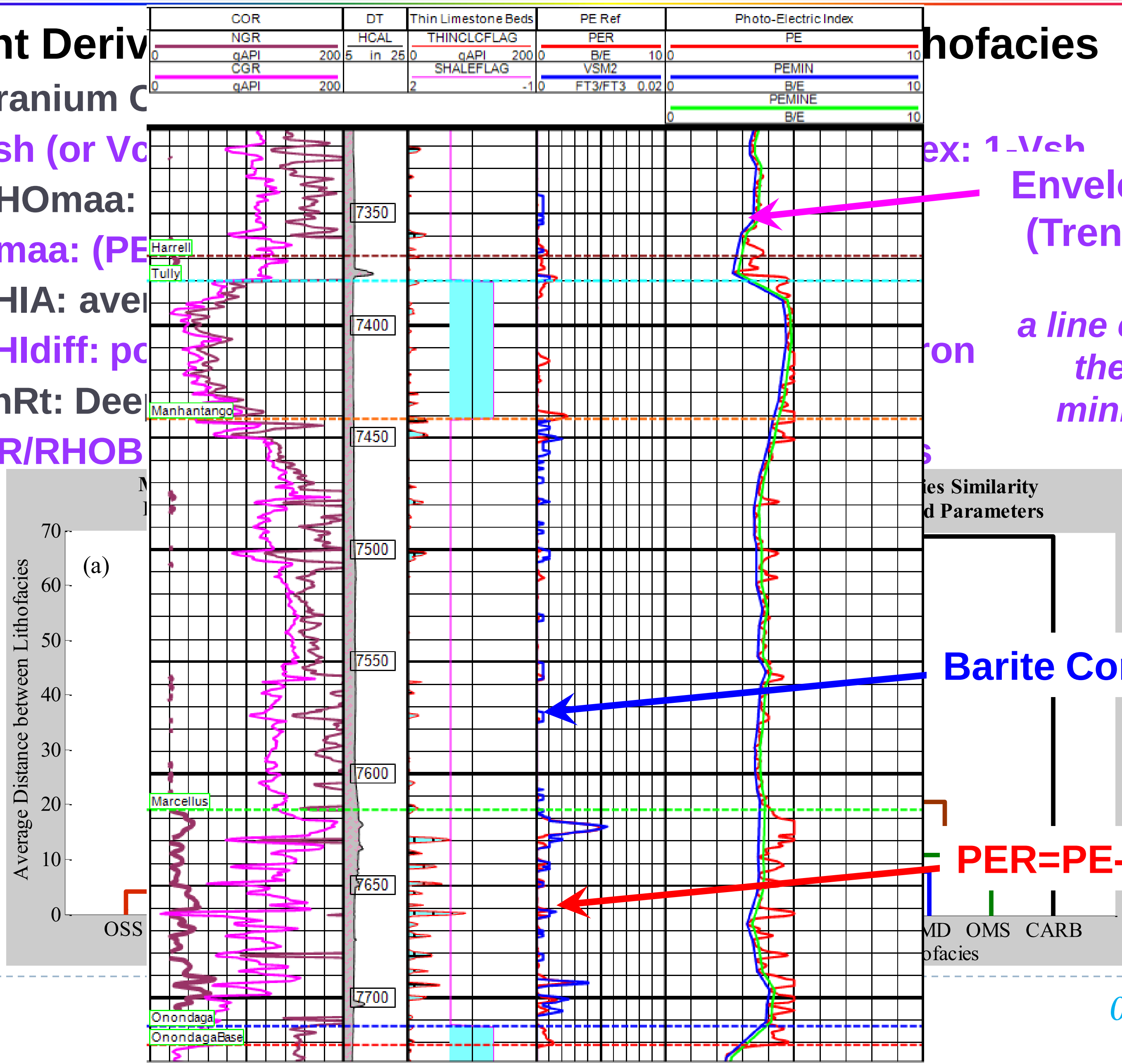
- **Eight Derived Parameters for Marcellus Shale lithofacies**
  - Uranium Concentration: spectral gamma ray
  - Vsh (or Vclay): shale volume; or Shale Brittleness index: 1-Vsh
  - RHOmaa: (RHOB-PHIA)/(1-PHIA)
  - Umaa: (PE×RHOB-0.5PHIA)/(1-PHIA)
  - PHIA: average porosity of density and neutron
  - PHIdiff: porosity difference between density and neutron
  - LnRt: Deep Resistivity natural logarithm
  - GR/RHOB: enhance the ability to detect organic zones

Input Variables



Lithofacies Identification-Well Scale

- **Eight Deriv ... hofacies**
  - Uranium C
  - Vsh (or Vc ... ex: 1-Vsh
  - RHOmaa:
  - Umaa: (PE
  - PHIA: aver
  - PHIdiff: po ... ron
  - LnRt: Dee
  - GR/RHOB ... s



