Marcellus Shale Asset Optimization through Increased Geological Understanding*

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Abstract

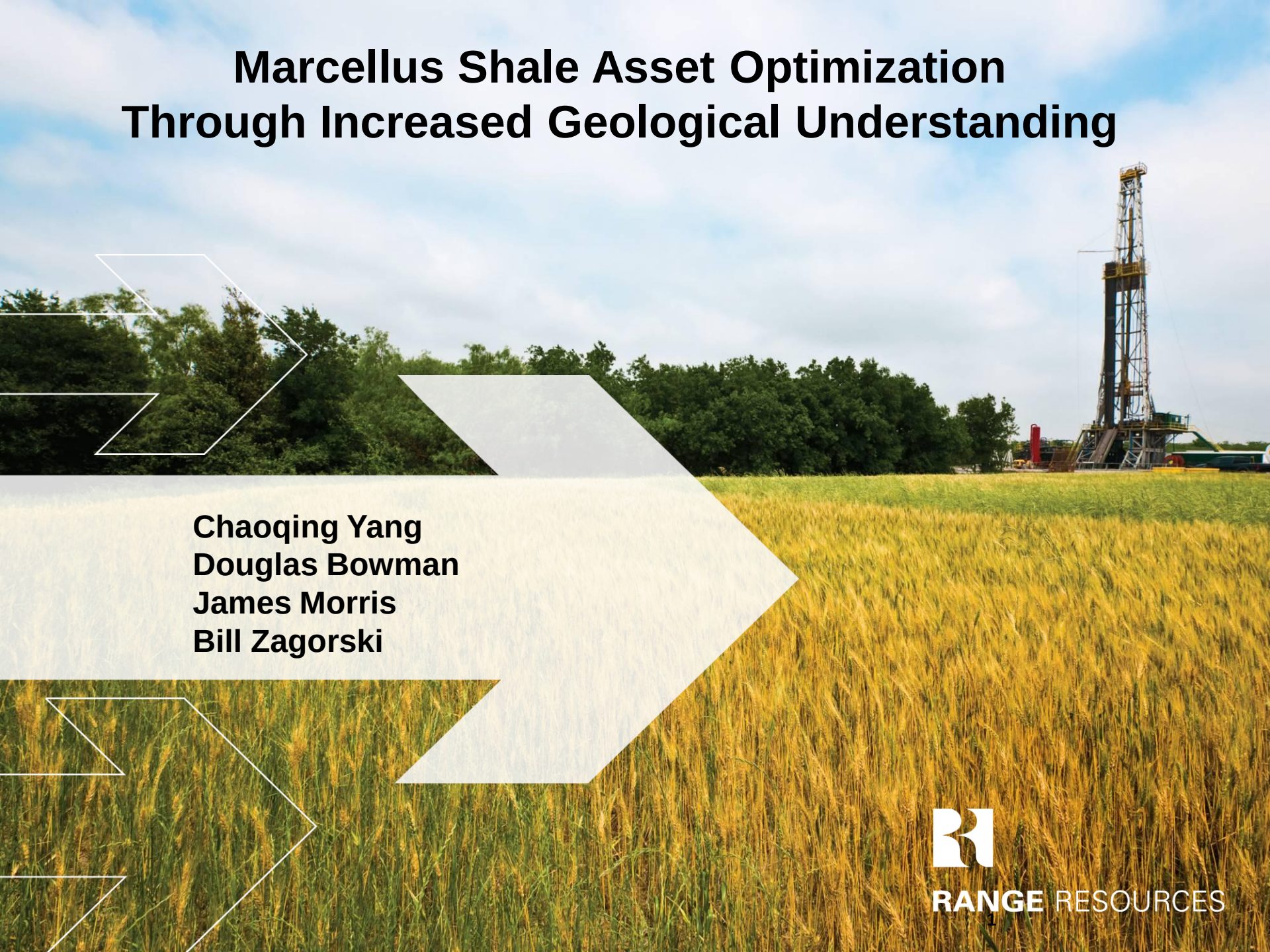
Large-scale, manufacturing-like shale gas development involves heavy capital investment. How to develop shale assets efficiently and effectively presents a big challenge to all of us, especially under current low-price market environment. Since 2007, the Marcellus Shale gas extraction has rapidly expanded. The industry has realized a cookie-cutter approach would not work well for this complex shale gas system. To increase efficiency and maximize asset value, different teams need to work together to identify key drivers to well performance and formulate a field development strategy.

As a vital part of this combined effort, many geological and geophysical investigations have increased our understanding of the Marcellus Shale. In addition to the identification of sweet spots, we appreciate the importance of placing the laterals in the high-quality target zone. Further studies reveal interdependence between various reservoir properties. Several parameters, such as thermal maturity, porosity, permeability, abnormal pore pressure, and rock mechanical properties, all play a key role in field development optimization. A solid geological understanding of reservoir quality, geomechanical properties, and geohazards helps to tailor our drilling and completion designs to honor variations in the shale gas reservoir, both vertically and horizontally across the field.

This presentation provides a few snapshots of our geological studies in the following areas:

- Marcellus stratigraphy
- Log analysis/Petrophysical modeling
- Key reservoir parameter mapping
- 3-D shared earth modeling
- FIB SEM investigation
- Role of seismic
- Landing point analysis

Marcellus Shale Asset Optimization Through Increased Geological Understanding



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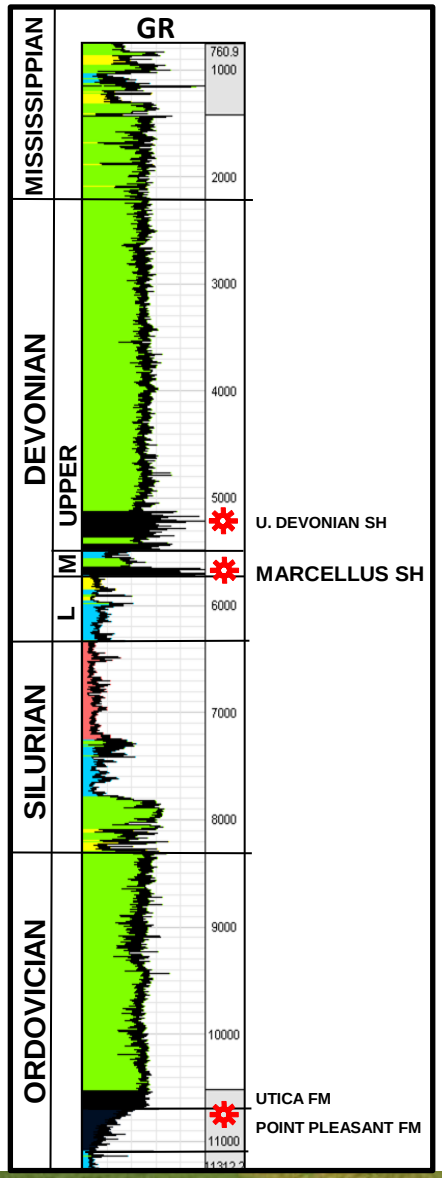
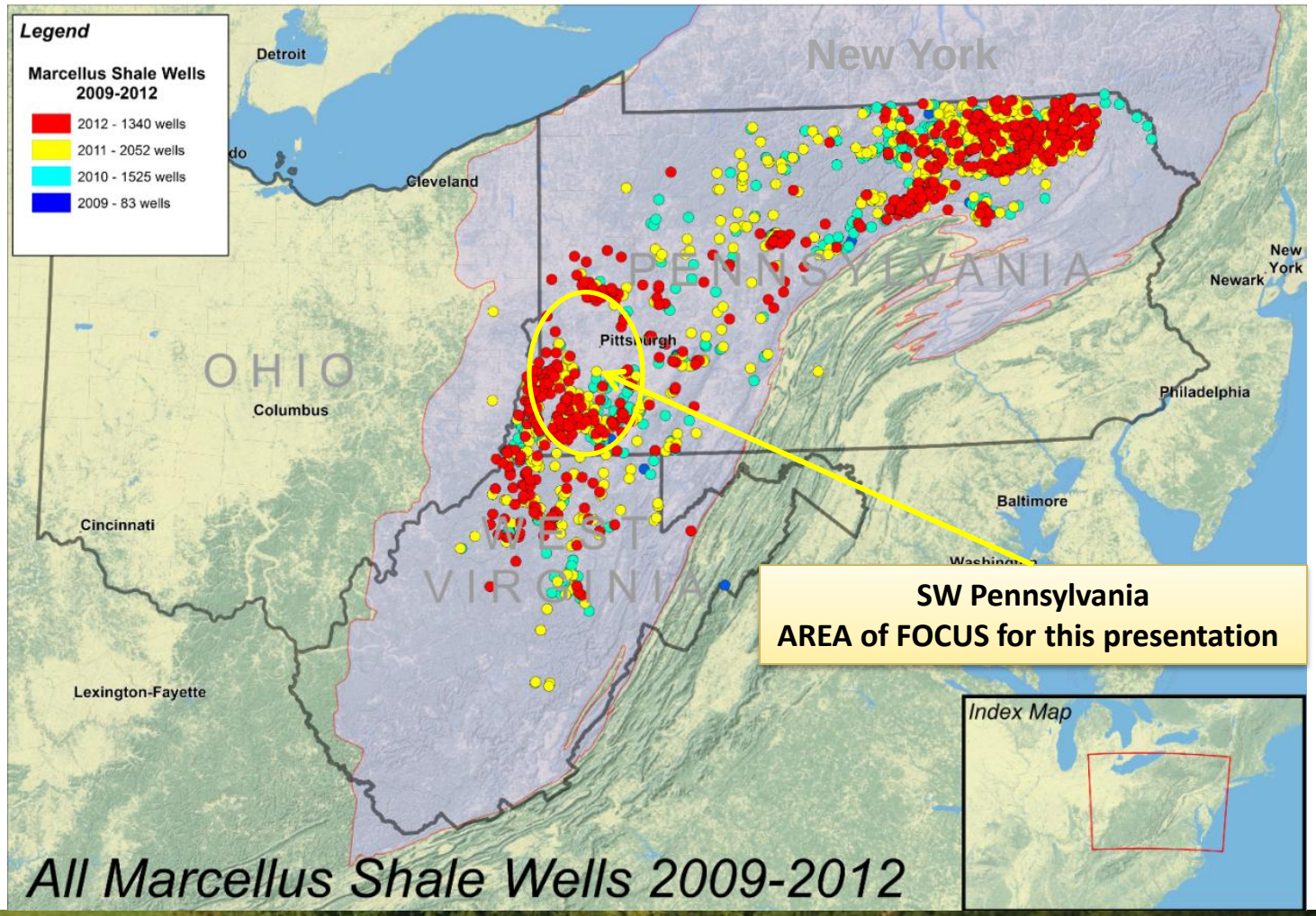
RANGE RESOURCES

