PSUniting Petrophysics and Stratigraphy to Decipher Classified Facies from a Pre-Stack 3D Inversion: Wolfcamp and Spraberry, Howard County, Midland Basin*

Stephen P. Gardner[1], Katie-Joe McDonough[2], Robert Lieber[3], Ray Vogler[4], Scott Cook[5], and Michael Pollachek[5]

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Abstract

Geologically-constrained prestack 3D seismic inversion can potentially predict reservoir properties ahead of the drill bit. Using a 3D seismic dataset from the Midland Basin, we integrate prestack seismic inversion with petrophysics and sequence stratigraphy to derive reservoir facies architecture and corresponding geomechanics. This multi-disciplinary collaboration results in seismic volumes of classified lithofacies and geomechanical properties that assist Wolfberry exploitation, and is testimony to achieving full value from 3D seismic data in an unconventional play.

The Wolfcamp and Spraberry (Wolfberry) sections lie in toe-of-slope depositional positions within the Midland Basin. Production is from organic-rich, transgressive basinal mudstones interbedded with siliciclastic and carbonate debrite and turbidite beds. Optimal completions practices rely on fully understanding the lateral and vertical distribution of the desired mudrock source beds.

Prestack inversion allows capturing of shear wave velocity information, otherwise lost in the offset domain of poststack inversion. Prestack inversion provides P and S impedance (I_p and I_s) which in turn yield elastic constants Lambda and Mu. Petrophysically-defined, wireline log-derived facies classifications can be cross-plotted to define Lambda-Rho, Mu-Rho (LMR) regions. Comparing Lambda-Mu-Rho (LMR) cross plots calculated from the well log data with similar data derived from inverted seismic impedances helped delineate facies families, or depositional trends within the 3D seismic. Wolfberry lithofacies and geomechanical properties were thus highlighted from inversion results and mapped into the sequence-scale basin architecture. Geomechanical parameters were defined from the inversion results at a scale useful for completion engineers. This up-scaling of the petrophysical solution yields vertical resolution of the inversion comparable with the scale of mechanical stratigraphy that controls well completions.

Using a properly processed seismic dataset as input, prestack seismic inversion deliverables (Ip and Is) were used in conjunction with petrophysics to define facies and geomechanical parameters critical to efficient exploitation. Because of its superior areal extent and degree of spatial sampling, 3D seismic data can be extensively mined for reservoir properties and geomodel characteristics to become the canvas for a multidisciplinary compilation for any given unconventional play.

Uniting Petrophysics and Stratigraphy to Decipher Classified Facies From a PreStack 3D Inversion, Wolfcamp and Spraberry, Midland Basin

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[1]LAGO PETROLEUM CONSULTING, [2]KJM CONSULTING, [3]CORSAIR PETROPHYSICS, [4]NEOS, [5]CONSULTANT

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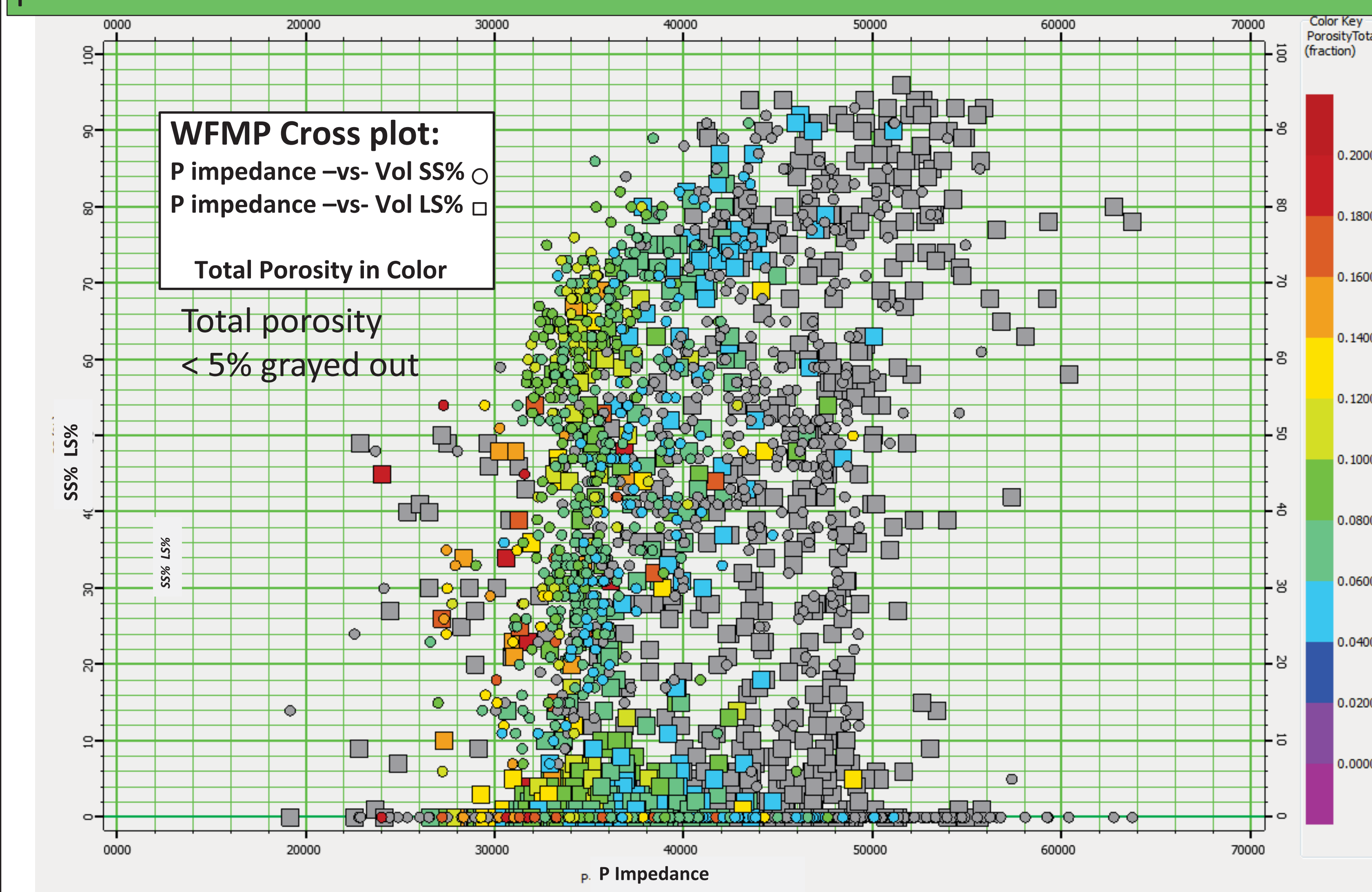
Key challenge:
To expand the utility of 3D seismic into the realm of unconventional reservoir exploitation by mining the wealth of lithofacies information contained within the seismic wavelet. We can do more than mere hazards-avoidance with all those 3D volumes!

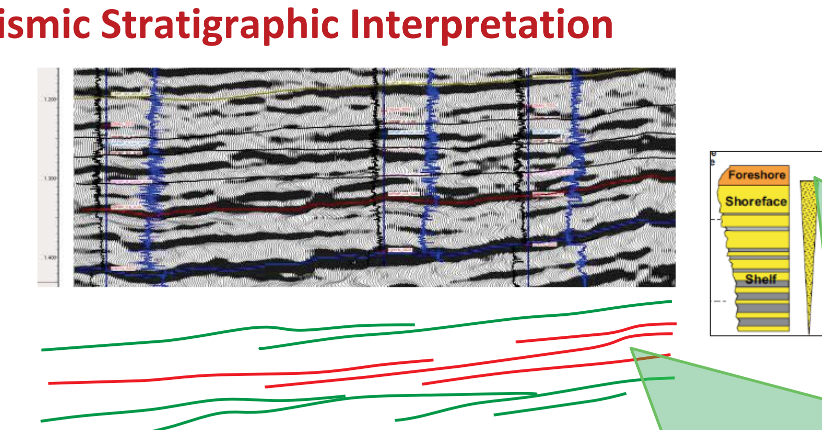
Our response to the challenge:
Relate variable mudstone reservoir composition and facies to seismic prestack inversion via petrophysically-defined facies classifications. Then map mudrock facies within 3D volume.

Problem:
Cannot differentiate lithology based upon P impedance alone –which is output of poststack inversion!

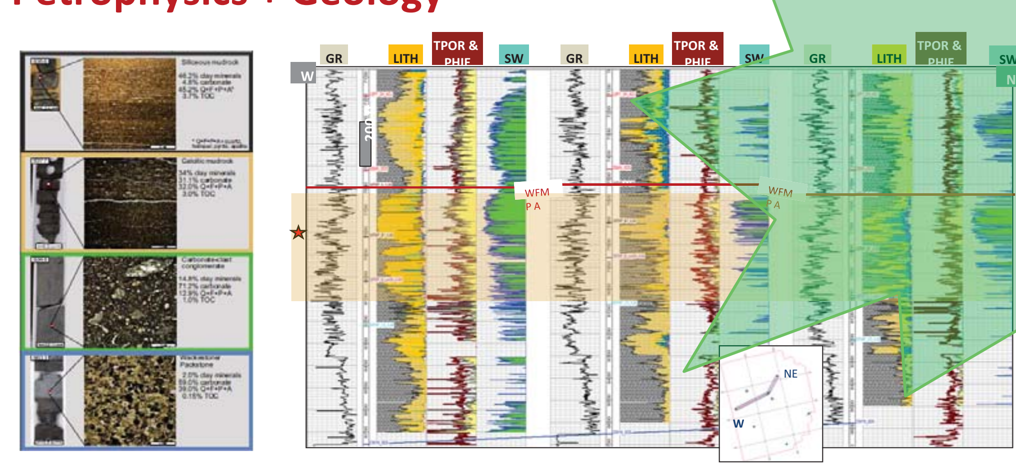


Multi-disciplinary Data Integration:

Seismic Stratigraphic Interpretation

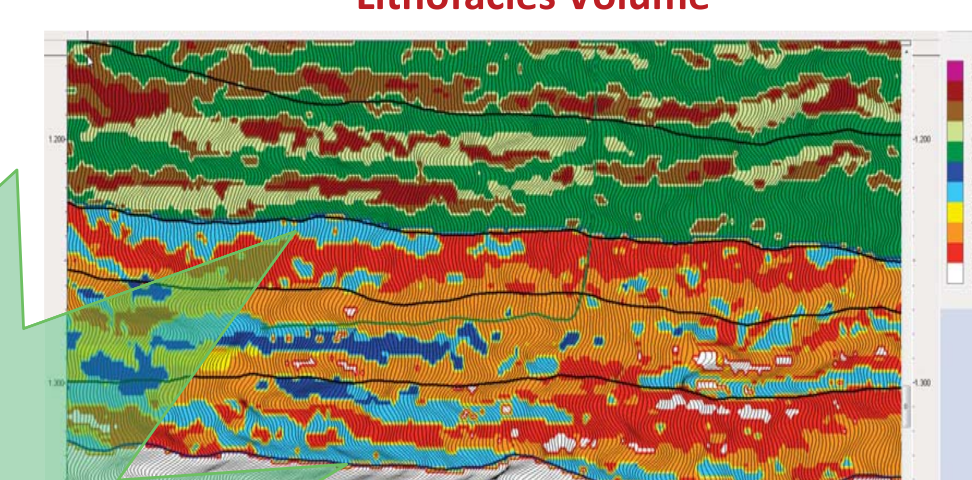


Petrophysics + Geology

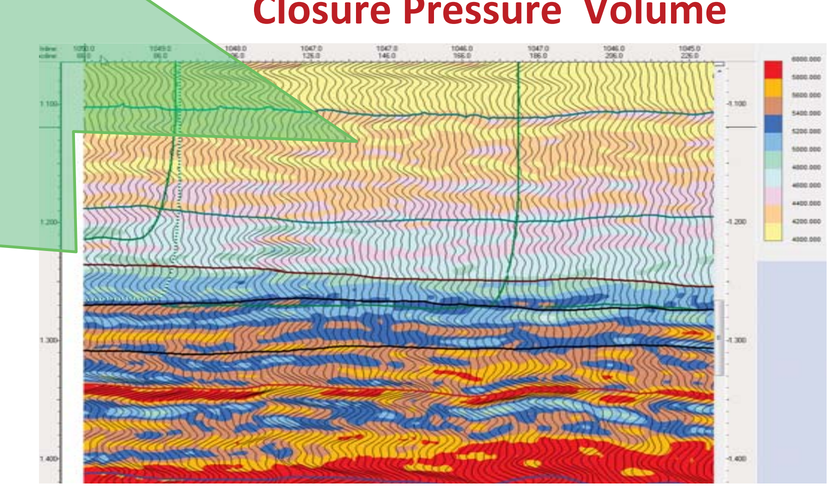


Achieves optimum value from 3D seismic by incorporating stratigraphic, lithologic, petrophysical info