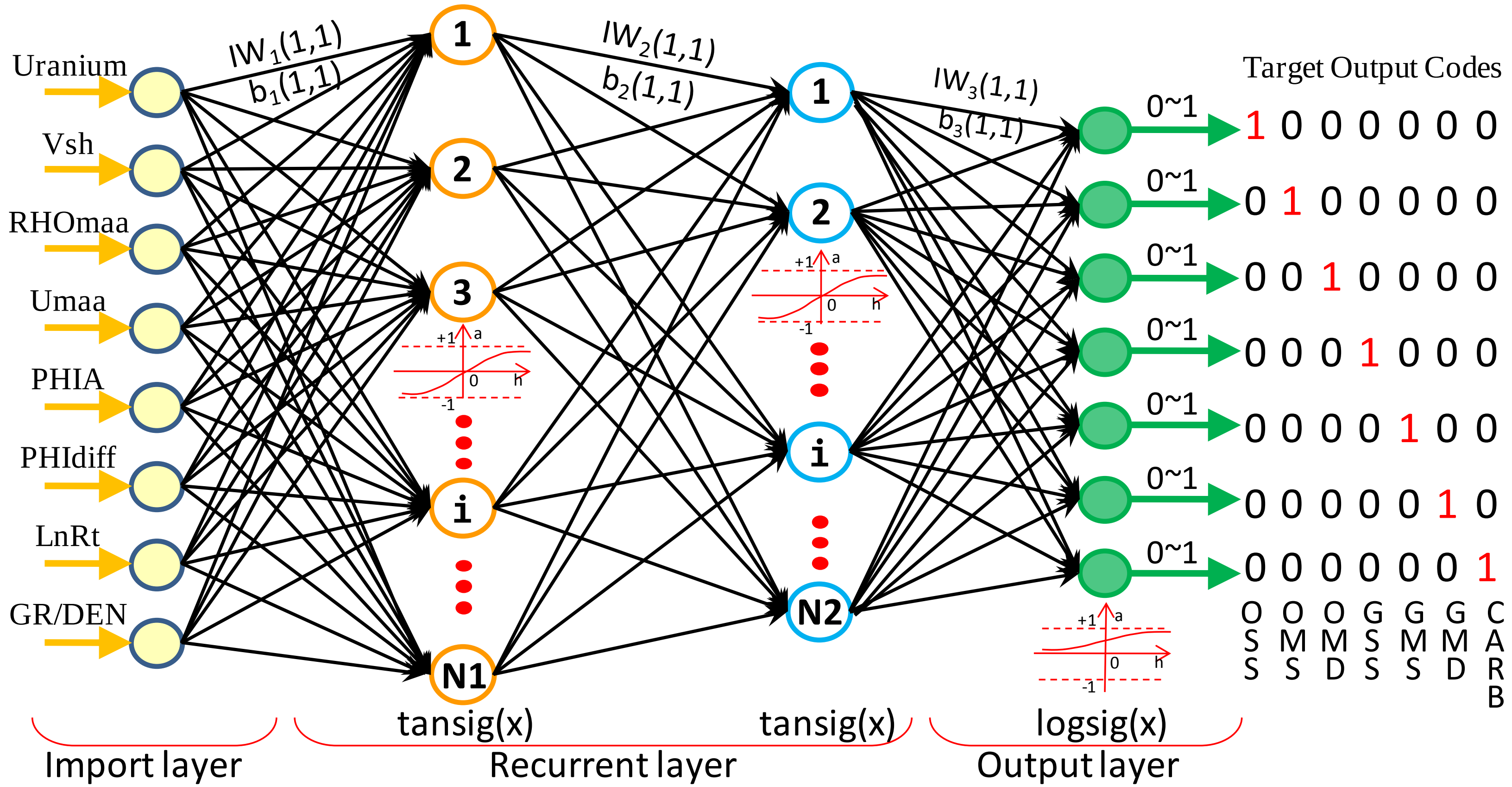
Envelope Line (Trend Line):