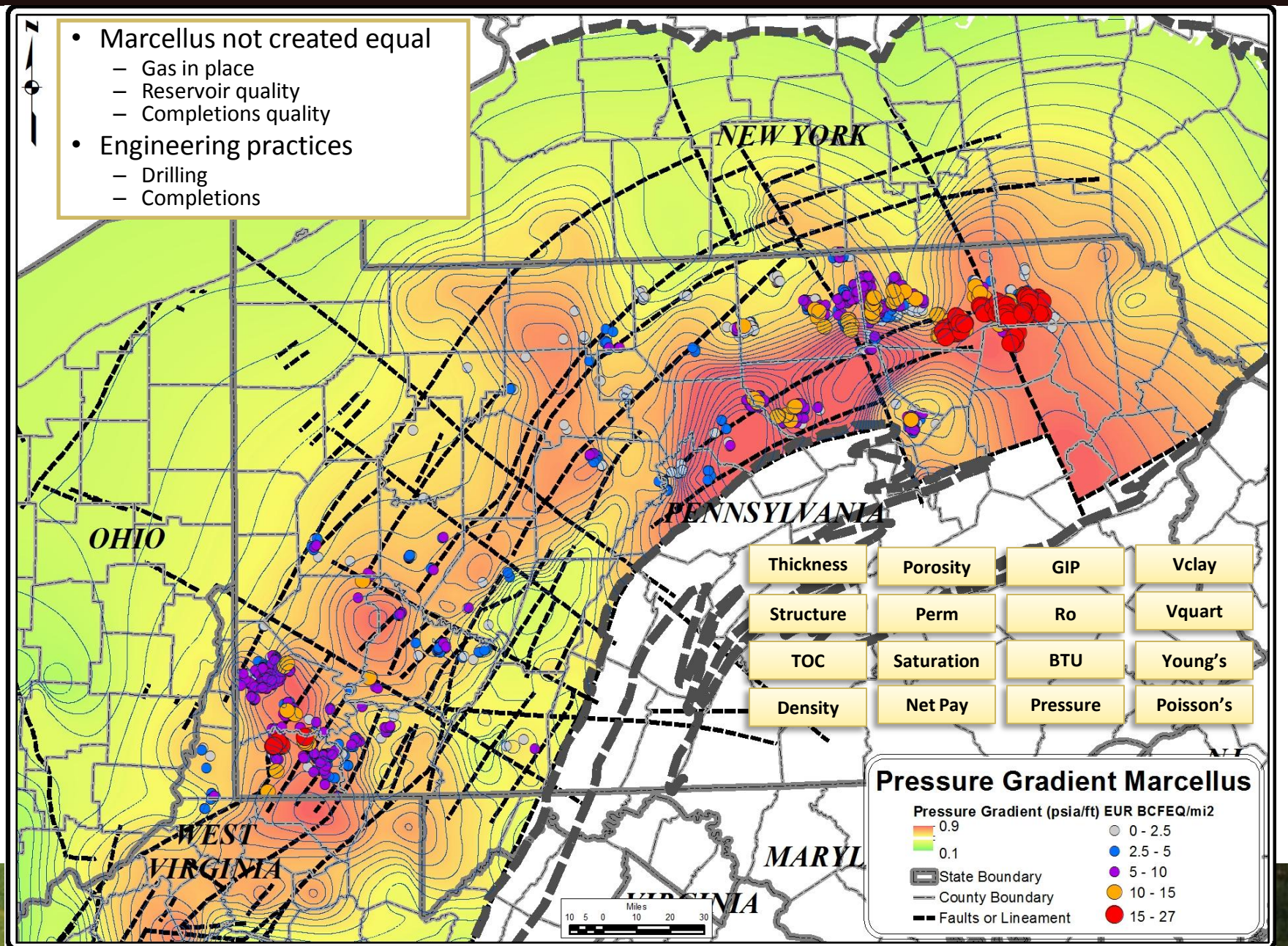
Marcellus: One of the World-Class Supergiant Gas Fields



- Marcellus fairway is 40,000 – 50,000 square miles
- Largest producing field in North America
- SW PA acreages produce dry gas, wet gas, and super rich gas with condensate



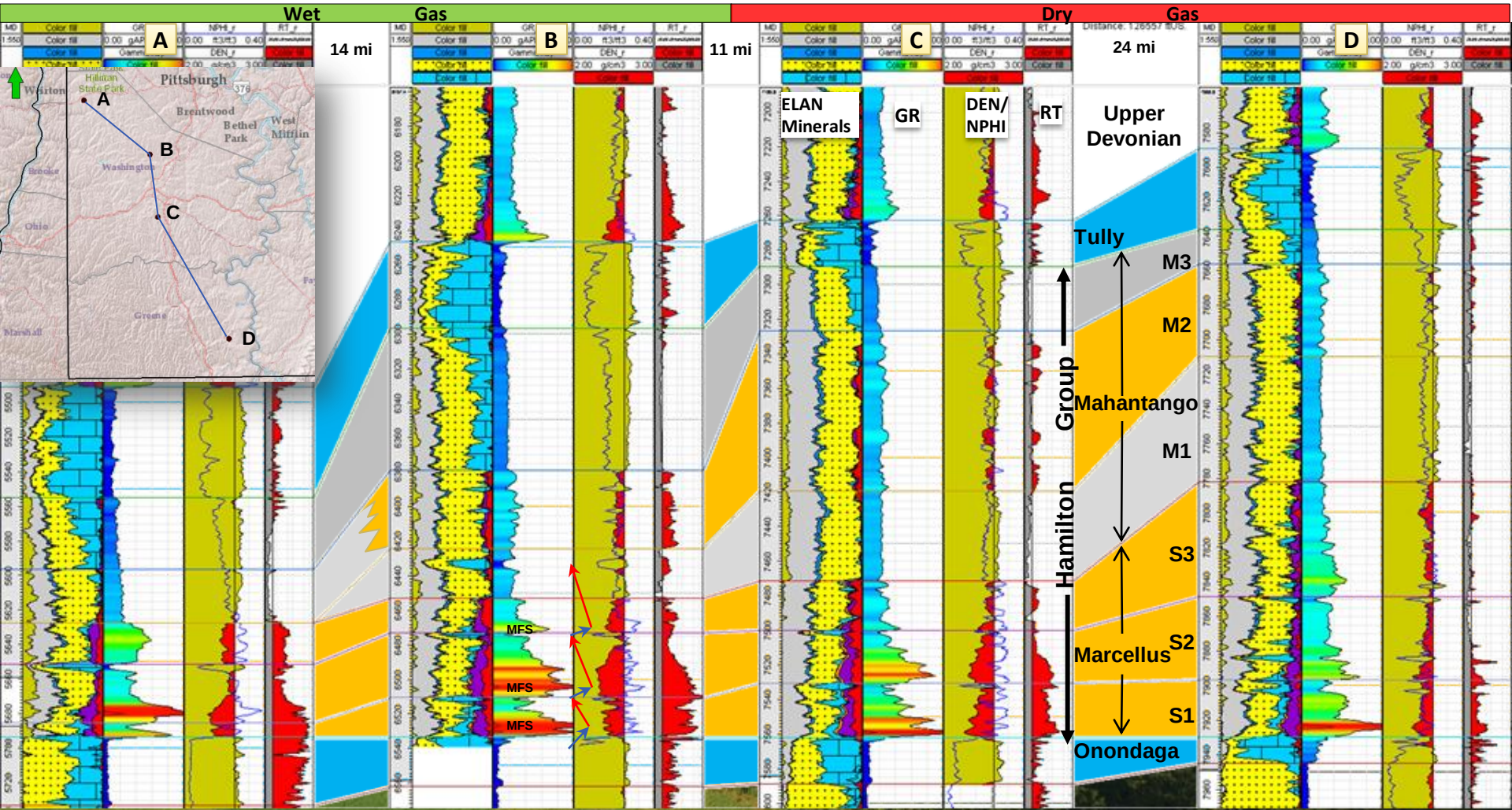
Regional Study to Define Play Variability