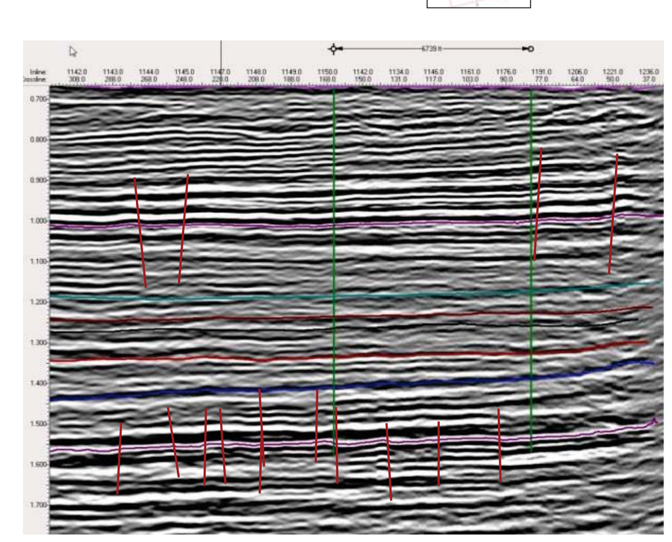
Lithofacies Volume



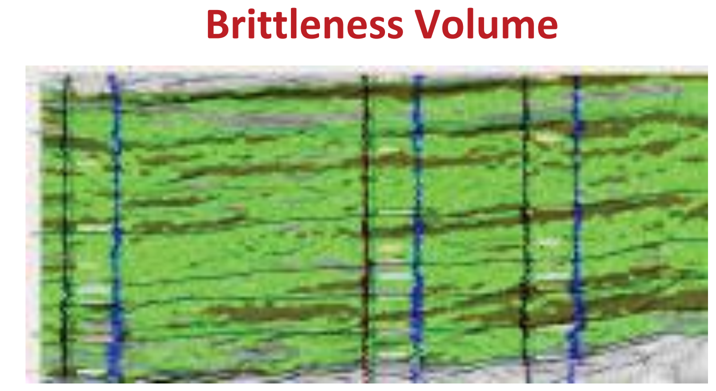
Closure Pressure Volume



Structural Interpretation



Brittleness Volume



- Geomechanical stratigraphy
- Rock fabric
- Net fracture pressure controls

Acknowledgements
We acknowledge Tall City and Surge for giving permission to work on and show this data. We also thank Sterling Seismic Services Ltd for use and permission to show portions of the Hammer 3D survey.

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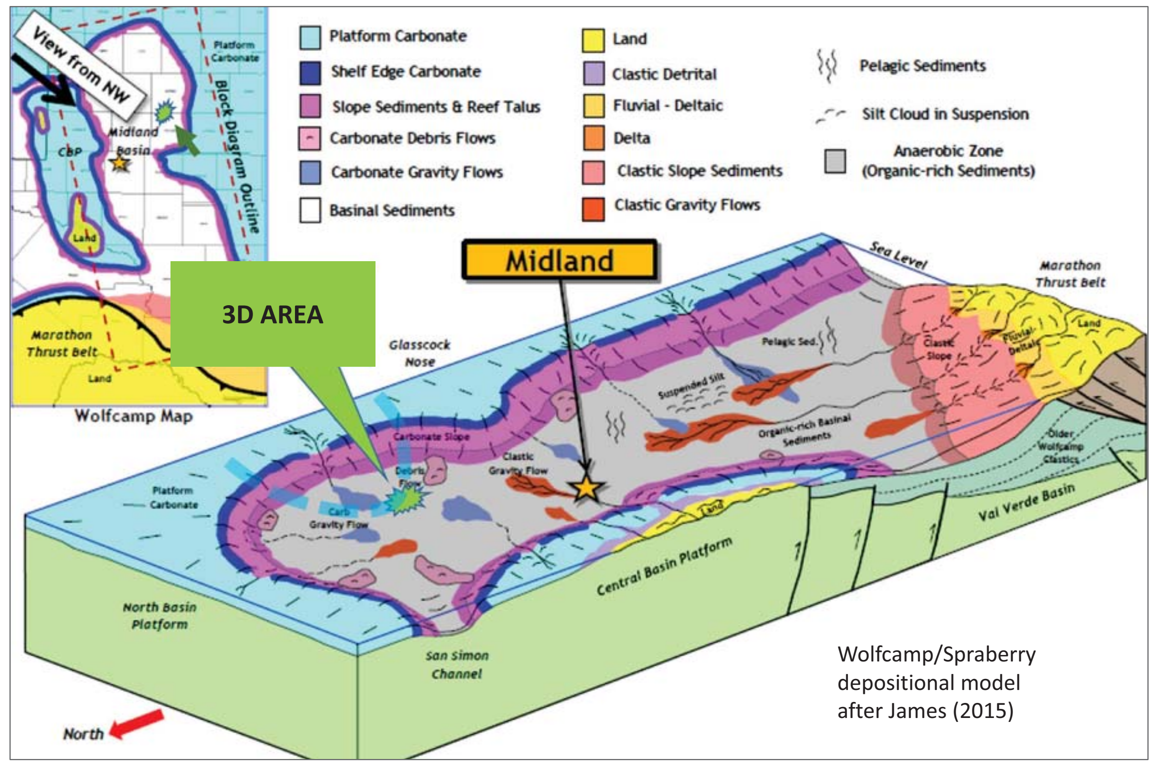
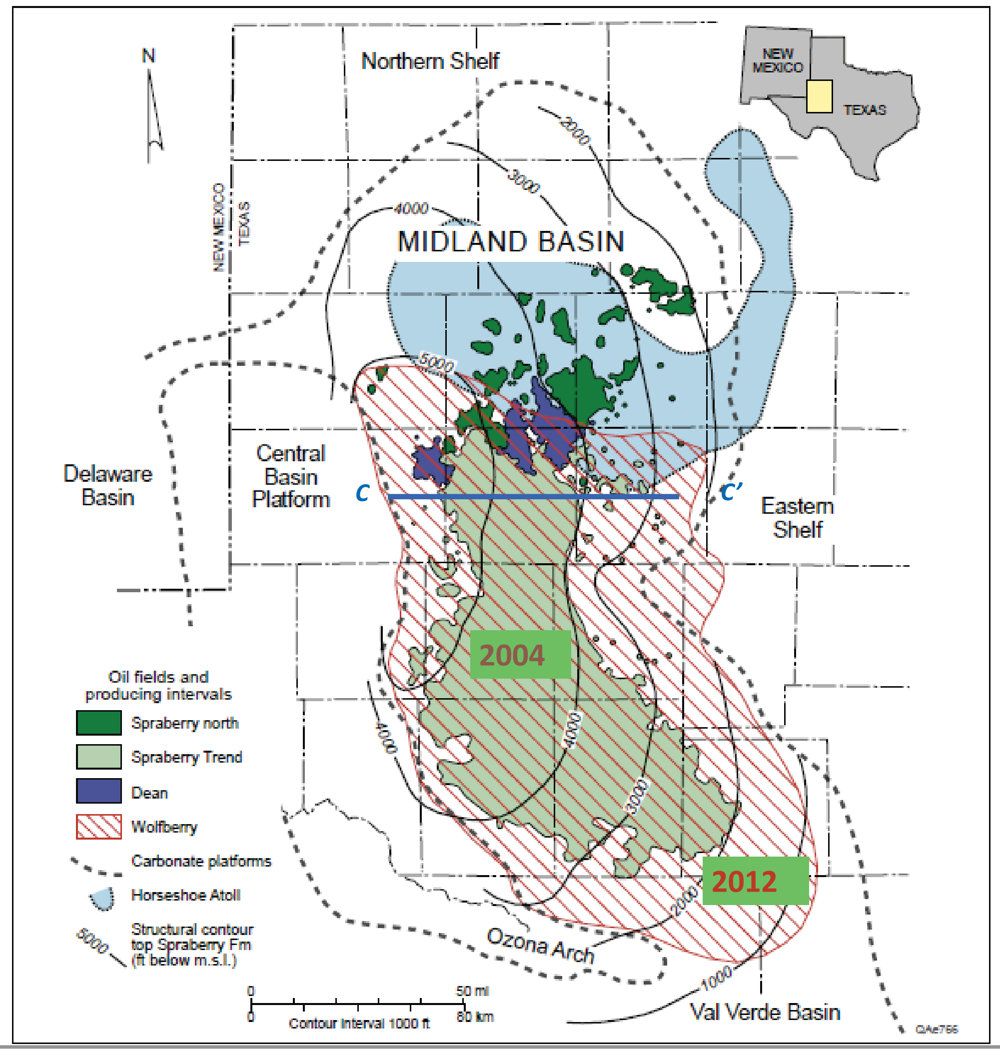
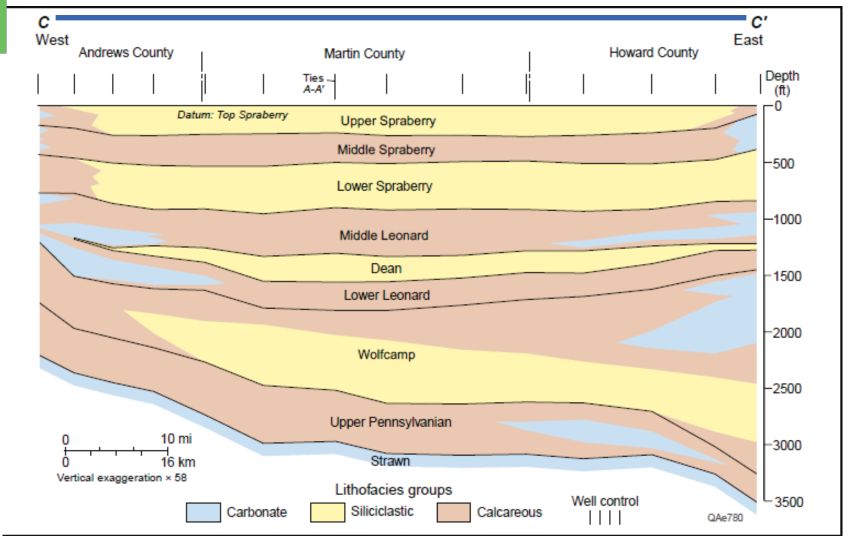


Wolfcamp:
- Toe-of-slope with nearby carbonate margin rimming basin
- Laminated mudrocks interbedded with carbonate debrites
- Siliceous and carbonate mudrock (reservoir) composition varies cyclically

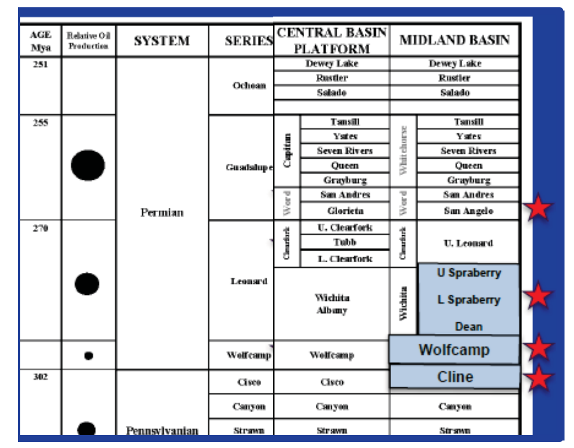
Spraberry:
- Toe-of-slope, low-gradient depositional setting
- Laminated mudrocks interbedded with turbidite/fan lobe siltstones
- More siliceous mudrock (reservoir) composition; siltstones also reservoirs