a line connects the local minimums

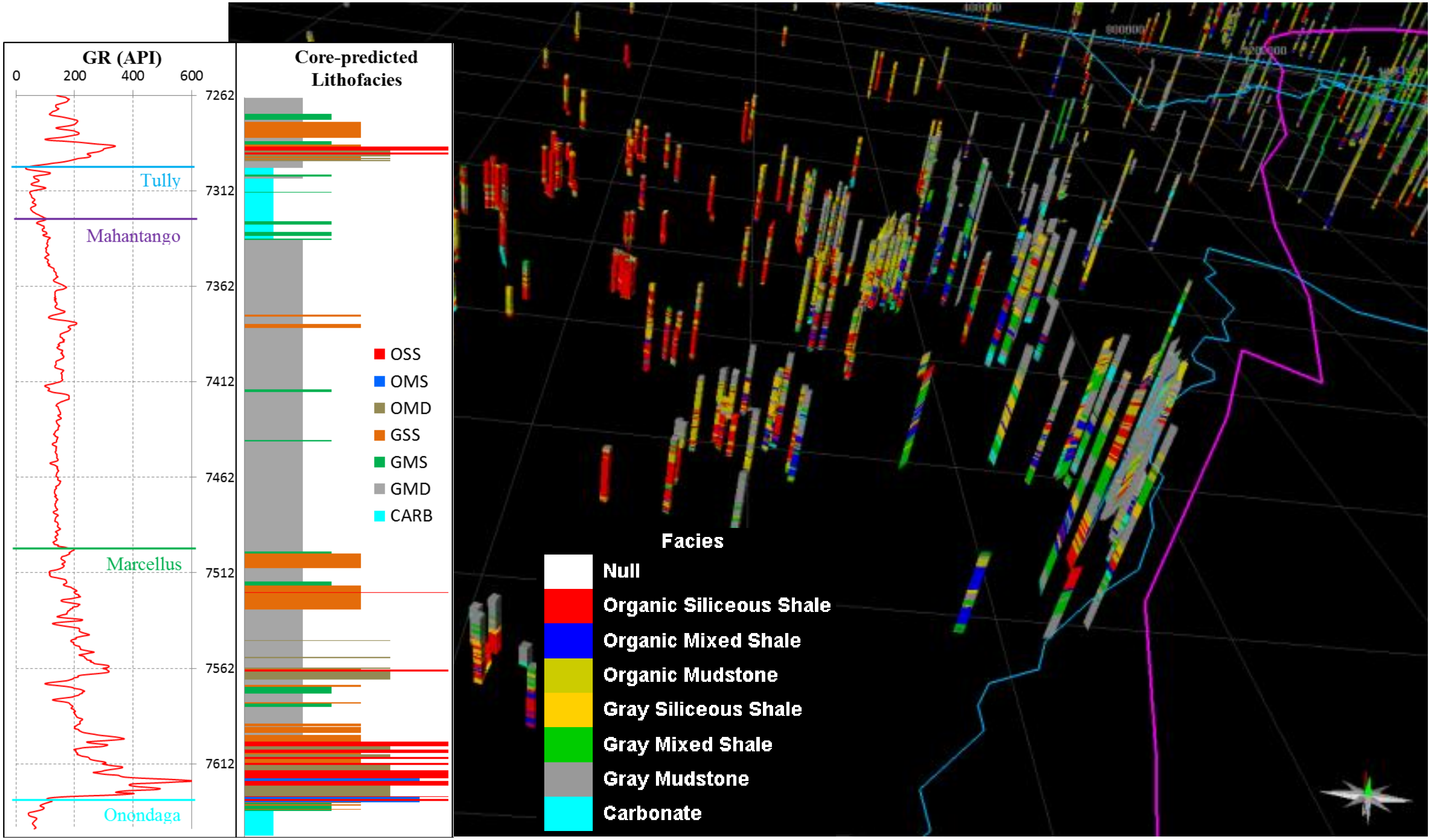
Barite Content

PER=PE-PEminE

Lithofacies Identification-Well Scale



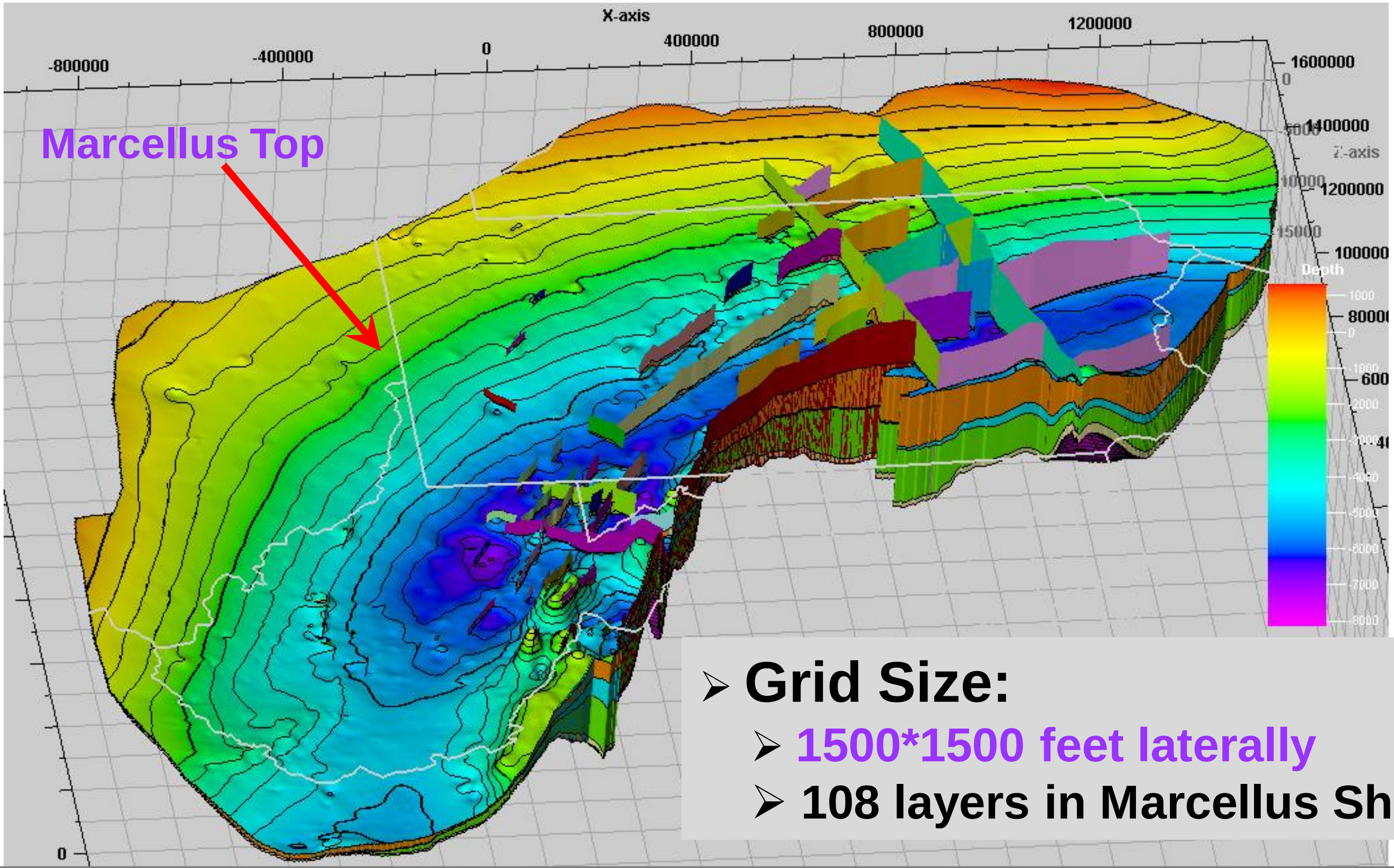
Lithofacies Identification-Well Scale



The predicted Marcellus Shale lithofacies in wells with 5 conventional logs

3-D Lithofacies Modeling

Structure Model



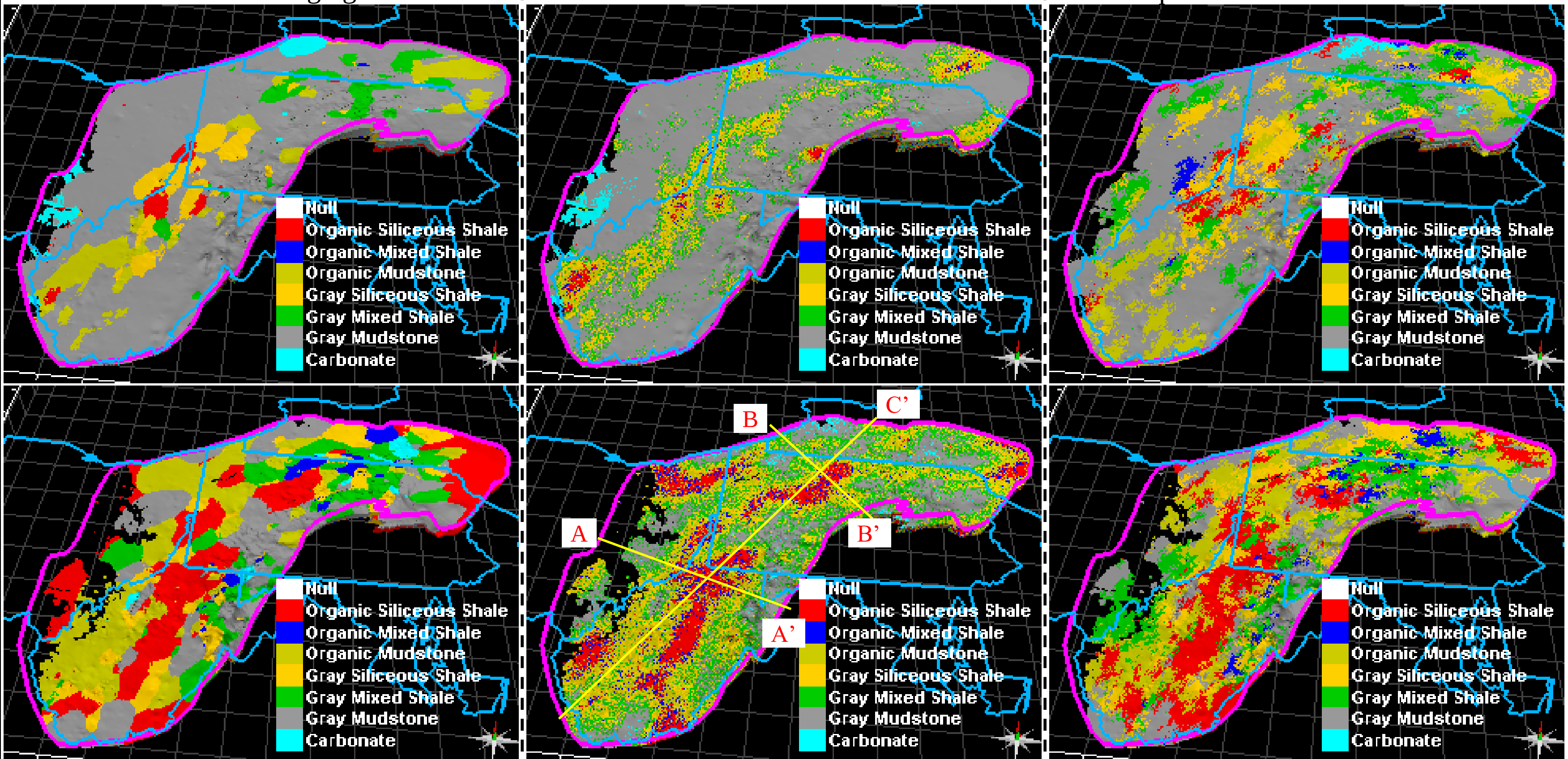
- **Grid Size:**
  - **1500*1500 feet laterally**
  - **108 layers in Marcellus Shale**