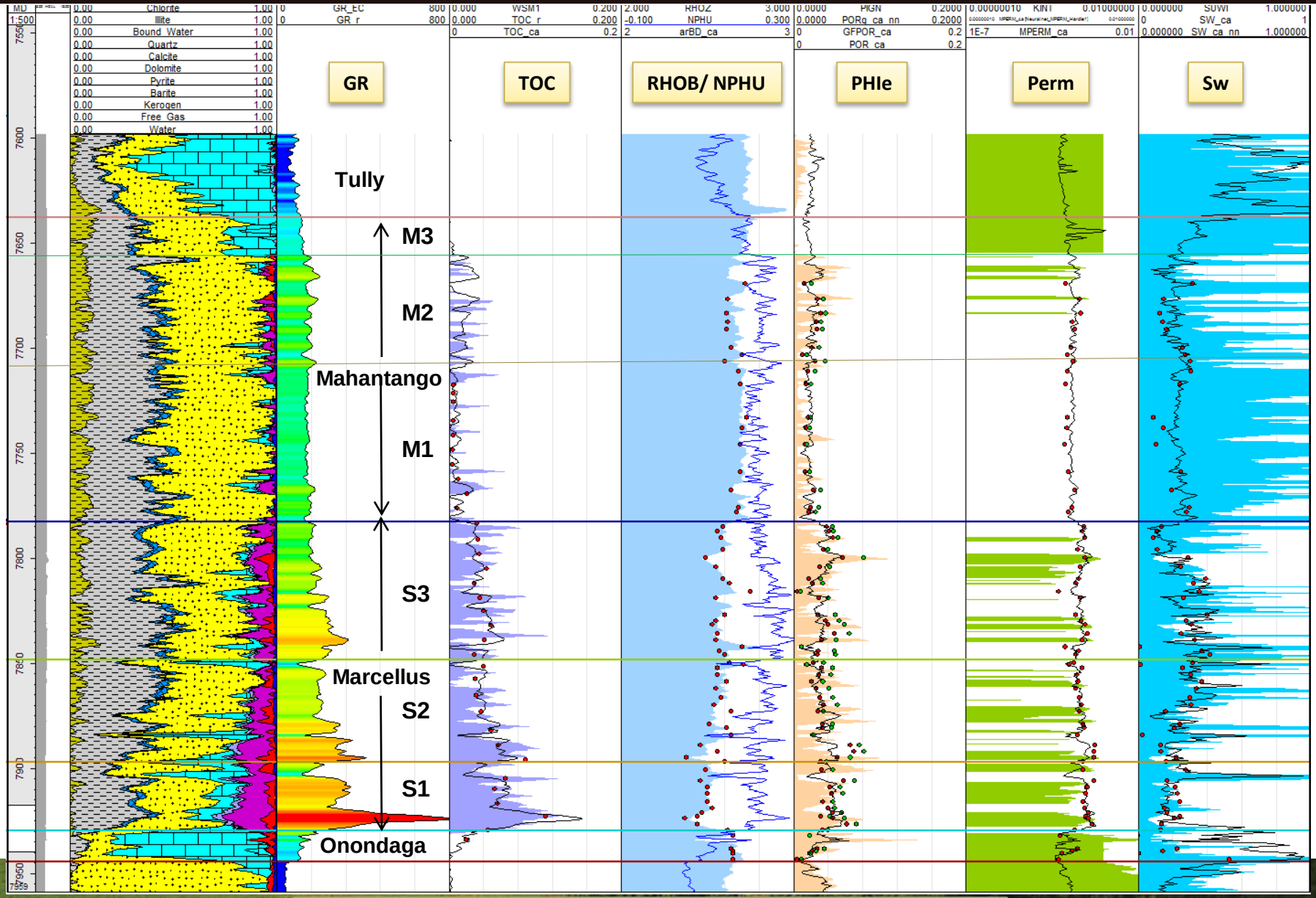
Stratigraphic Analysis

- Cyclic depositions (T/R sequences)
- 2 main pay packages in the Hamilton (S1-3, M2)
- Thickness and facies change from NW-SE
- Reservoir quality changes both horizontally and vertically

Organic Black shale log signature
- High GR
- Low bulk density
- High neutron porosity
- High resistivity