Midland Basin Wolfberry Play—Still Expanding



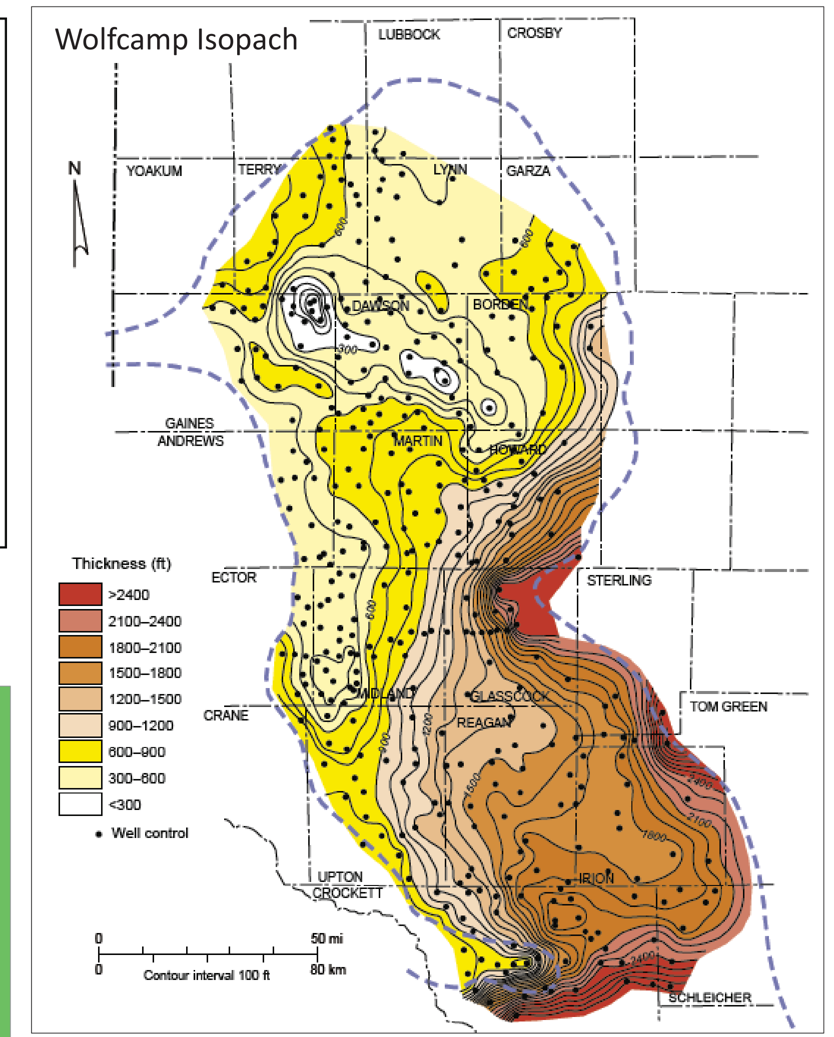


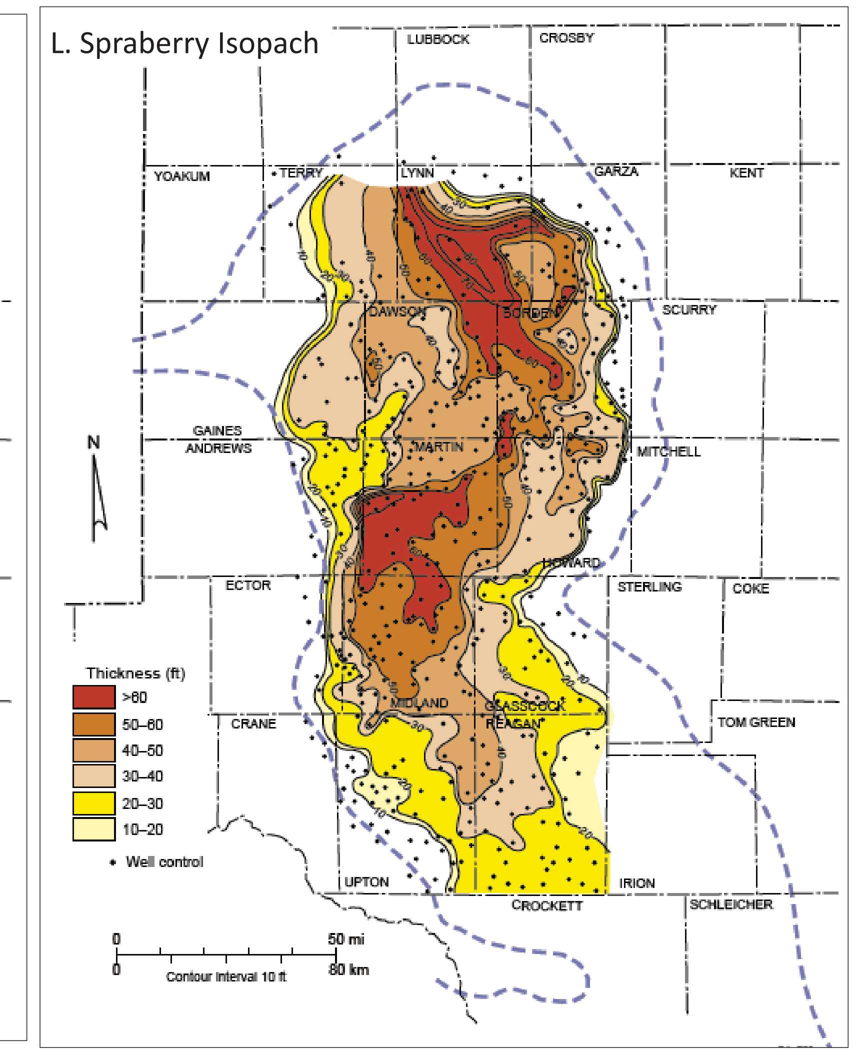
Maps and cross section from Hamlin & Baumgardner (2012)



Wilson (2015)

Wolfcamp vs Spraberry depositional systems differ in style and sediment source direction.



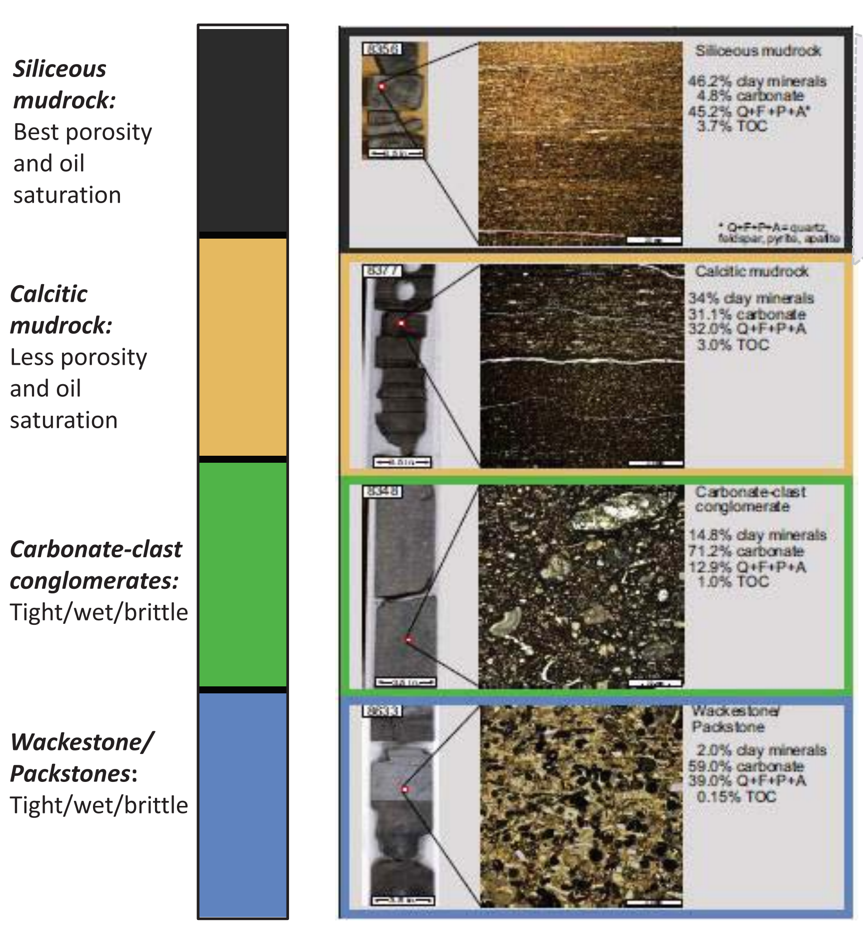


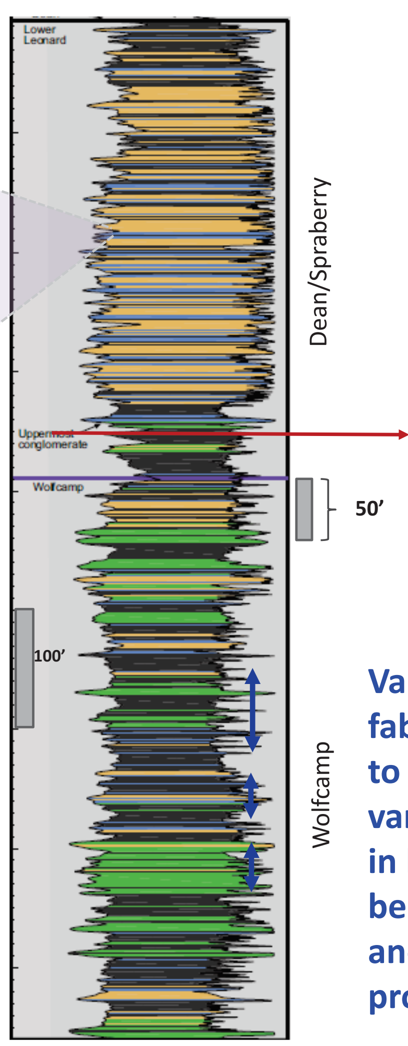
Therefore we expect differing lithofacies, petrophysical models, and reservoir distribution.