One suggestion: interpret one key structure map (Marcellus Top) in detail and construct other formations' structures according to the associated isopach maps.

3-D Lithofacies Modeling

Geostatistic Modeling

Indicator Kriging	Truncated Gaussian Simulation	Sequential Indicator Simulation	



Upper Marcellus

Lower Marcellus

Strength & *Weakness*

Indicator Kriging

- Generates repeatable results;
- Works well with abundant constraint data;
- *Forms sharp boundary among different lithofacies;*
- *Ignores numerous local variations*

Truncated Gaussian Simulation

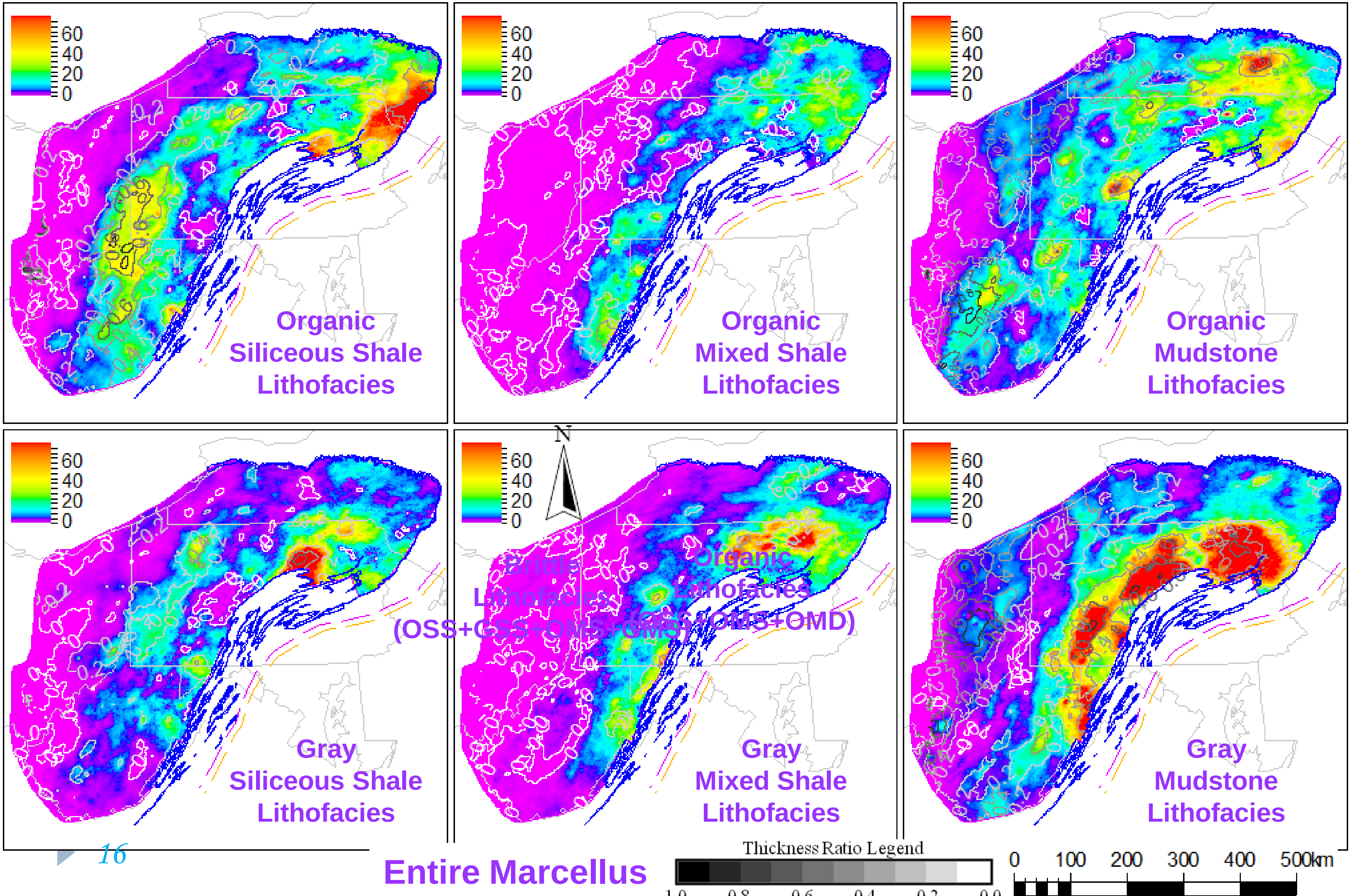
- Works well with clear ordering (one dimension) of lithofacies;
- Possesses Gaussian distribution;
- *Produces too discrete distribution of lithofacies*
- *Loses power for 2-D/3-D ordering*