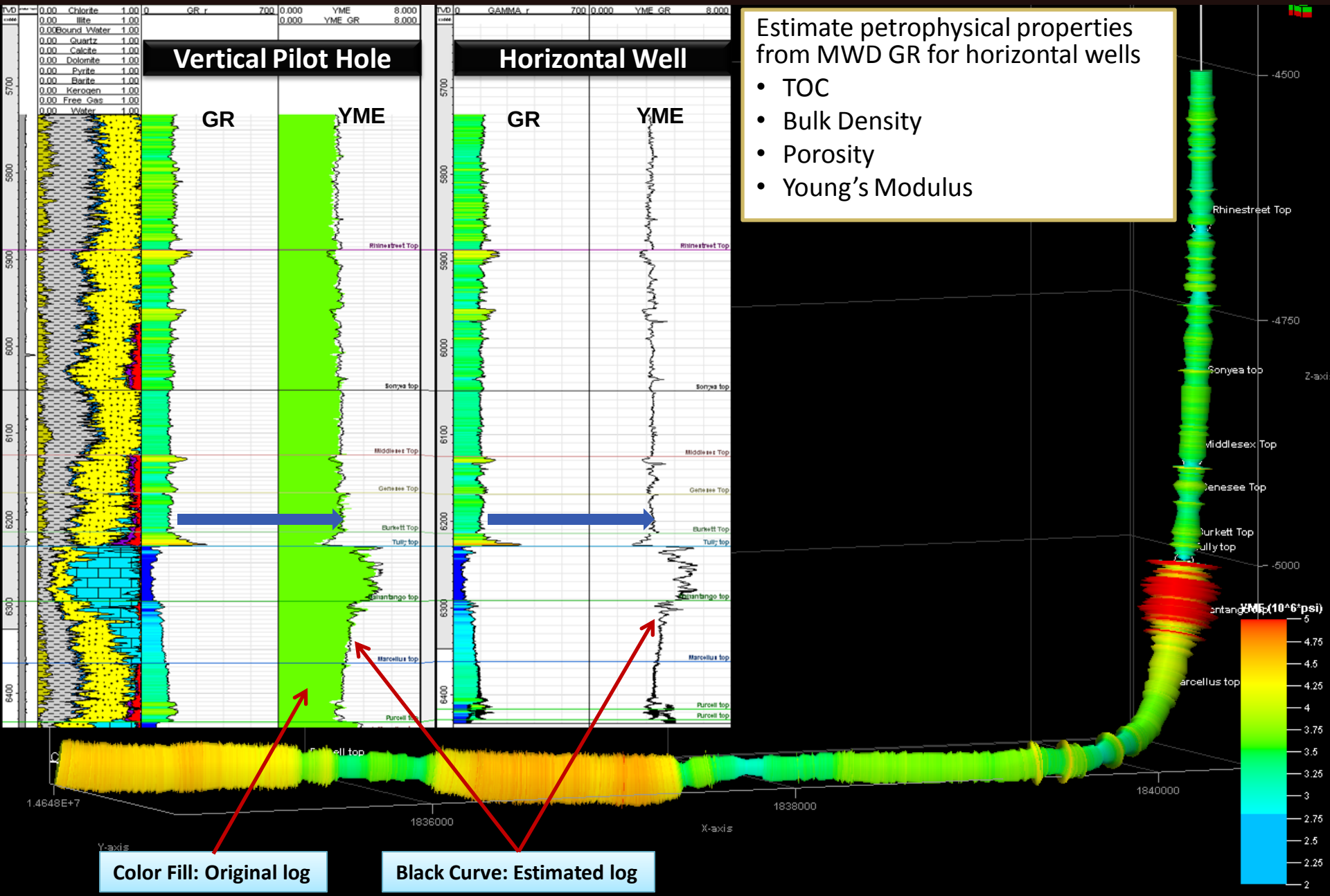


Log Analysis: Calibrated to Core Data



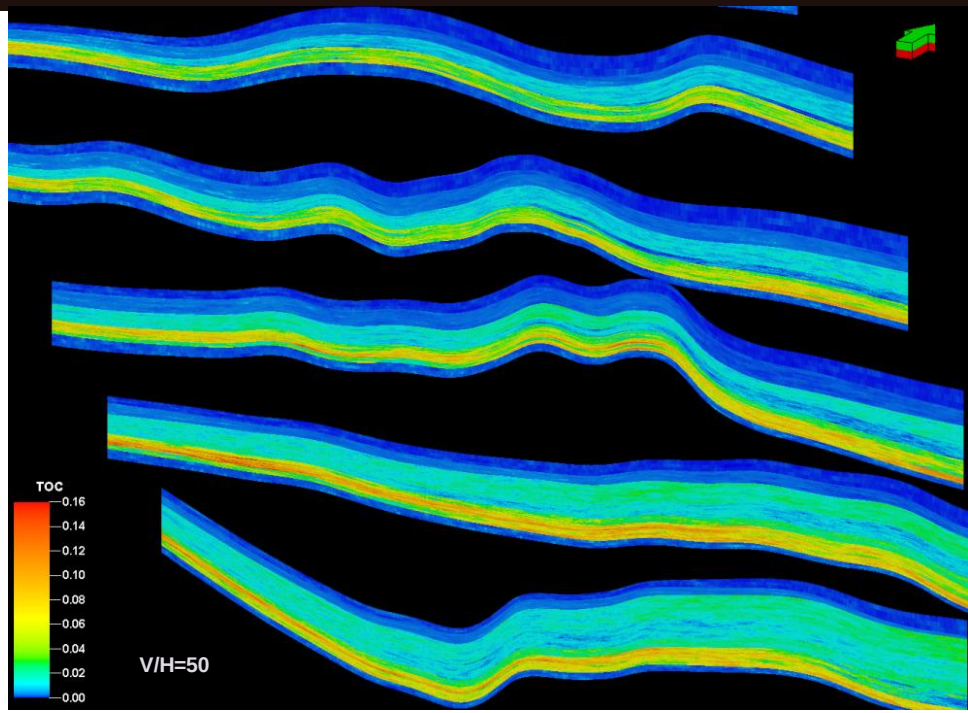
Color fill: original log Black curve: new log Dots: core measurement

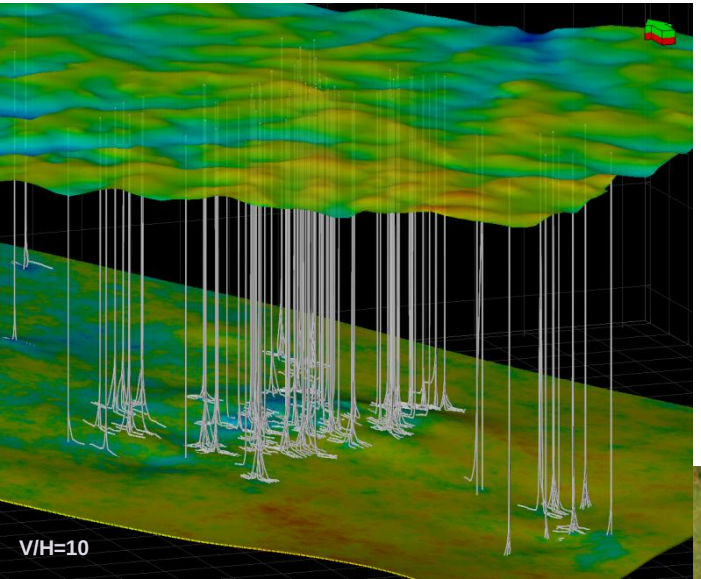
Petrophysic Characterization of Horizontal Wells

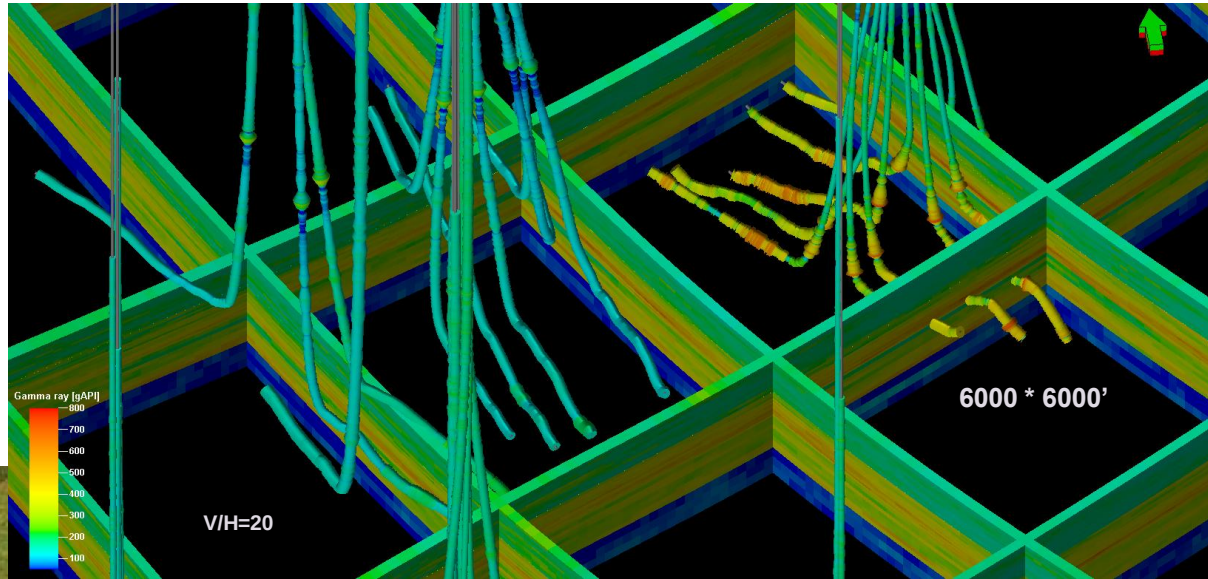


Shared Earth Modeling: Keep it alive

- Build 3D shared earth models at very early stage of field development (1st static modeling and dynamic simulation in 2008)
  - Provide static models for reservoir simulation
  - Help visual understanding of reservoir heterogeneity
  - Aid drilling/completions look-back studies
- Keep the models updated with new data