Developing a Petrophysical Model

Wolfcamp core/thin-section lithofacies

from Baumgardner & Hamlin (2014)

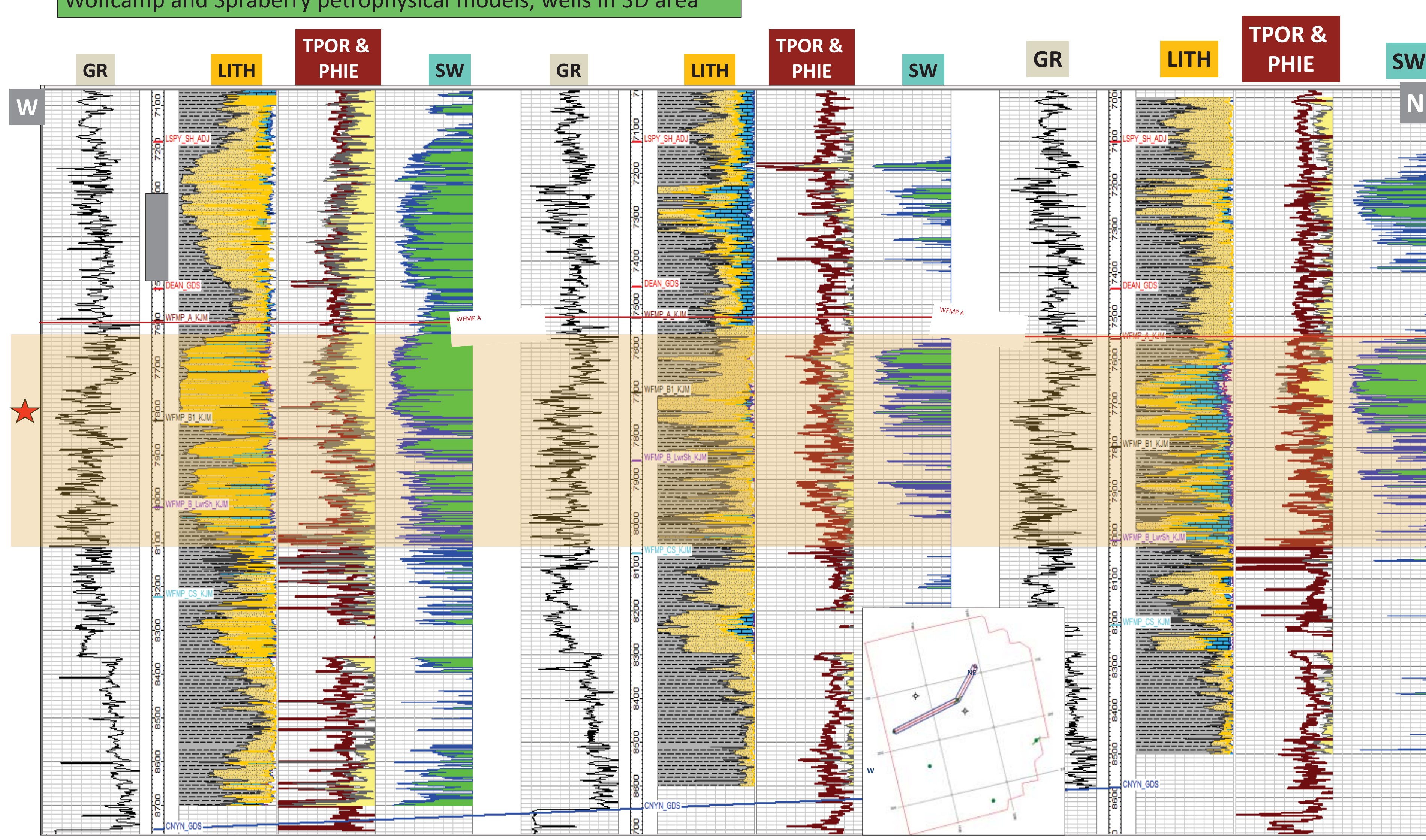


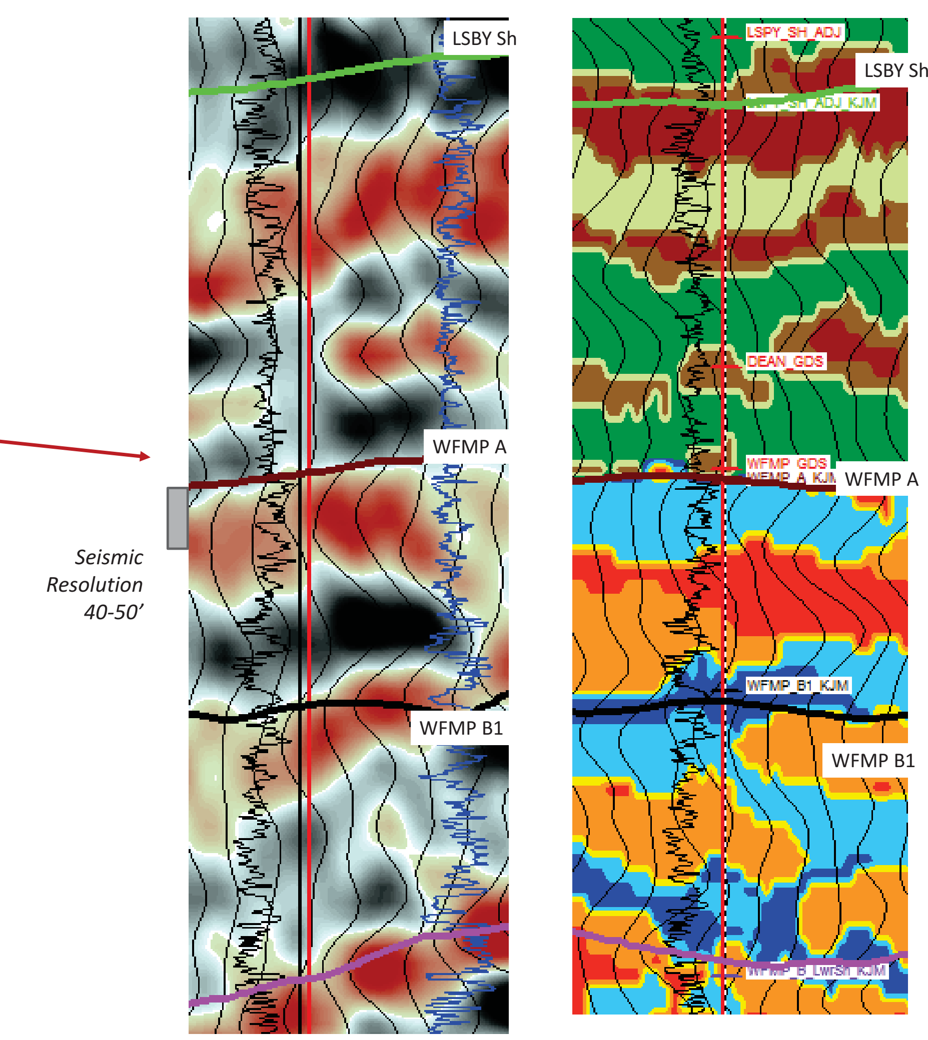


Variable fabrics due to variations in laminae, bedding and facies proportions

Upscaling the Petrophysical Model into the Seismic Data

Wolfcamp and Spraberry petrophysical models, wells in 3D area





Rock fabric implications captured in the petrophysical model and cm- to bedding-scale geology from core. These petrophysical, rock fabric and geomechanical implications are then upscaled into the seismic data.

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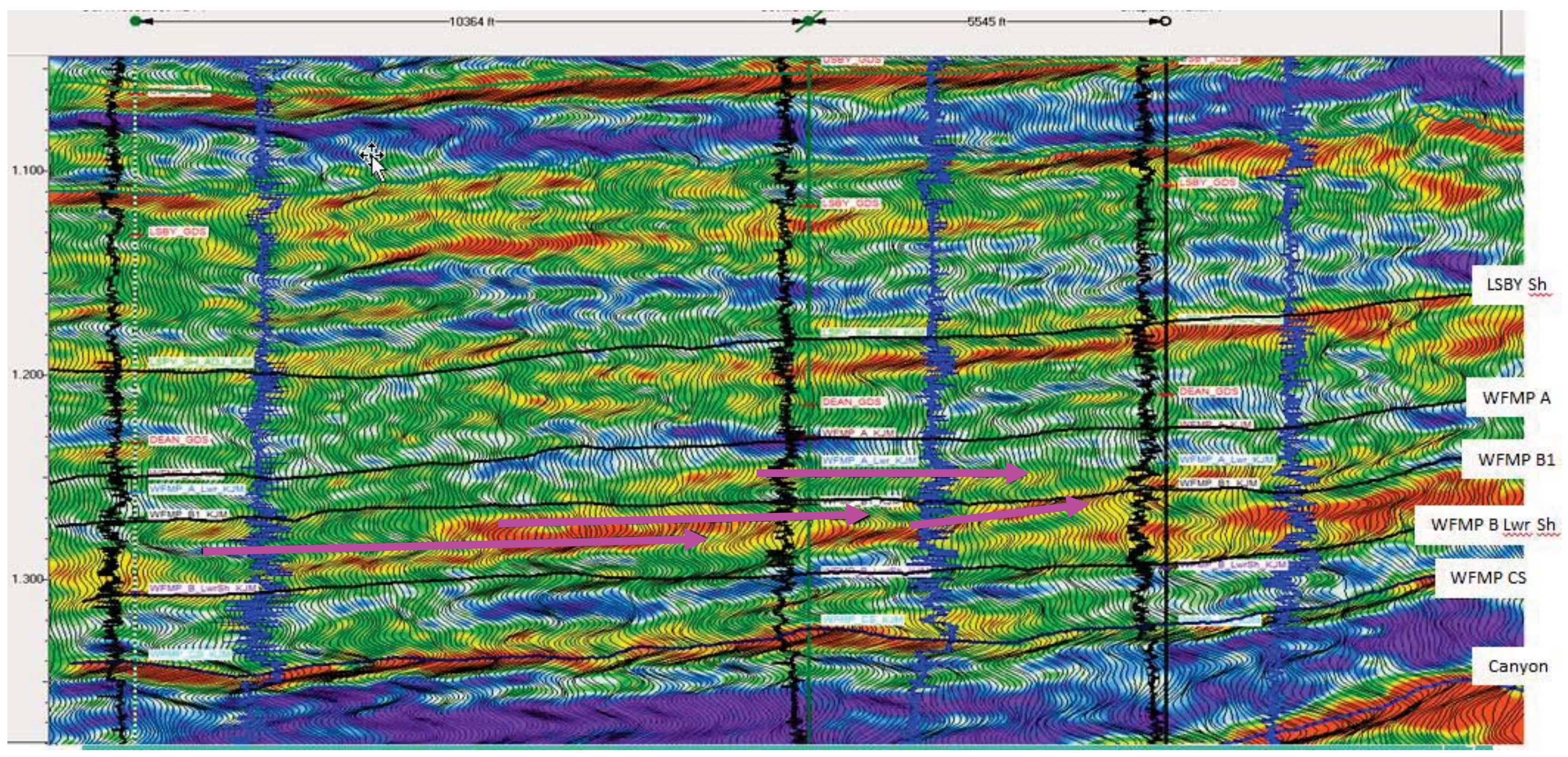
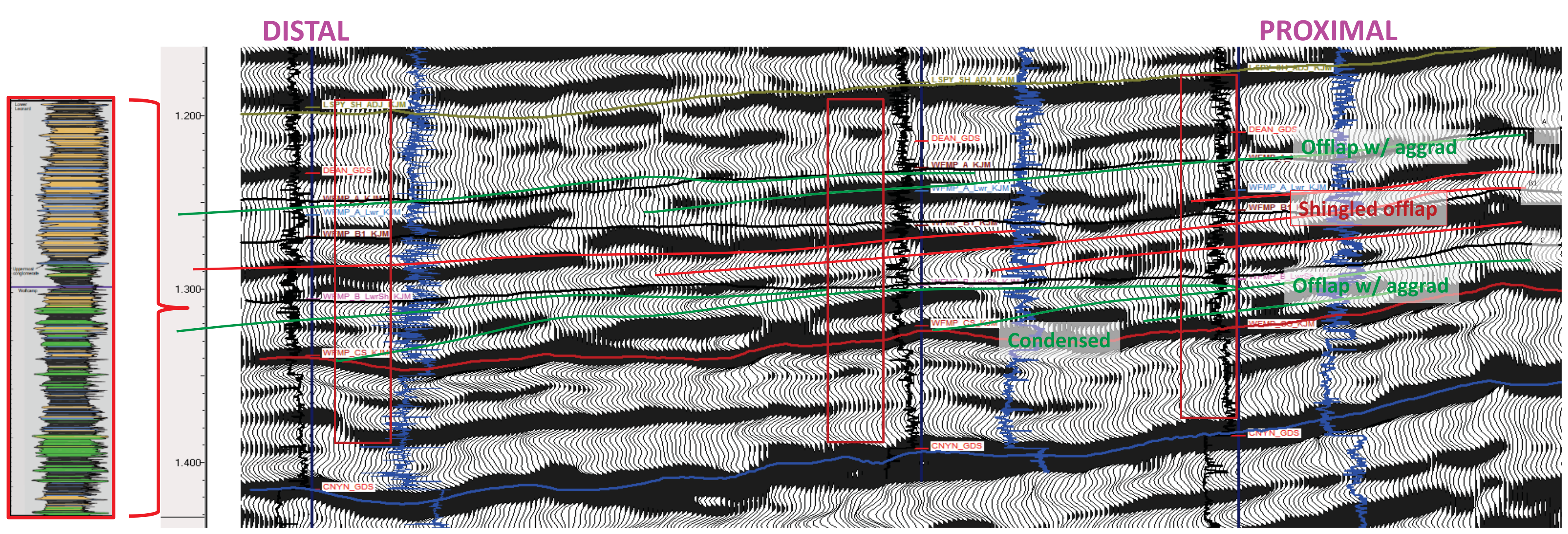
PostStack Seismic Inversion