Sequential Indicator Simulation

- Is widely used wih no strong geometric pattern or clear ordering;
- Provides better realization of local high-frequent lithofacies;
- Makes reasonable distribution of Marcellus Shale;

3-D Lithofacies Modeling

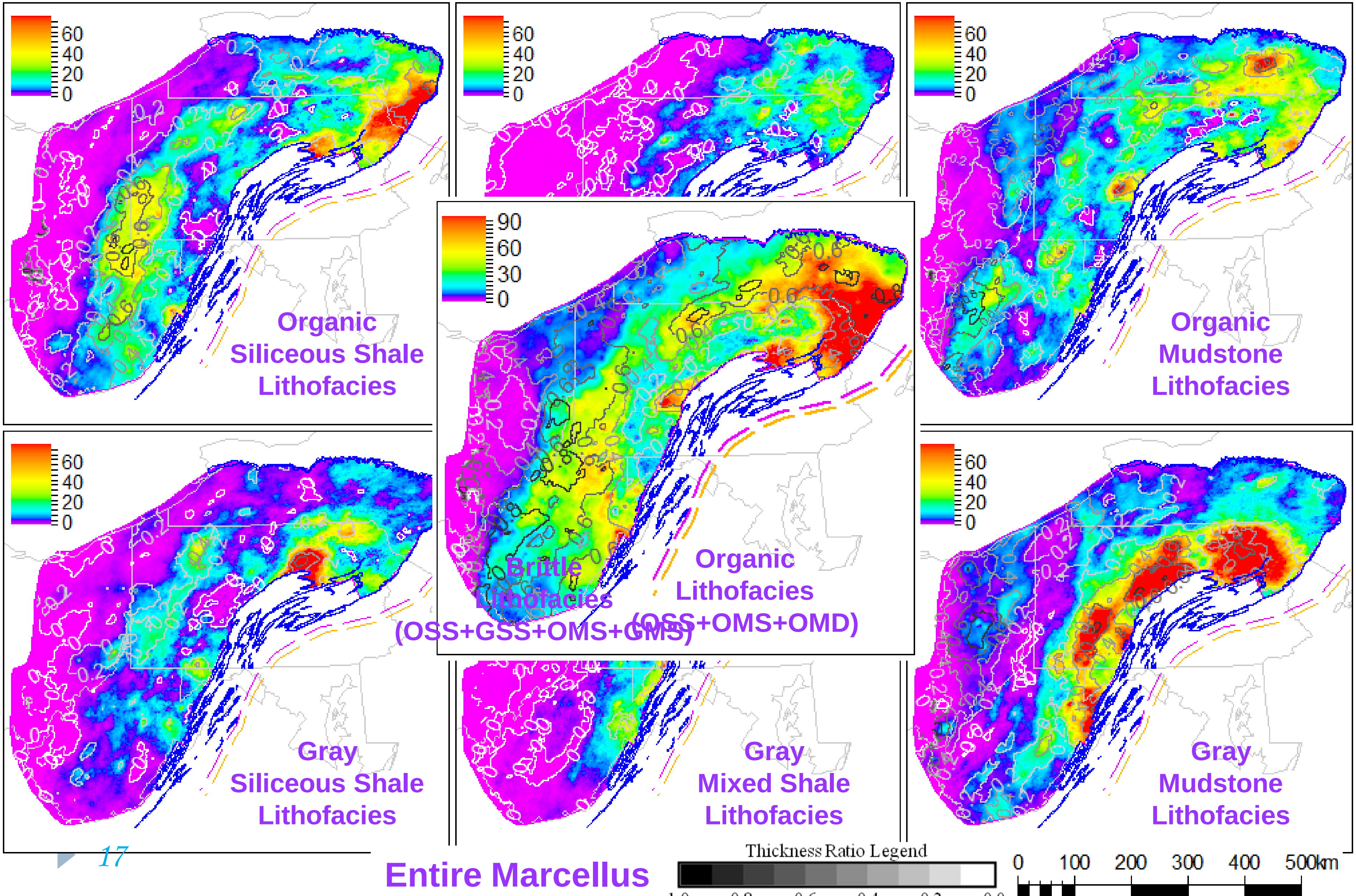
Geostatistic Modeling



Entire Marcellus

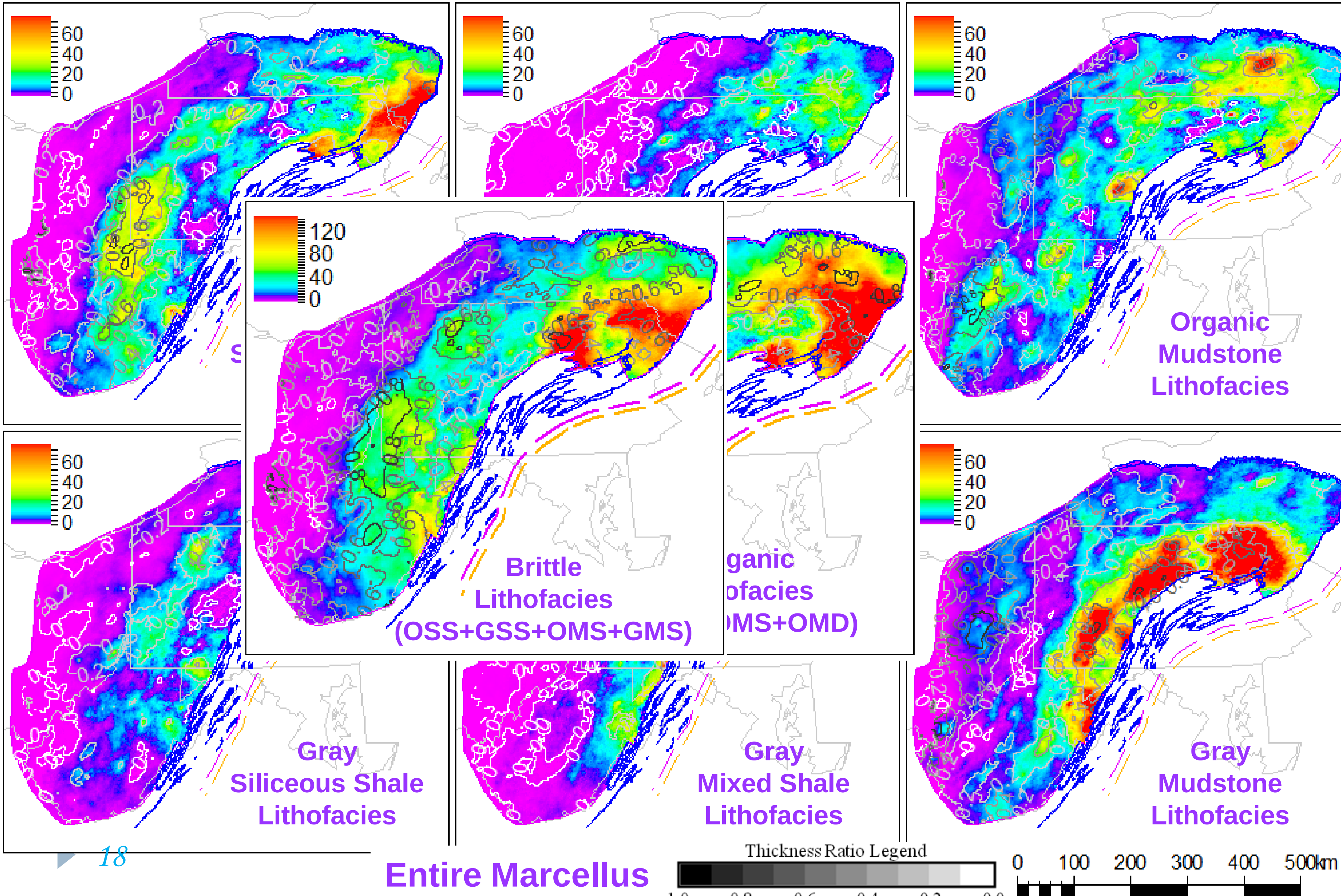
3-D Lithofacies Modeling

Geostatistic Modeling