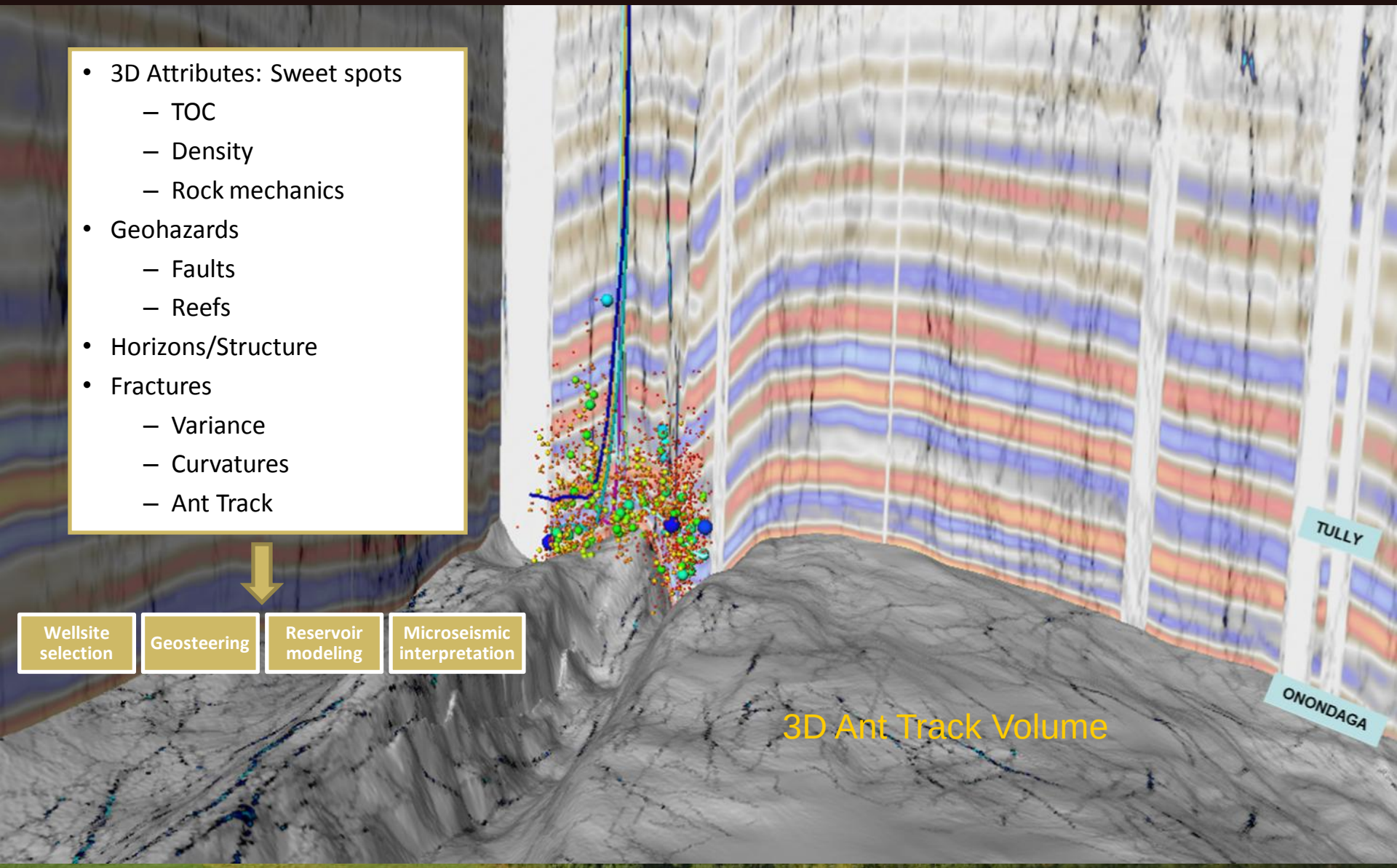




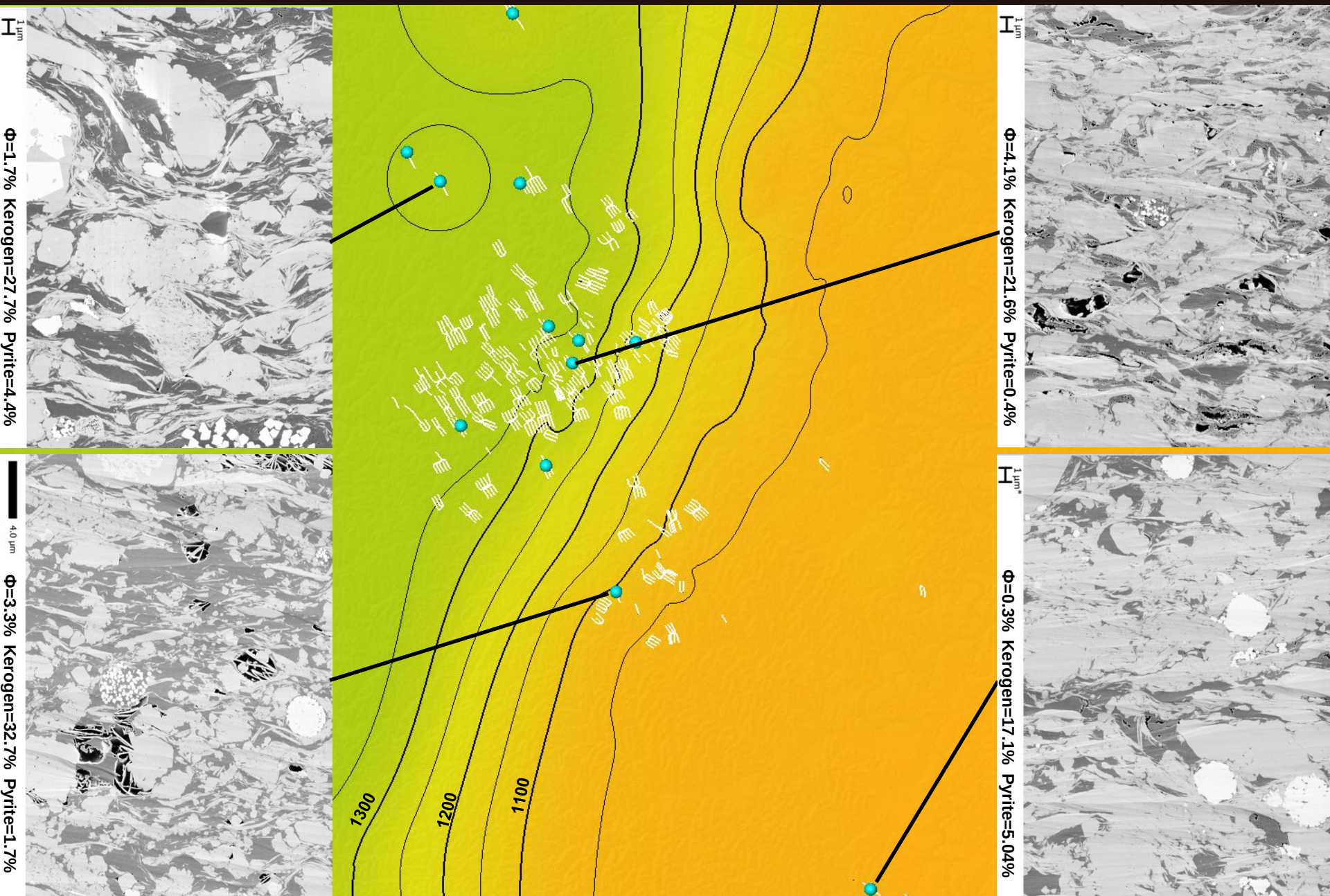
Seismic Interpretation and Applications

- 3D Attributes: Sweet spots
  - TOC
  - Density
  - Rock mechanics
- Geohazards
  - Faults
  - Reefs
- Horizons/Structure
- Fractures
  - Variance
  - Curvatures
  - Ant Track

Wellsite selection | Geosteering | Reservoir modeling | Microseismic interpretation

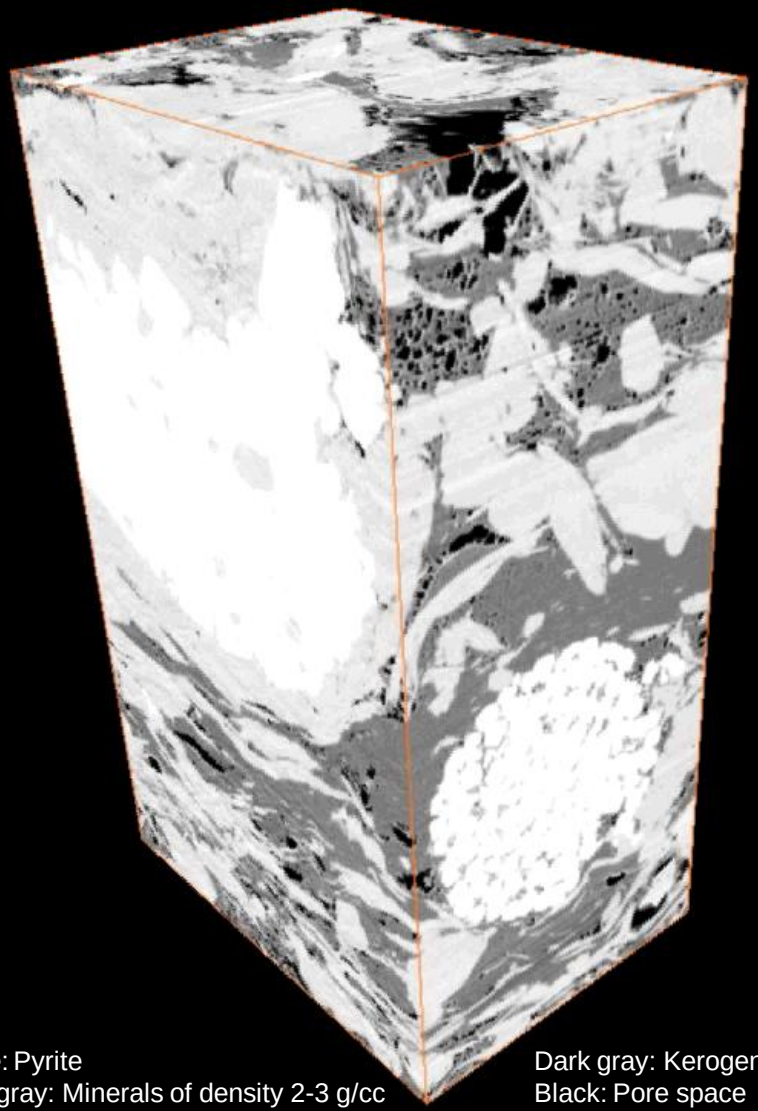


FIB-SEM Images Indicate Pore Development Variation across the Field



Marcellus 3D FIB-SEM Images (Wet Gas)

View video of pore geometry



White: Pyrite
Light gray: Minerals of density 2-3 g/cc

Dark gray: Kerogen
Black: Pore space

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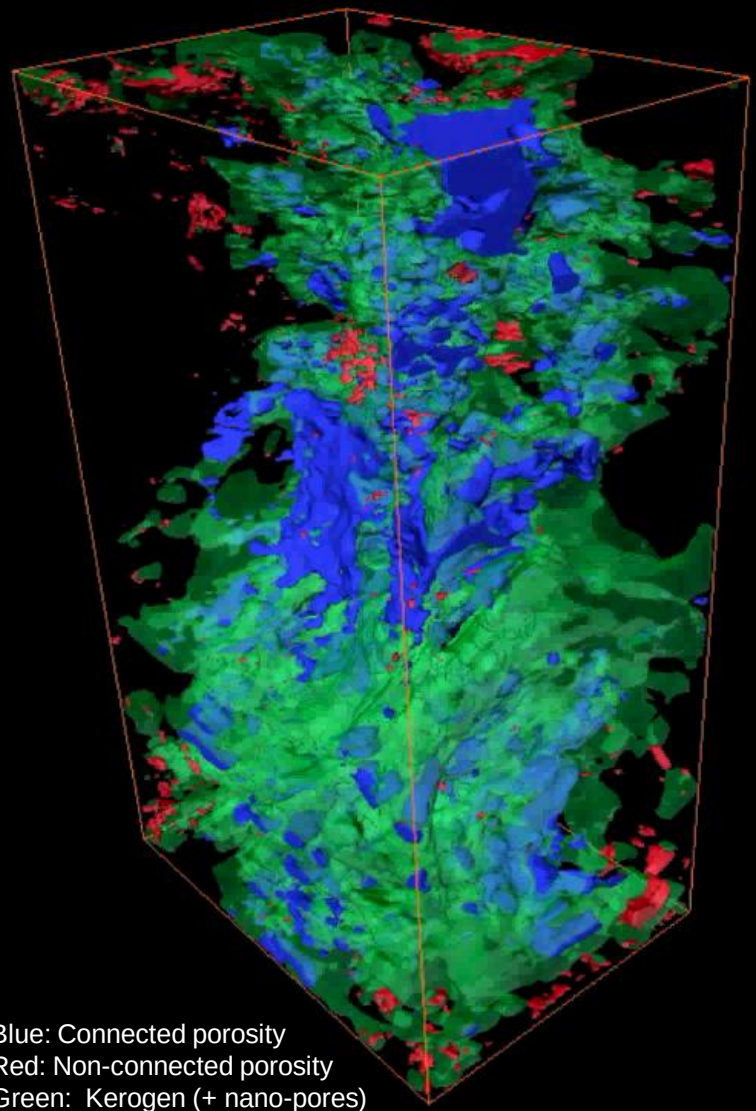