- **Yields I_p (Acoustic impedance)**
- Has value of enhancing stratigraphic interpretation; closer to vertical and horizontal variations in geology
- First order prediction of impedance/facies distribution
- Limited ability to discriminate facies using p-impedance alone

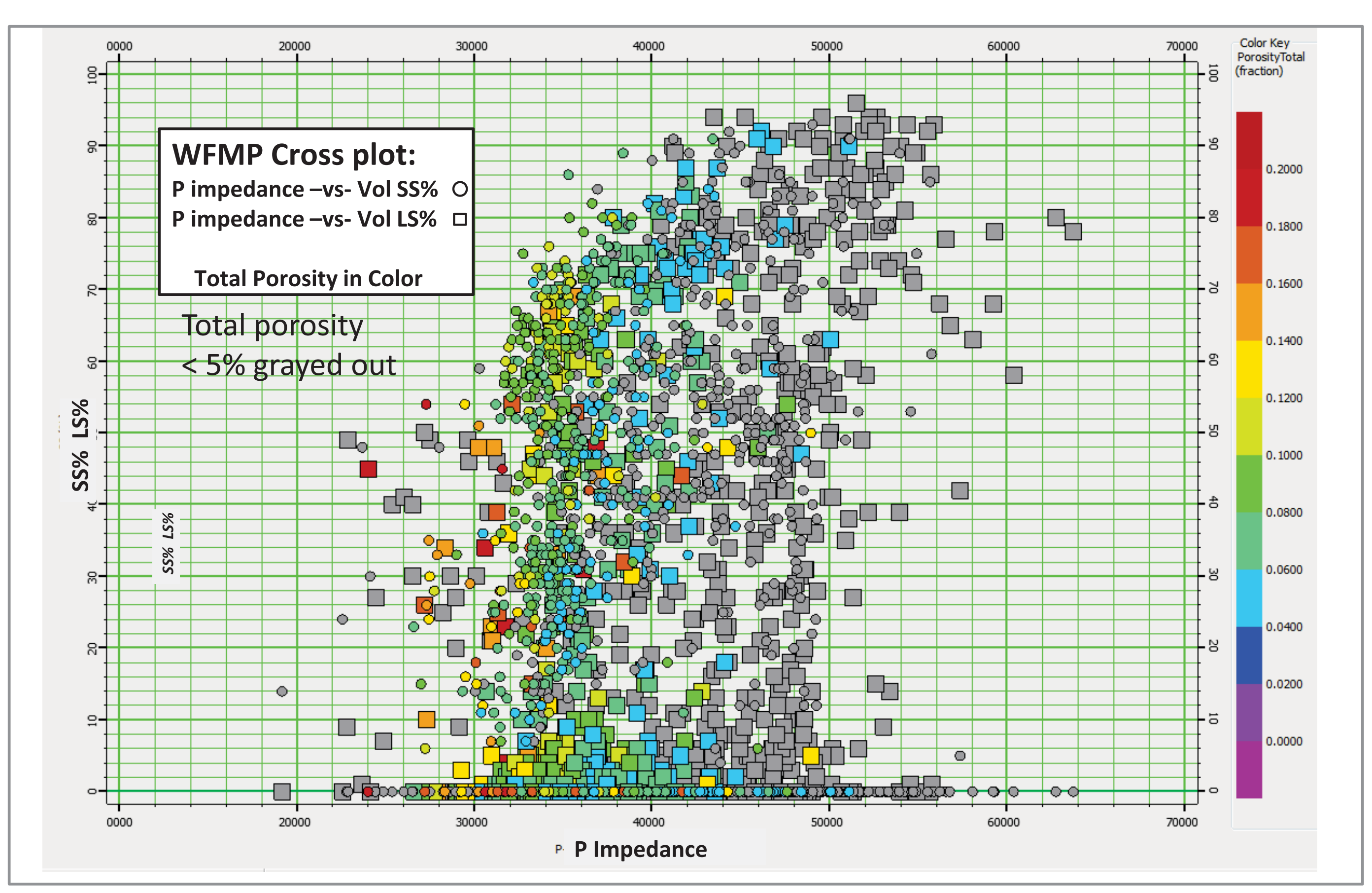


Litho-stratigraphic versus chronostratigraphic interpretation enhanced using impedance volume output by poststack inversion



Vertical facies stacking patterns *and their contained rock fabric and geomechanical implications* are upscaled into the seismic data via stratigraphic geometry. These stacking patterns and their 2D geometric equivalents drive facies proportions, which we discern in the pre-stack inversion classified facies volumes.

Problem:
Cannot differentiate lithology based upon P impedance alone – which is output of post-stack inversion!



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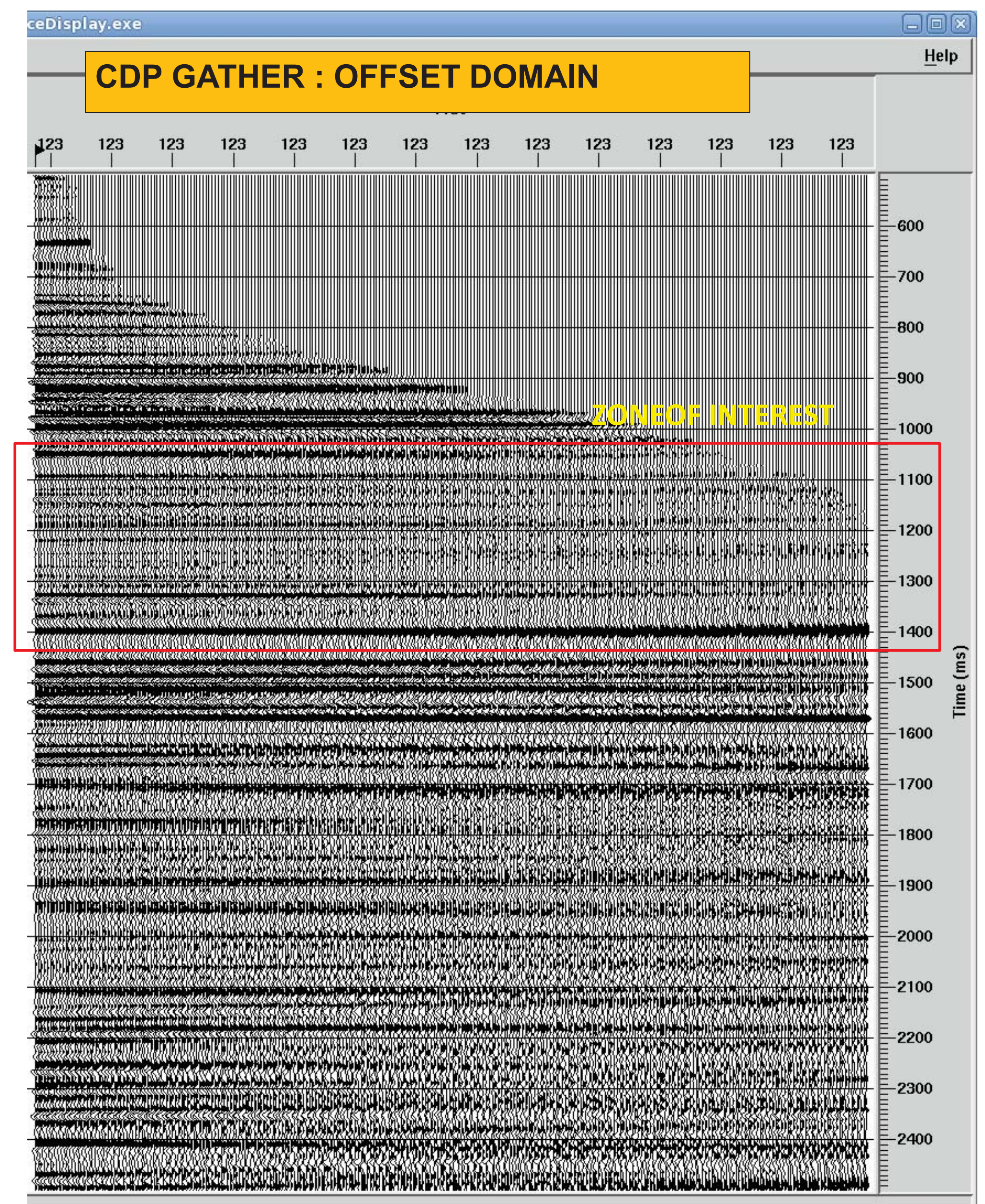
PreStack Seismic Inversion

- **Yields I_p and I_s (Acoustic, Shear impedance)** which enables calculation of $\lambda\rho$ (Lambda-Rho) $\mu\rho$ (Mu-Rho) elastic moduli which in turn enables petrophysical LMR facies classification

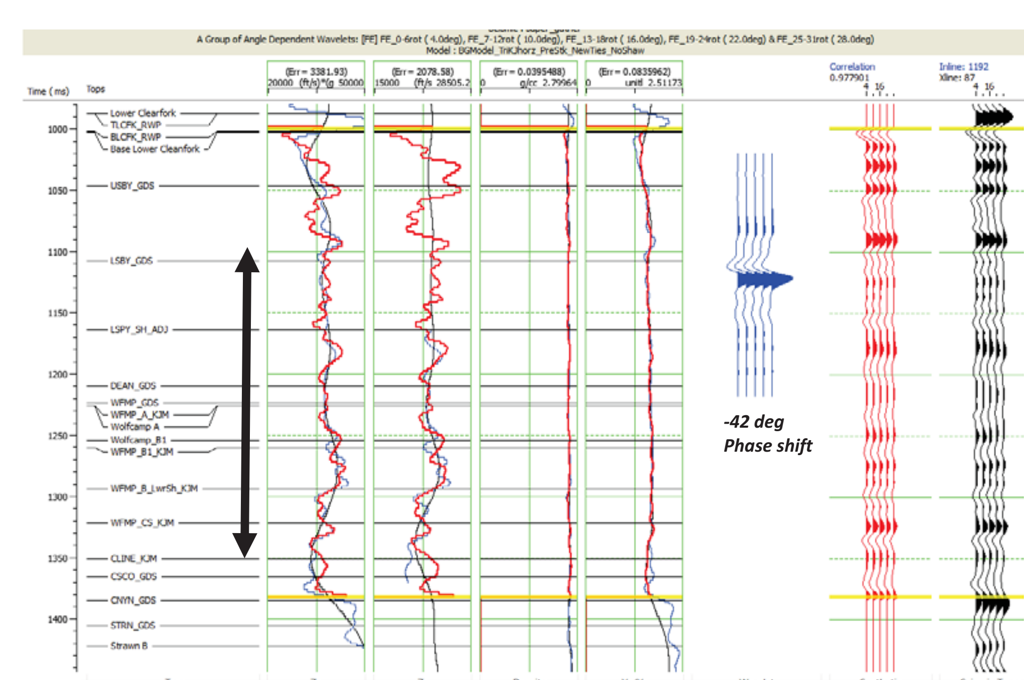
Optimized processing steps applied

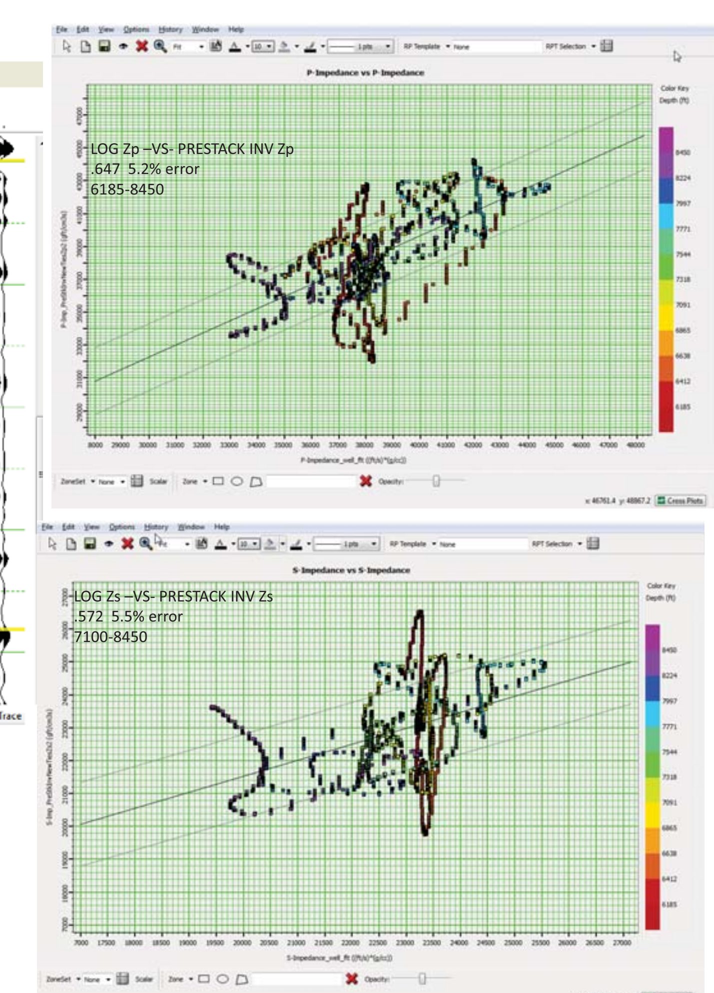


- Retain and enhance low frequencies as possible
- Signal preserving noise attenuation (model-based)
- Strict attention to velocity analysis
- Relative amplitude preservation
- Proper focusing via prestack migration
- 5D Interpolation
- Correcting for VTI and HTI