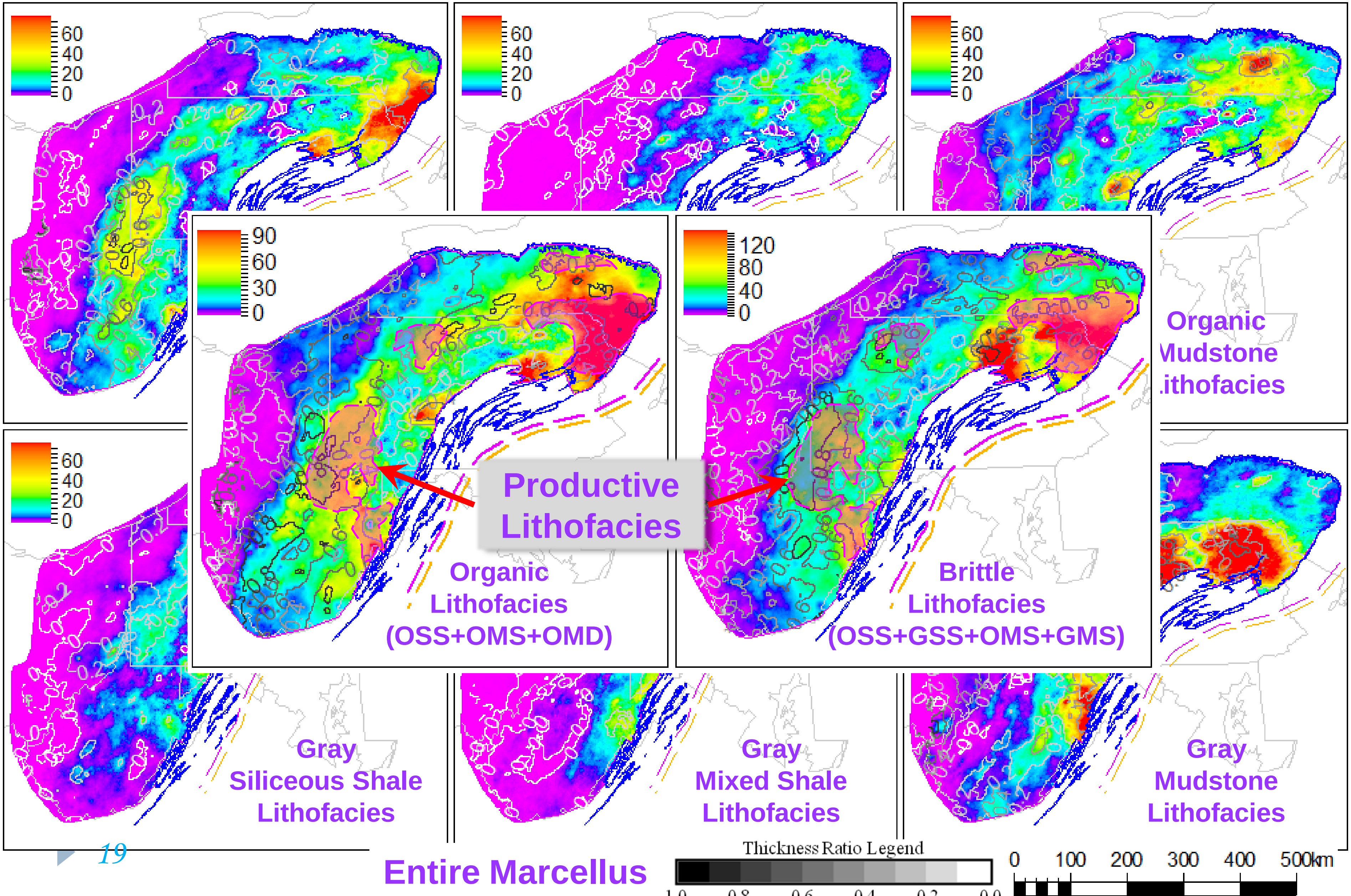


3-D Lithofacies Modeling

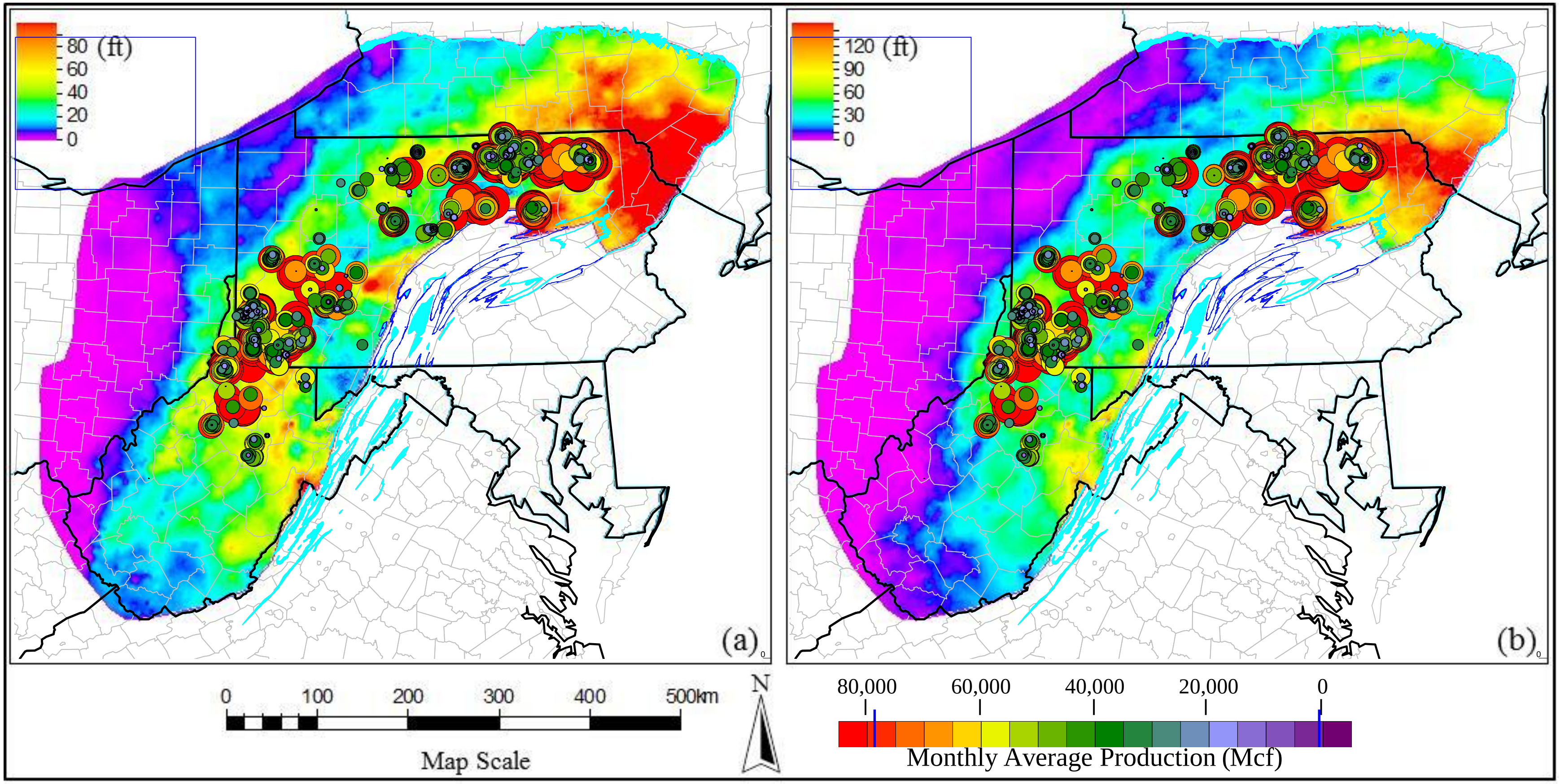
Geostatistic Modeling



Productive Facies Distribution

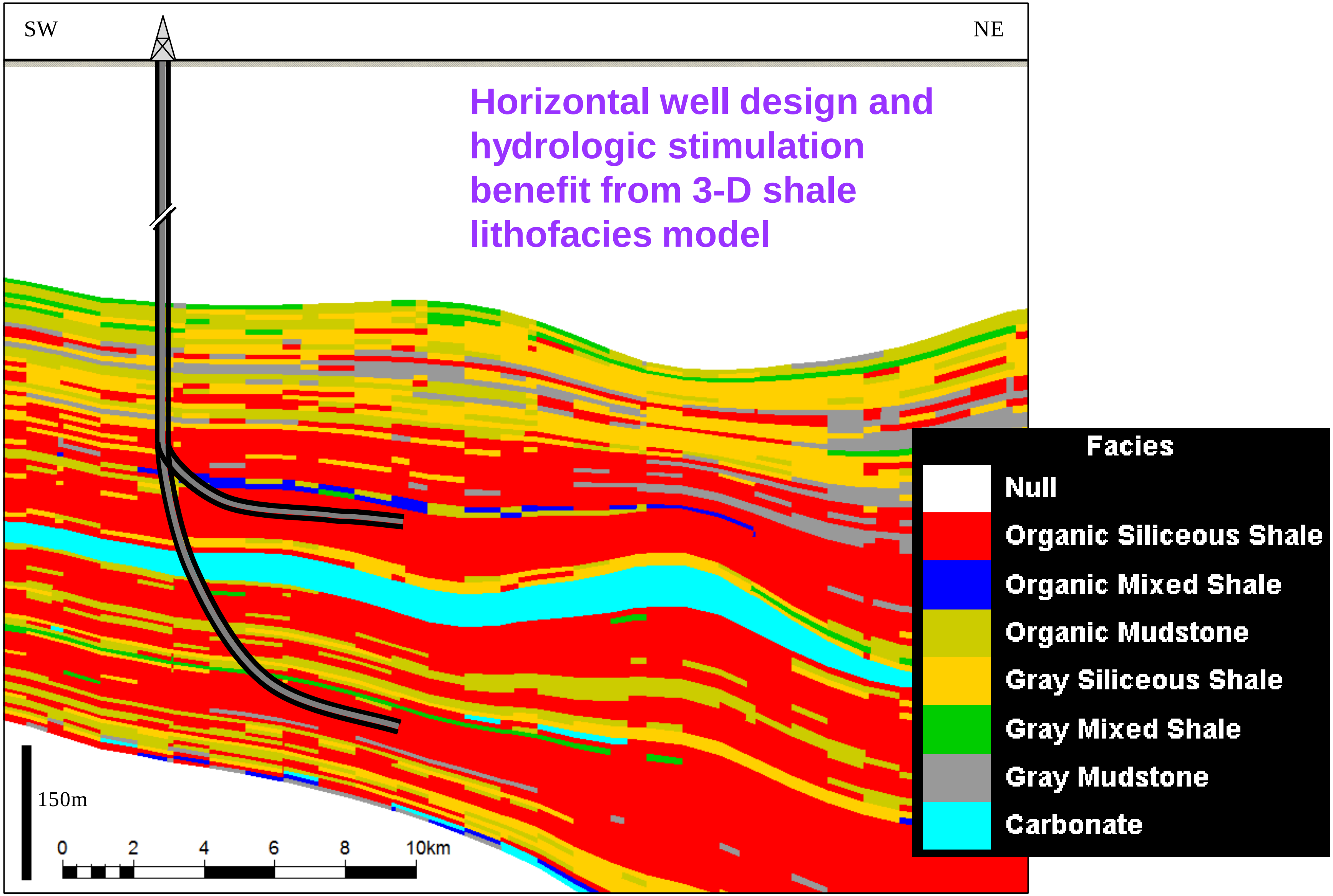


Productive Facies Distribution

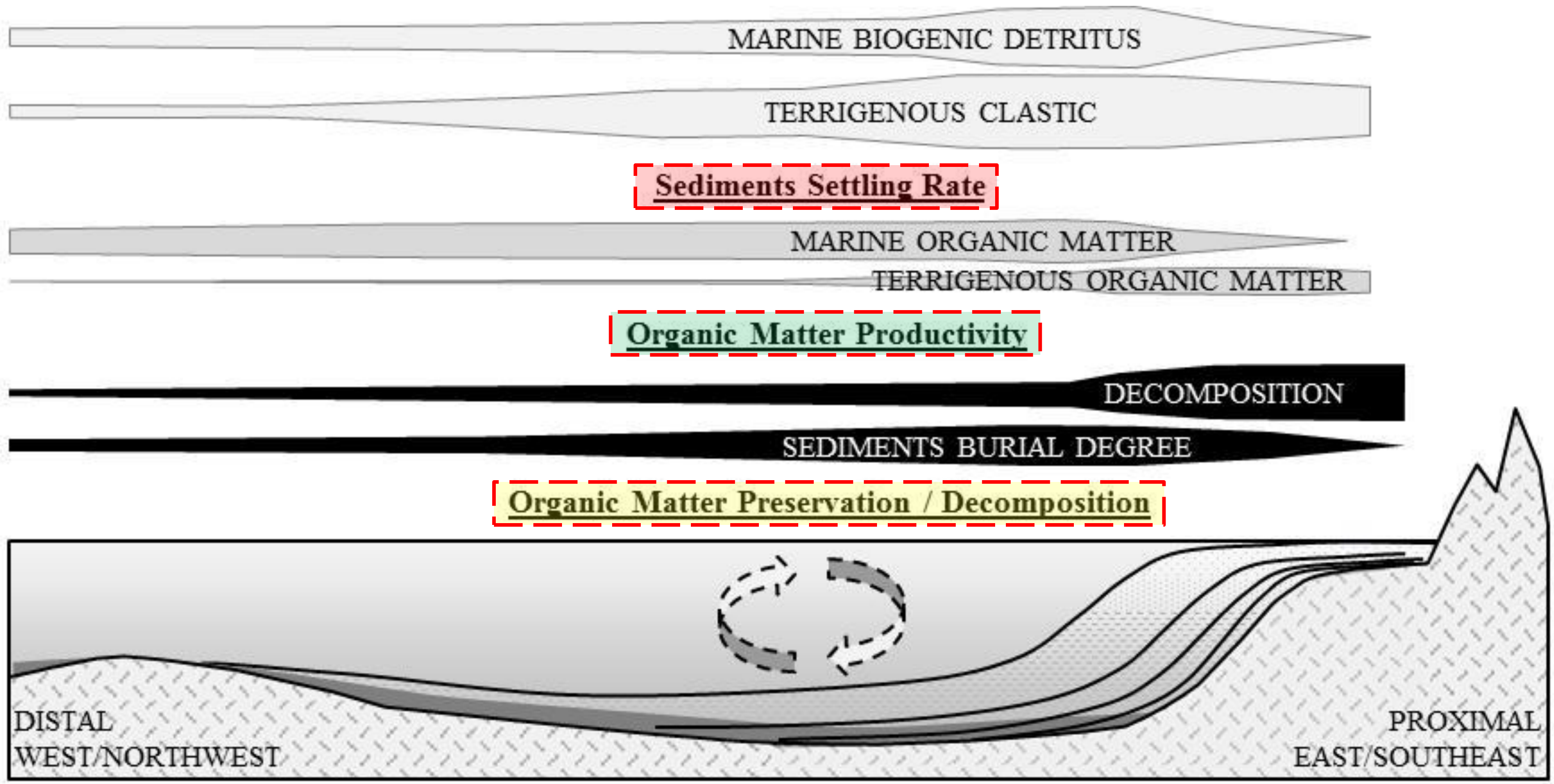


Relationship between Marcellus Shale Productive Lithofacies and Average Gas Production Ratio from Horizontal Wells

Productive Facies Distribution



Productive Facies Distribution



Marcellus Shale Depositional Model Based on 3-D Lithofaices Model

This model could be extended to other organic-rich shale reservoirs!

Conclusions

- **Define seven Marcellus Shale lithofacies based on three criteria: *clay volume*, *ratio of quartz to carbonate*, and *TOC*;**
- **Classify shale lithofacies using conventional logs integrated with core and PNS logs by artificial neural network;**
- **Interpret shale mineral composition by Statistic Reverse Model and then recognize lithofacies;**
- **Sequence Indicator Simulation (SIS) algorithm works better for Marcellus Shale lithofacies modeling than Indicator Kirging and Truncated Gaussian Simulation;**
- **Productive facies (organic-rich and brittle) are primarily deposited near carbonate shelf break;**

Acknowledgments

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Petrel, Petra, Matlab and PowerLog