Blue: Connected porosity
Red: Non-connected porosity
Green: Kerogen (+ nano-pores)

Microns

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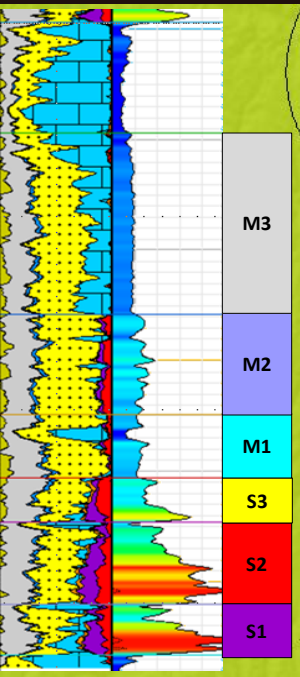
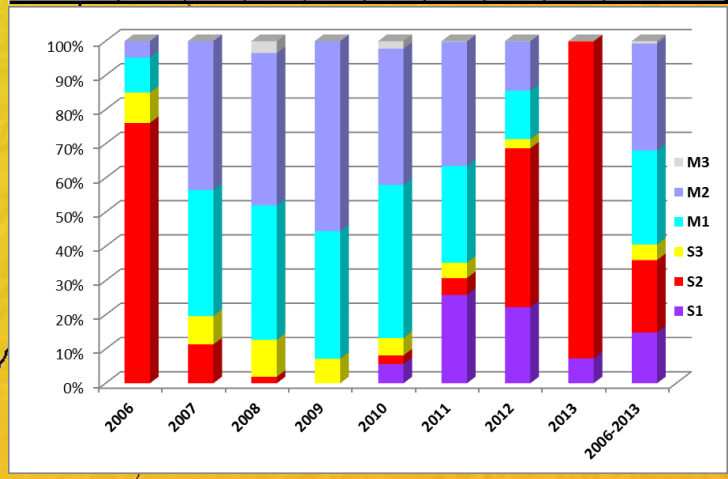
Majority of porosity and permeability is associated with kerogen. Three visible pore types; large mega pores, smaller pores, and a third textural indication any level of smaller pores below resolution and included in Kerogen in the right image.

Landing Target History and Variations

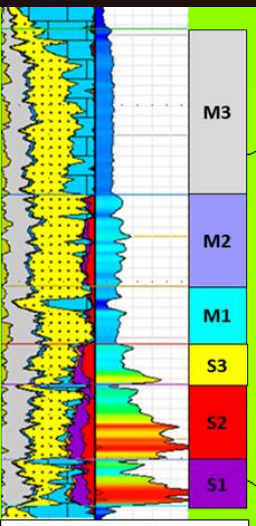


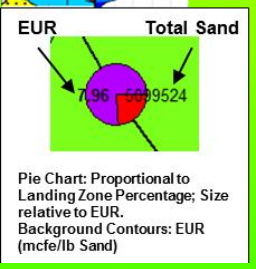
	2006	2007	2008	2009	2010	2011	2012	2013	2006-2013
M3	0%	0%	3%	0%	2%	0%	0%	0%	1%
M2	5%	44%	45%	56%	40%	36%	14%	0%	31%
M1	10%	37%	39%	37%	45%	28%	14%	0%	27%
S3	9%	8%	11%	7%	5%	5%	3%	0%	5%
S2	76%	11%	2%	0%	3%	5%	46%	93%	21%
S1	0%	0%	0%	0%	6%	26%	22%	7%	15%
Wells	3	9	26	54	98	149	125	37	501

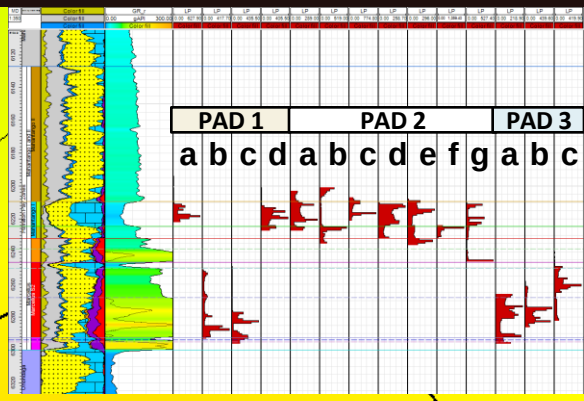


Landing in the Right Target Can Make a Huge Difference

- Pad 1 low-land wells have average 48% upside on mcfe per lb. of sand base
- Comparing Pad 2 and 3, low-land wells have 46% upside