Inversion example result; importance of well-to-seismic tie

Good well to seismic ties critical





LSBY-BaseWFMP interval

7100-8285 Zp: r=.807 3.5% error
Zs: r=.692 3.9% error

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Seismic Inversion Integration With Petrophysics—Predicting Lithofacies

CROSS-PLOT IS THE TOOL FOR INTEGRATING PETROPHYSICS INTO SEISMIC INVERSION

OUTPUT FROM PRESTACK INVERSION: I_p & I_s (Density also with sufficient angle range)

Lambda-Rho, Mu-Rho

$\lambda * \rho \qquad \mu * \rho$

λ= incompressibility
μ= rigidity

How do we compute $\lambda\rho$ and $\mu\rho$ from I_p and I_s?

$\lambda\rho = (Ip)^2 - 2*(Is)^2$

$\mu\rho = (Is)^2$

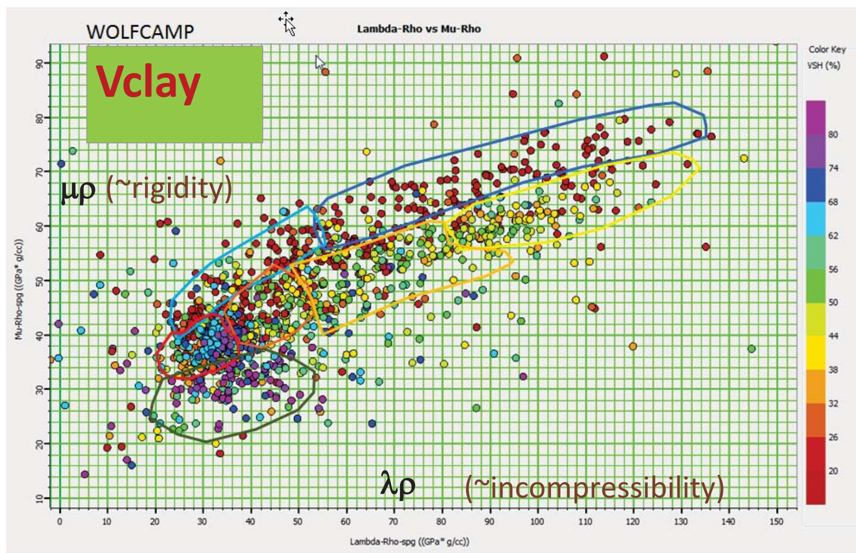
Where have we seen λ and μ before?

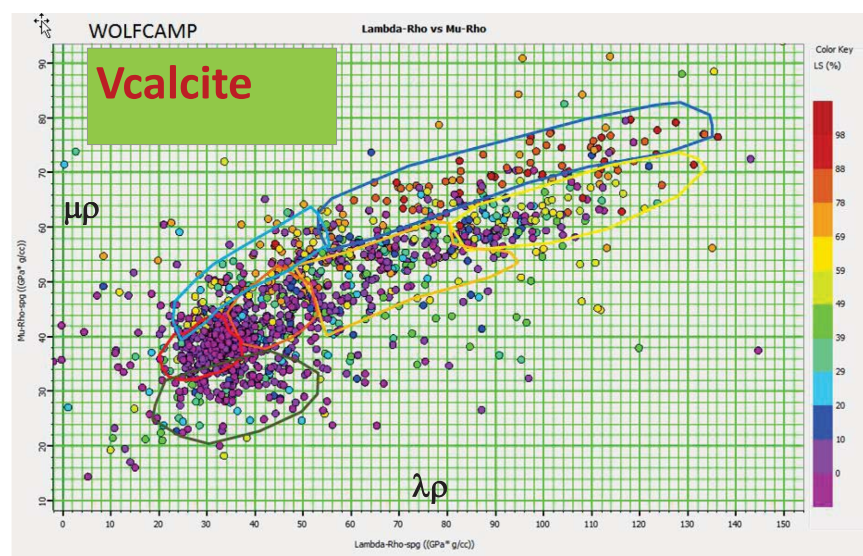
$$V_P = \sqrt{\frac{K + (4/3)\mu}{\rho}} = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

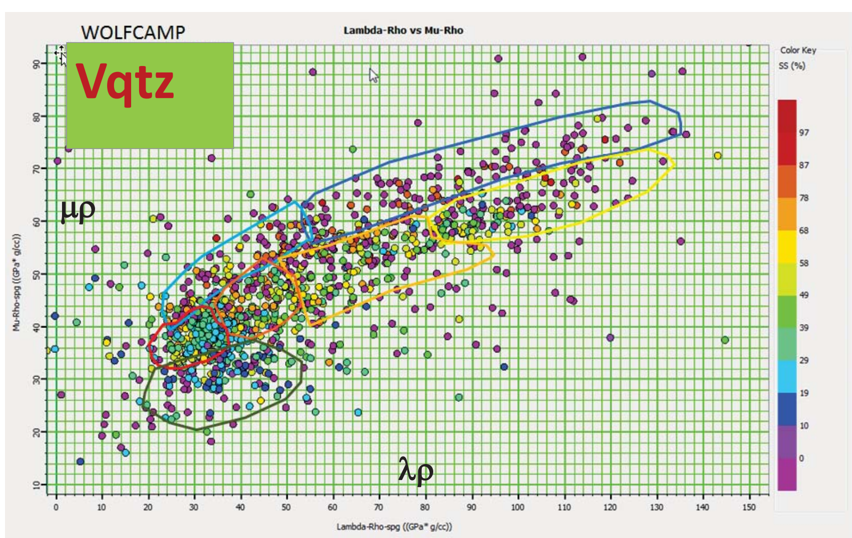
$$V_S = \sqrt{\frac{\mu}{\rho}}$$

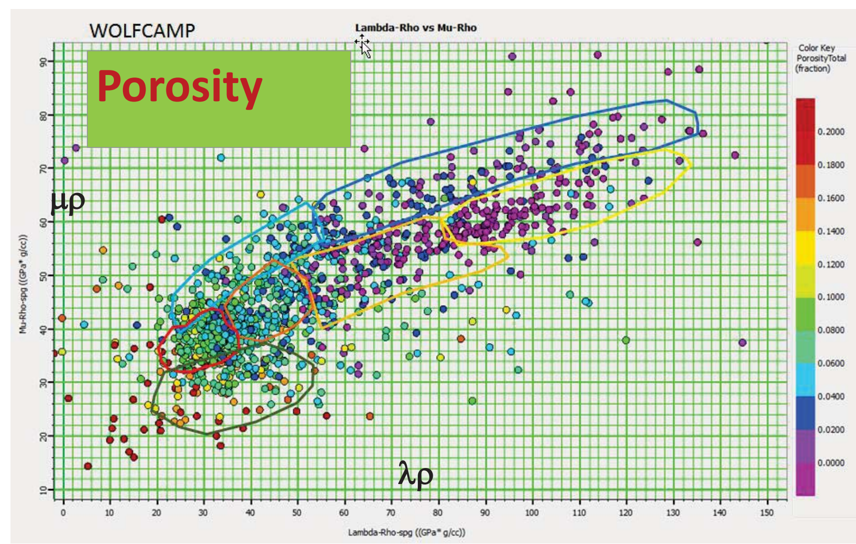
$$E_{\text{Young's (Mod)}} = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu}$$

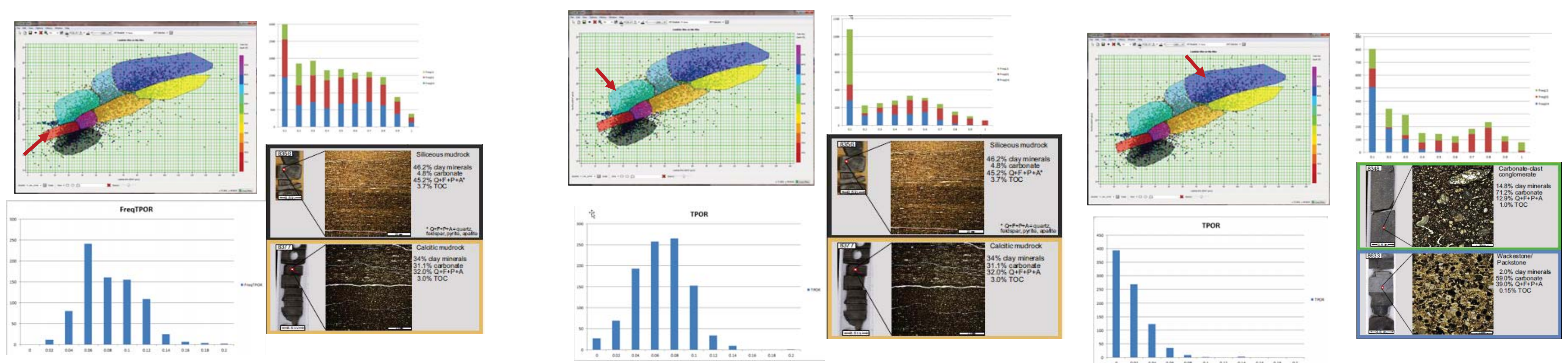
$$\nu_{\text{(Poisson's Ratio)}} = \frac{\lambda}{2(\lambda + \mu)}$$

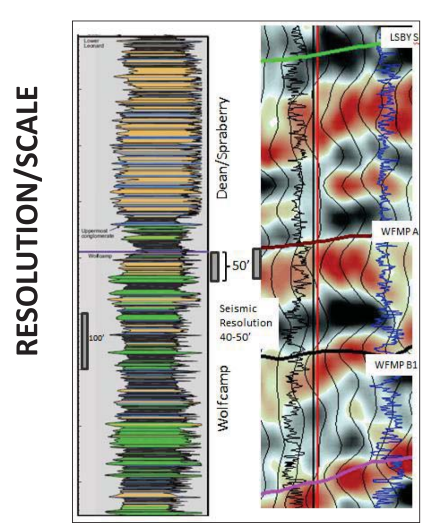


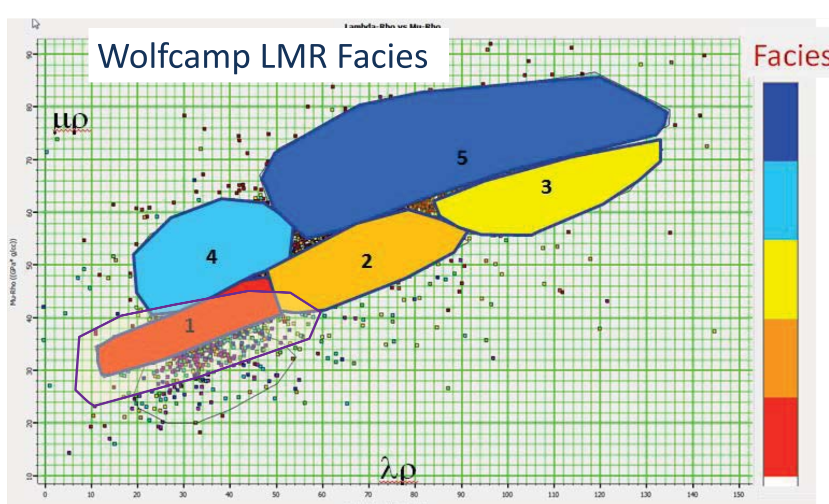




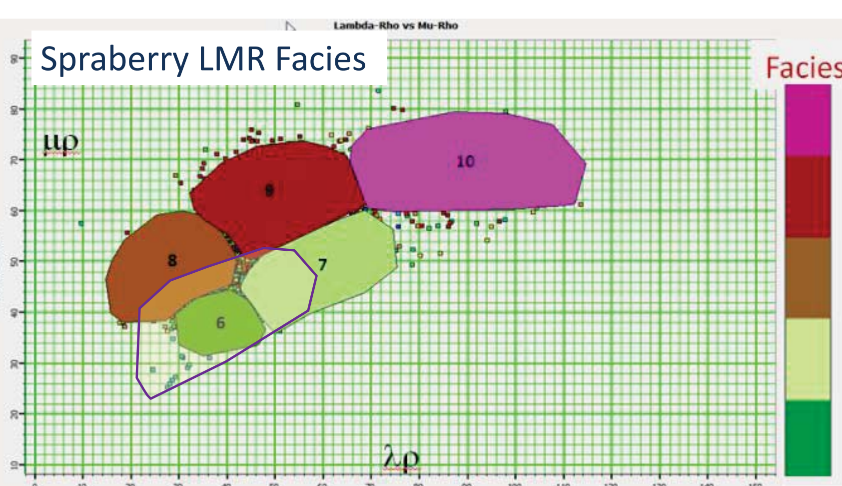








Facies Zones defined in crossplots used as templates to create classified volumes of "LMR Facies" in Wolfcamp and Spraberry

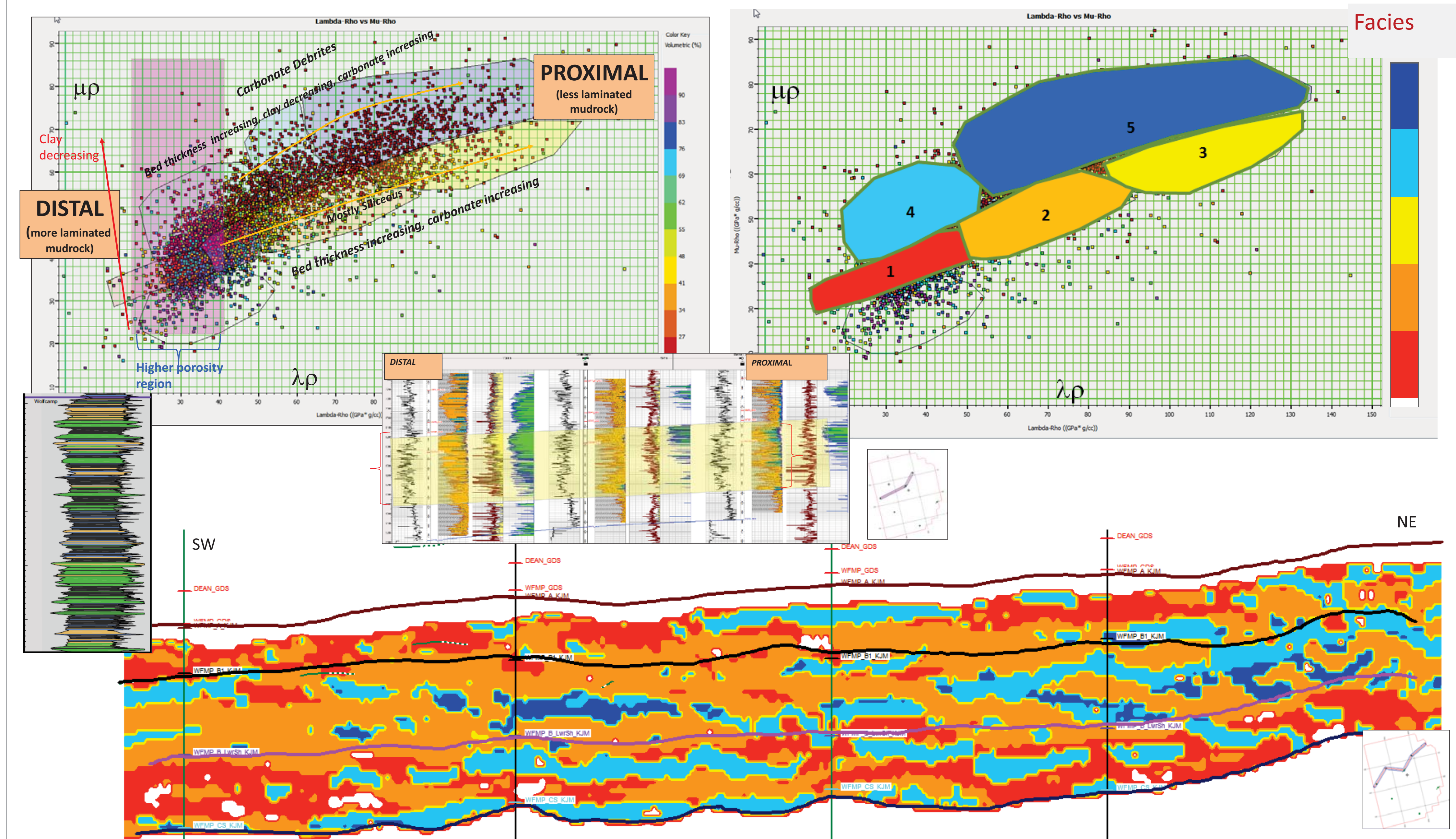


Wolfcamp "Best" LMR-defined reservoir facies with most fracable fabric; Laminated quartz-rich mudrock with thin interbeds of siliceous or calcareous siltstones.

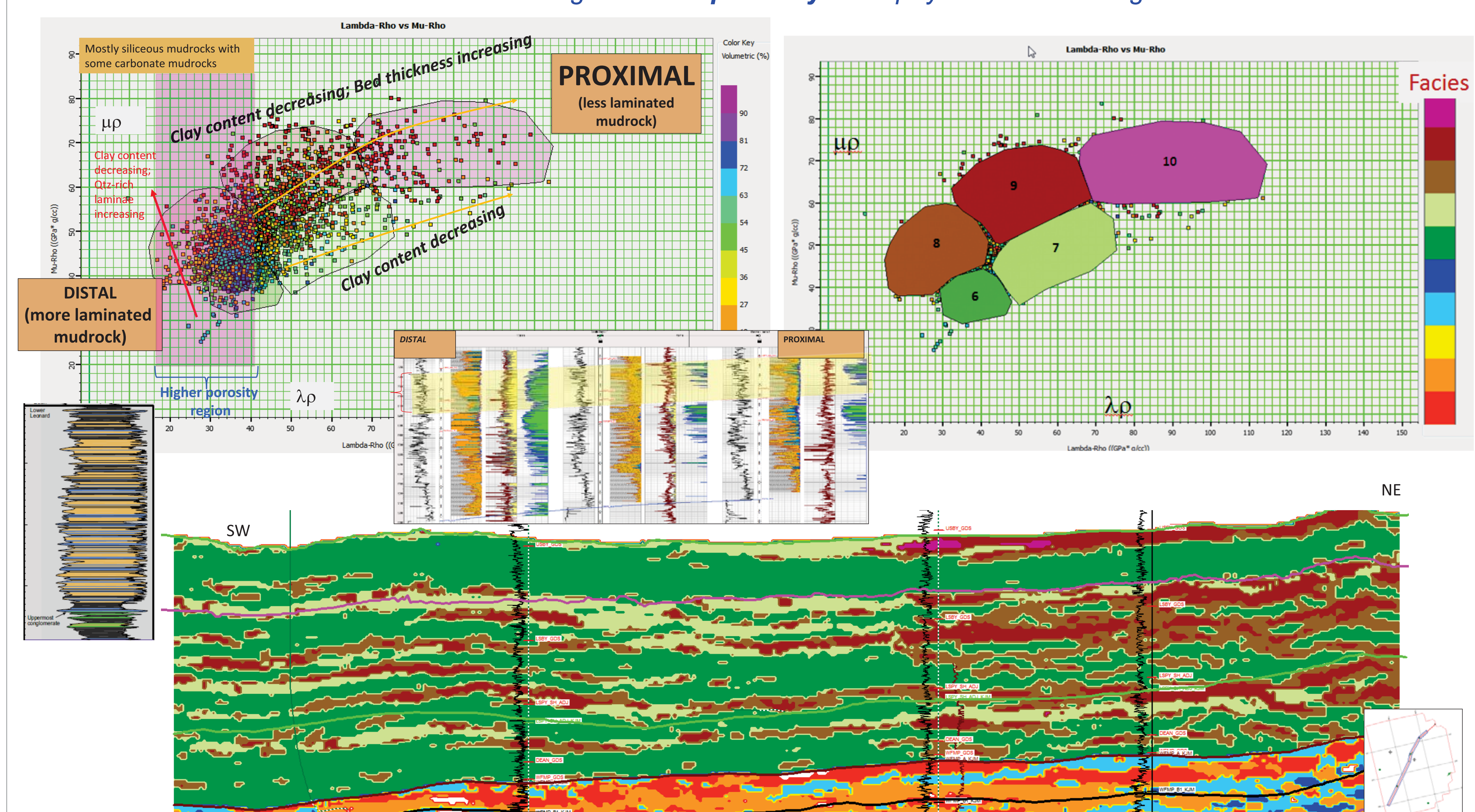
Spraberry "Best" LMR-defined reservoir facies with most fracable fabric; Laminated mudrock with thin interbeds of quartz-rich siltstones.

FACIES

LMR Domain: Integration of Wolfcamp Petrophysical and Geologic Model



LMR Domain: Integration of *Spraberry* Petrophysical and Geologic Model



- Facies classifications (Wolfcamp and Spraberry) from petrophysical LMR cross plots
- Use these templates to calculate and output facies classification 3D volumes
- Map facies proportions along borehole trajectories

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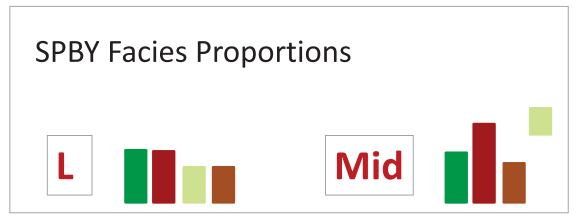
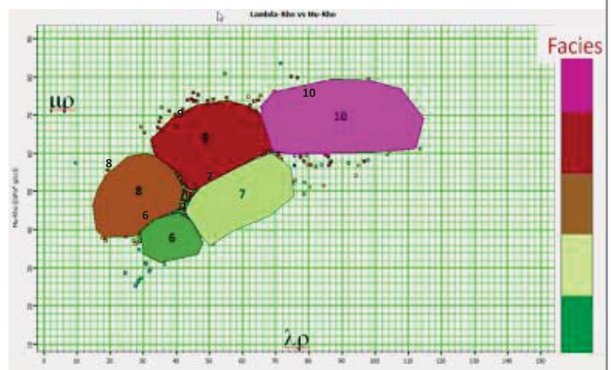
Inversion Results and Analysis—Integration with Lithofacies, Basin Architecture and Geomechanics