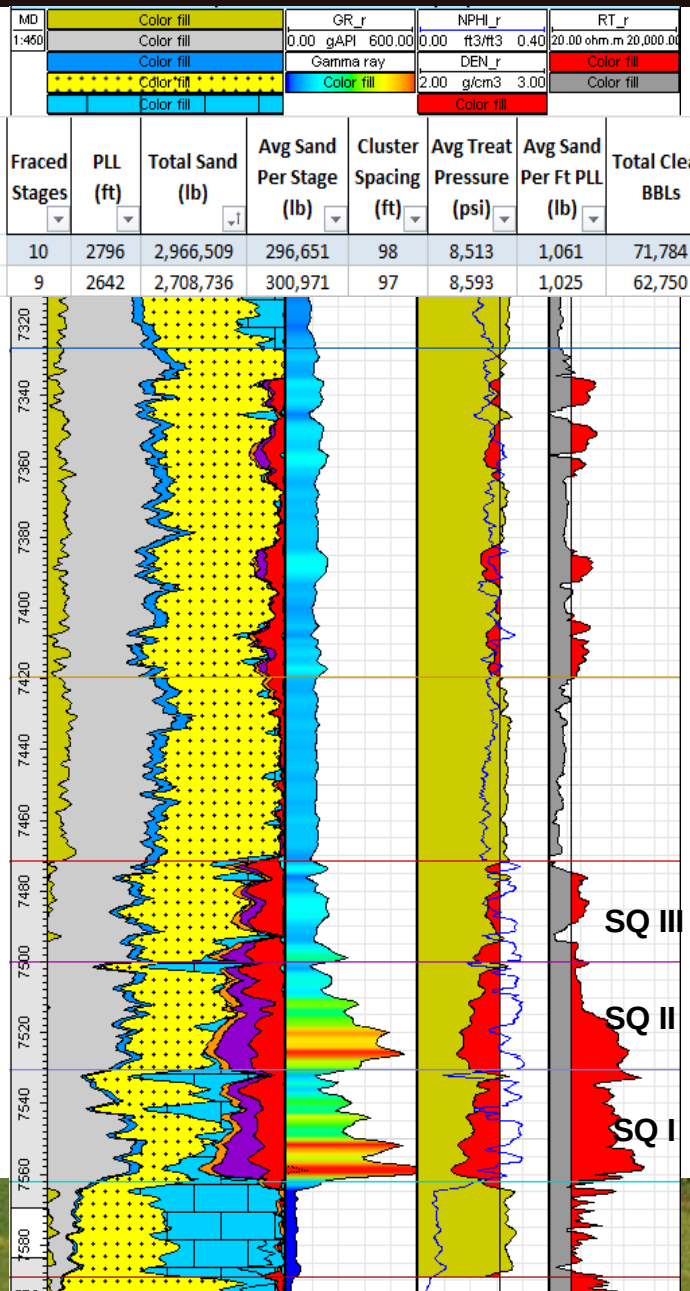


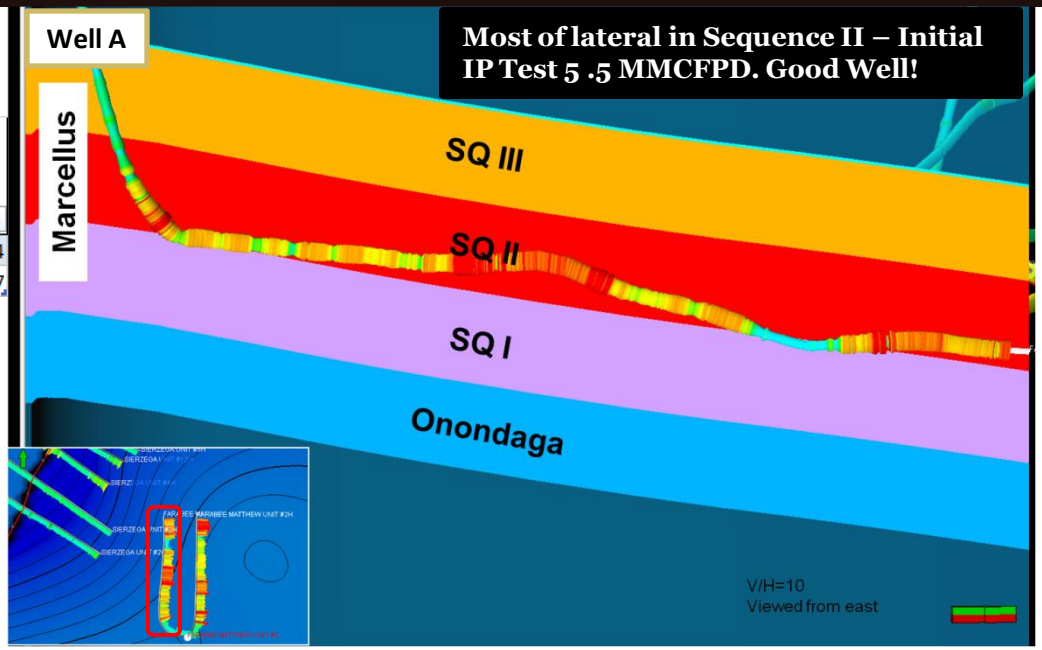


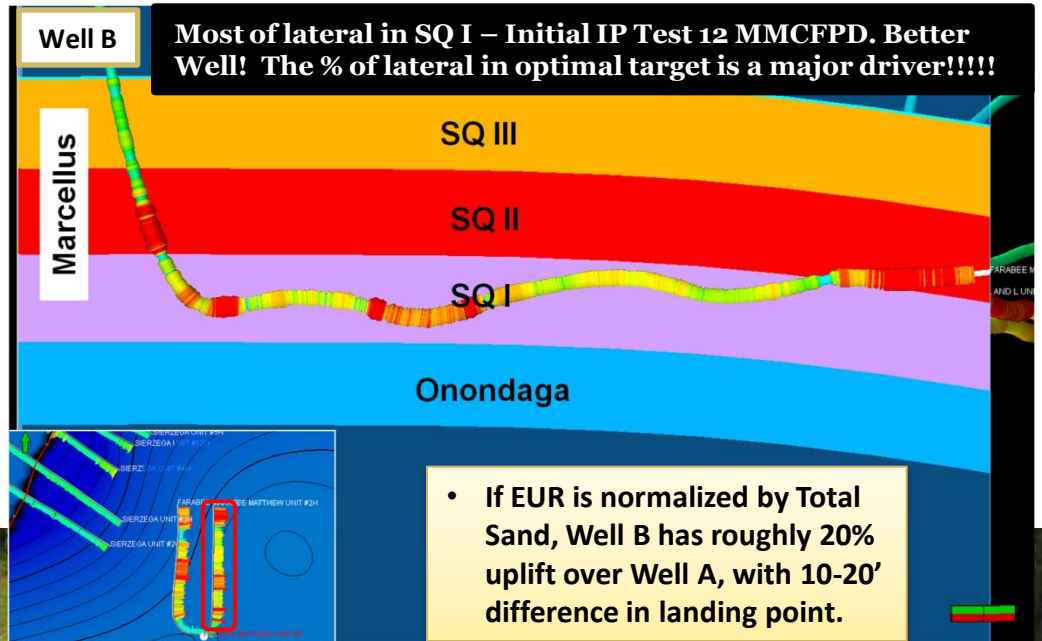
Well	Fraced Stages	PLL (ft)	Total Sand (lb)	Avg Sand Per Stage (lb)	Cluster Spacing (ft)	Avg Treat Pressure (psi)	Avg Sand Per Ft PLL (lb)	Total Clean BBLs	Avg Rate
P1a	14	2747	4,232,687	302,335	67	6,898	1,541	92,344	69
P1b	14	2747	4,258,487	304,178	67	6,973	1,550	94,018	68
P1c	15	2948	4,290,988	286,066	67	7,033	1,456	116,133	67
P1d	14	2747	4,164,506	297,465	67	7,114	1,516	105,321	67
P2a	13	2546	3,937,202	302,862	67	6,837	1,546	97,415	69
P2b	13	2747	3,863,166	297,167	67	6,929	1,406	102,321	63
P2c	13	2546	2,658,077	204,468	67	6,828	1,044	92,010	69
P2d	13	2546	2,636,464	202,805	67	6,984	1,036	91,351	69
P2e	14	2747	4,241,077	302,934	67	6,937	1,544	107,092	69
P2f	13	2546	3,909,855	300,758	67	6,591	1,536	100,633	69
P2g	13	2546	3,948,221	303,709	67	6,795	1,551	100,317	67
P3a	14	2715	4,211,186	300,799	67	7,232	1,551	105,168	70
P3b	14	2737	4,305,315	307,523	67	7,059	1,573	101,093	70
P3c	14	2723	4,335,056	309,647	67	6,937	1,592	101,420	70

Landing Point Analysis (Dry Gas)

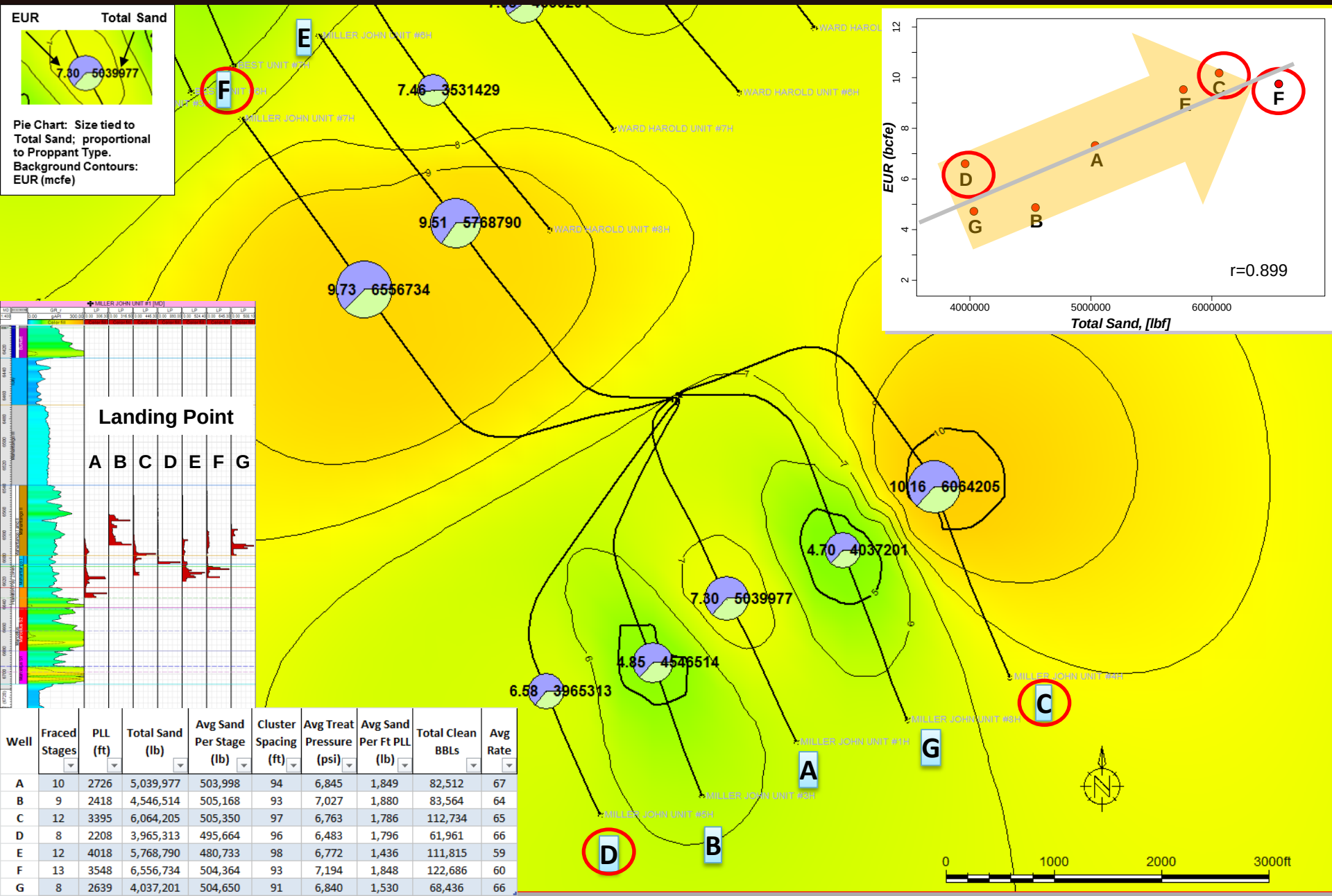
Well	Fraced Stages	PLL (ft)	Total Sand (lb)	Avg Sand Per Stage (lb)	Cluster Spacing (ft)	Avg Treat Pressure (psi)	Avg Sand Per Ft PLL (lb)	Total Clean BBLs	Avg Rate
A	10	2796	2,966,509	296,651	98	8,513	1,061	71,784	64
B	9	2642	2,708,736	300,971	97	8,593	1,025	62,750	67







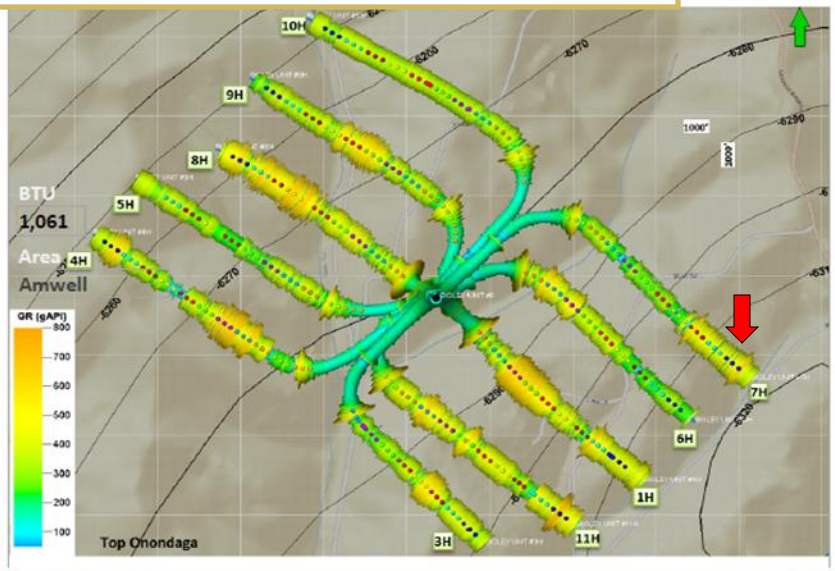
Completions Case Study: EUR vs. Total Sand

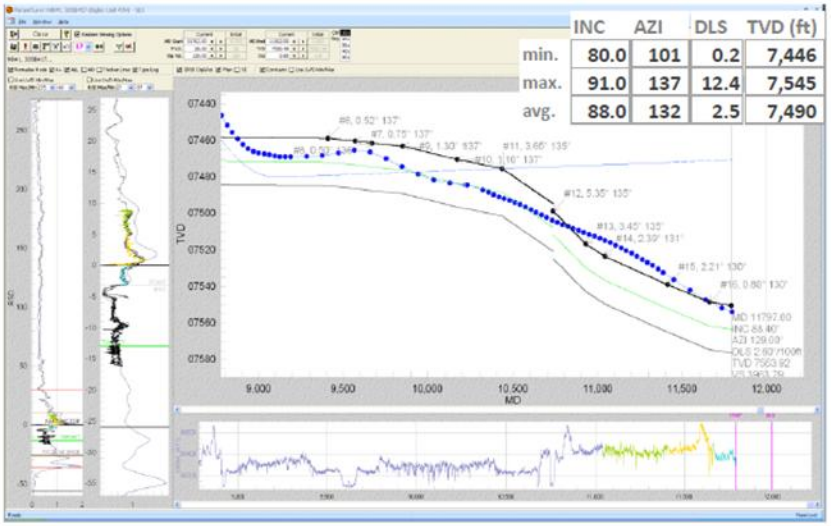


Well	Fraced Stages	PLL (ft)	Total Sand (lb)	Avg Sand Per Stage (lb)	Cluster Spacing (ft)	Avg Treat Pressure (psi)	Avg Sand Per Ft PLL (lb)	Total Clean BBLs	Avg Rate
A	10	2726	5,039,977	503,998	94	6,845	1,849	82,512	67
B	9	2418	4,546,514	505,168	93	7,027	1,880	83,564	64
C	12	3395	6,064,205	505,350	97	6,763	1,786	112,734	65
D	8	2208	3,965,313	495,664	96	6,483	1,796	61,961	66
E	12	4018	5,768,790	480,733	98	6,772	1,436	111,815	59
F	13	3548	6,556,734	504,364	93	7,194	1,848	122,686	60
G	8	2639	4,037,201	504,650	91	6,840	1,530	68,436	66

- **Compile a database-based Well Review Book integrating data from wellbores, geosteer, reservoir quality, completions, and IP/EUR for over 500 horizontal wells**

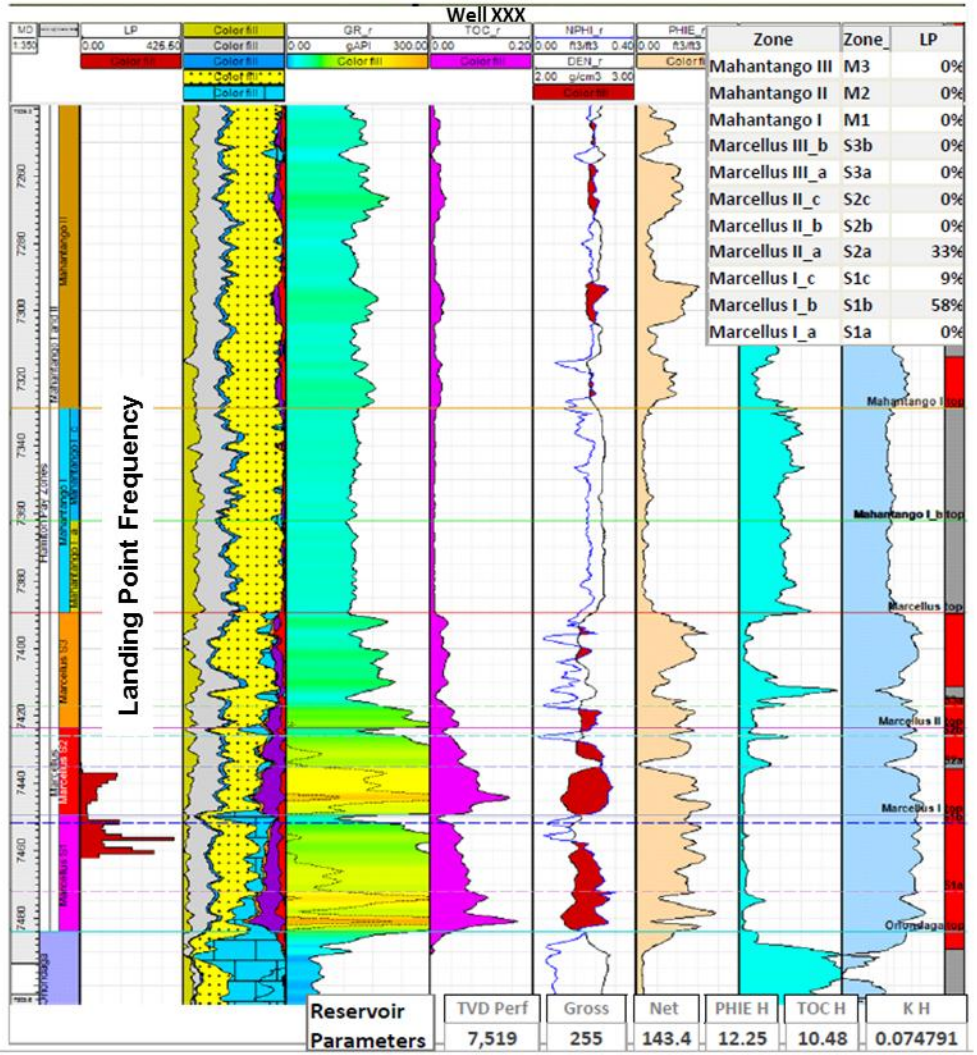
Max 24hr Rate Gas MCF	Max 24hr Rate Bbl Cond	Max 24hr Rate MCFE	30 Day Avg MCFGPD	30 Day Avg BCPD	30 Day Avg MCFEPD	EUR (bcfe)	EUR (mcfe) per LB Sand	EUR 1000' PLL (bcfe)
16,006	0	16,006	13,464	0	13,464	7.28	2.471	2.589





	INC	AZI	DLS	TVD (ft)
min.	80.0	101	0.2	7,446
max.	91.0	137	12.4	7,545
avg.	88.0	132	2.5	7,490

Land Point Frequency Plotted with Type Logs



Zone	Zone_	LP
Mahantango III	M3	0%
Mahantango II	M2	0%
Mahantango I	M1	0%
Marcellus III_b	S3b	0%
Marcellus III_a	S3a	0%
Marcellus II_c	S2c	0%
Marcellus II_b	S2b	0%
Marcellus II_a	S2a	33%
Marcellus I_c	S1c	9%
Marcellus I_b	S1b	58%
Marcellus I_a	S1a	0%

Reservoir Parameters	TVD Perf	Gross	Net	PHIE H	TOC H	K H
	7,519	255	143.4	12.25	10.48	0.074791

Fraced Stages	Mid MD 1st Perf Cluster	Mid MD Last Perf CLuster	PLL (ft)	Cluster Spacing	Total Clean BBLs	100 Mesh Total (lb)	30/50 Total (lb)	40/70 Total (lb)	Total Sand (lb)	Avg Sand Per Stage	Avg Sand Per Ft PLL (lb)	Avg Treat Pressure (psi)
10	11588.5	8775.5	2813	97	73,237	1,744,988	1,201,715	0	2,946,703	294,670	1,048	7,692

Lessons Learned

- A robust geological understanding is critical to our shale gas operations
- A well-planned field development strategy and timely and on-going review is vital to our success of large-scale shale gas development
- A small change in targeting and completions could make a big difference and creates huge impact considering number of wells to be drilled
- As a geoscientist, you can define sweet spots at many different scales, from regional, through local, and down to microscopic level