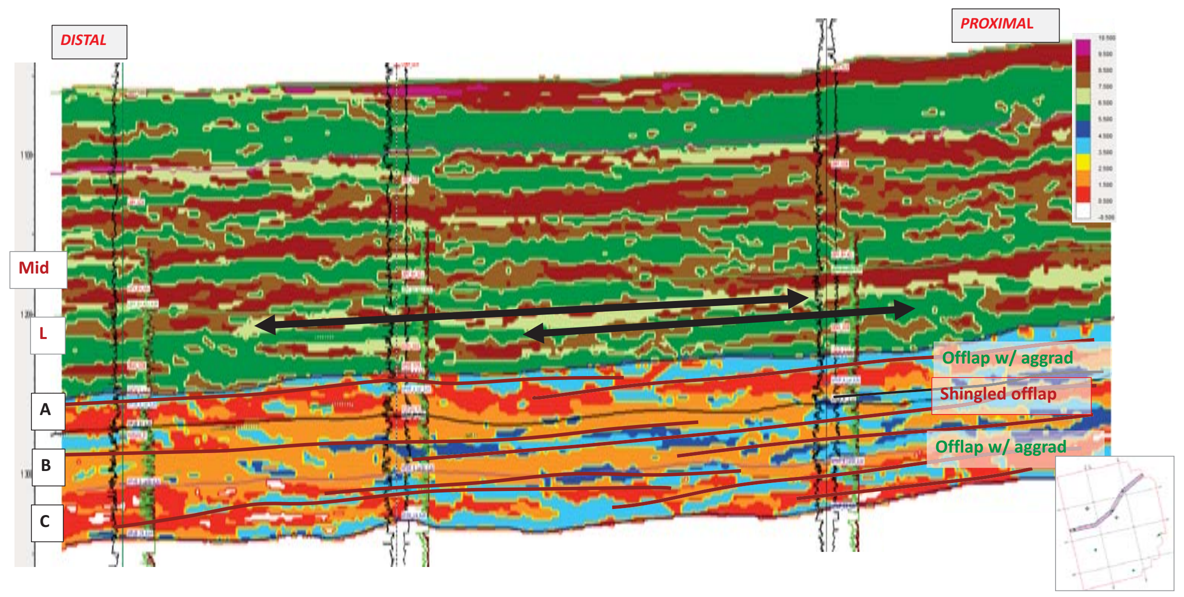
LMR FACIES DISTRIBUTION WITHIN STRATIGRAPHIC GEOMETRY

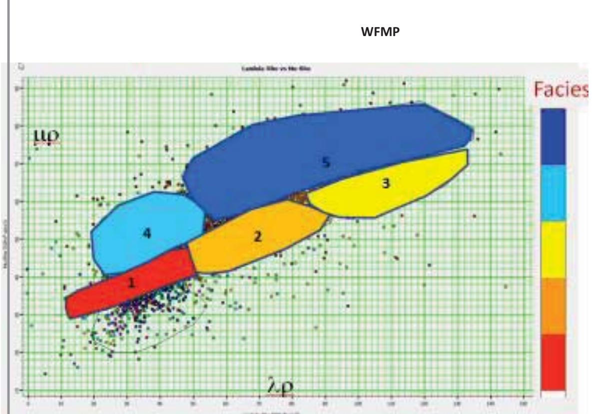
LMR Facies proportions correspond to stratal geometries

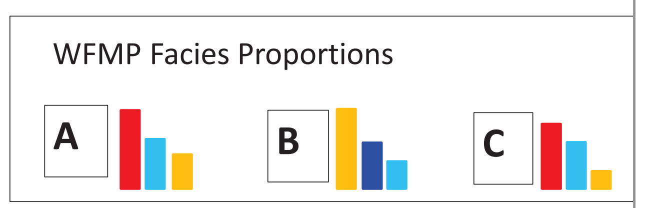




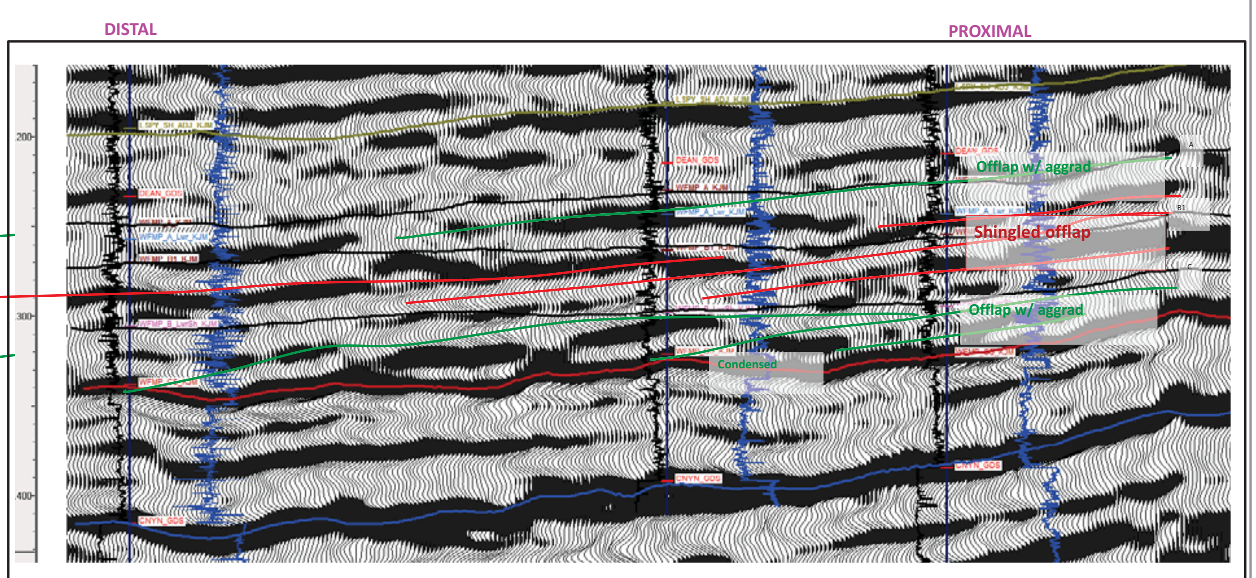
LSBY Facies
- Facies 7, 8/9 offlap, expand
- Sediment source direction shift







WFMP Facies:
A. Facies 1, 4 offlap w/aggrad
B. Facies 2, 4/5 shingled offlap
C. Facies 1, 4 offlap w/aggrad

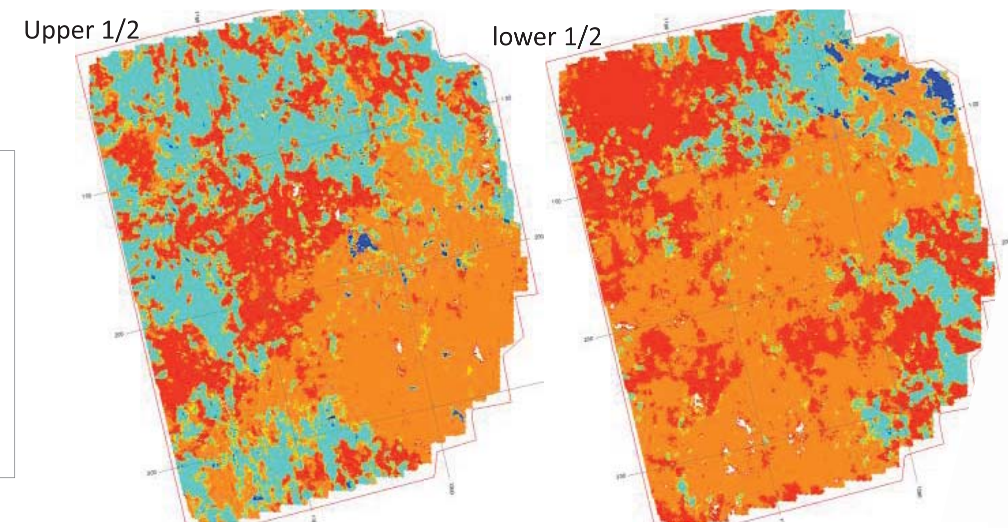


CORROBORATES EARLIER SEIS-STRAT ANALYSIS

LMR FACIES DISTRIBUTION WITHIN BASIN ARCHITECTURE

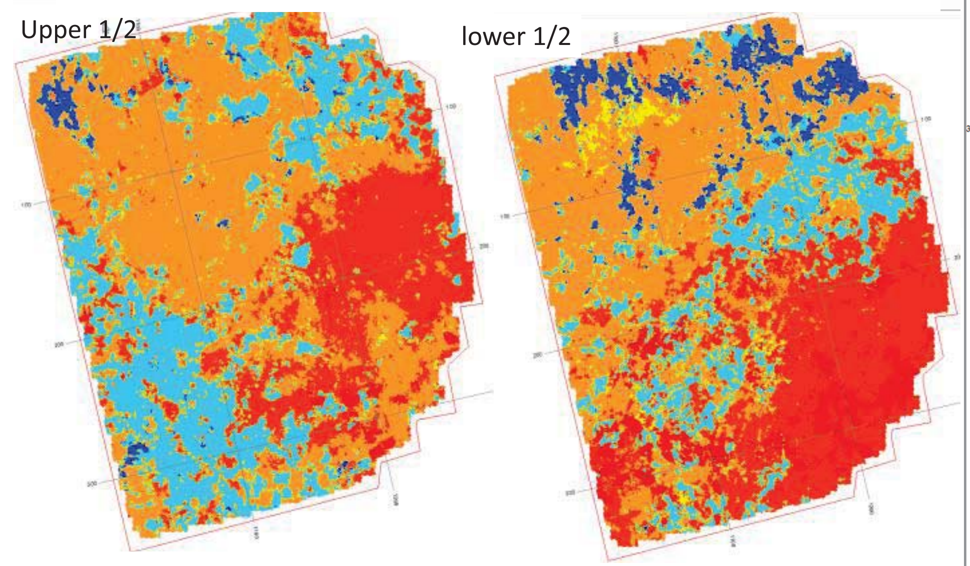
Wolfcamp

LMR Facies Distribution WFMP A



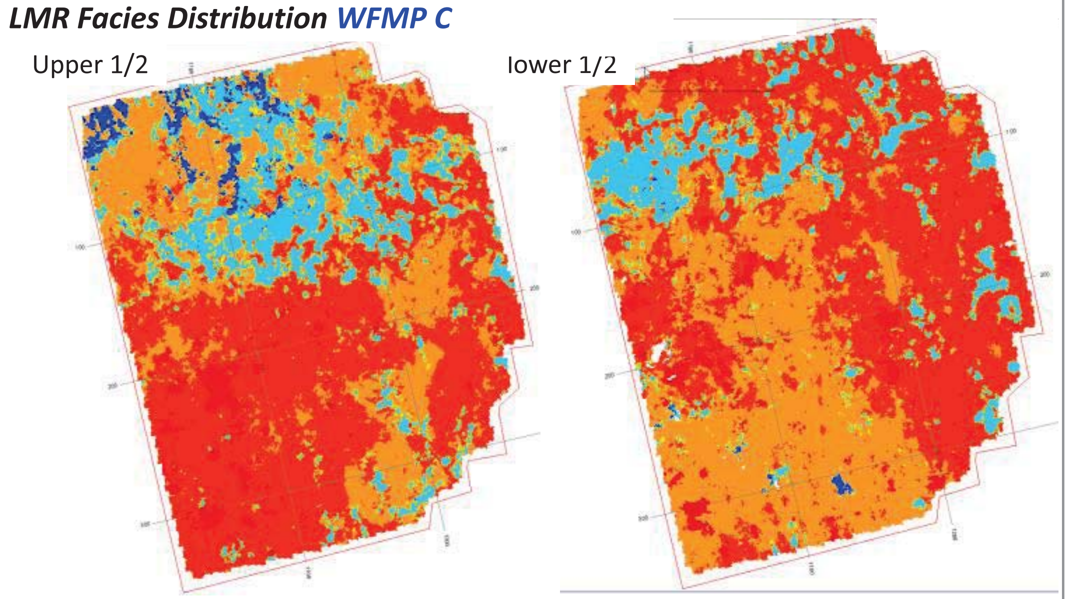
WFMP A—widespread oil-prone facies interbedded with carbonate debrites; advance of carbonate mudrocks into area towards top of WFMP A

LMR Facies Distribution WFMP B

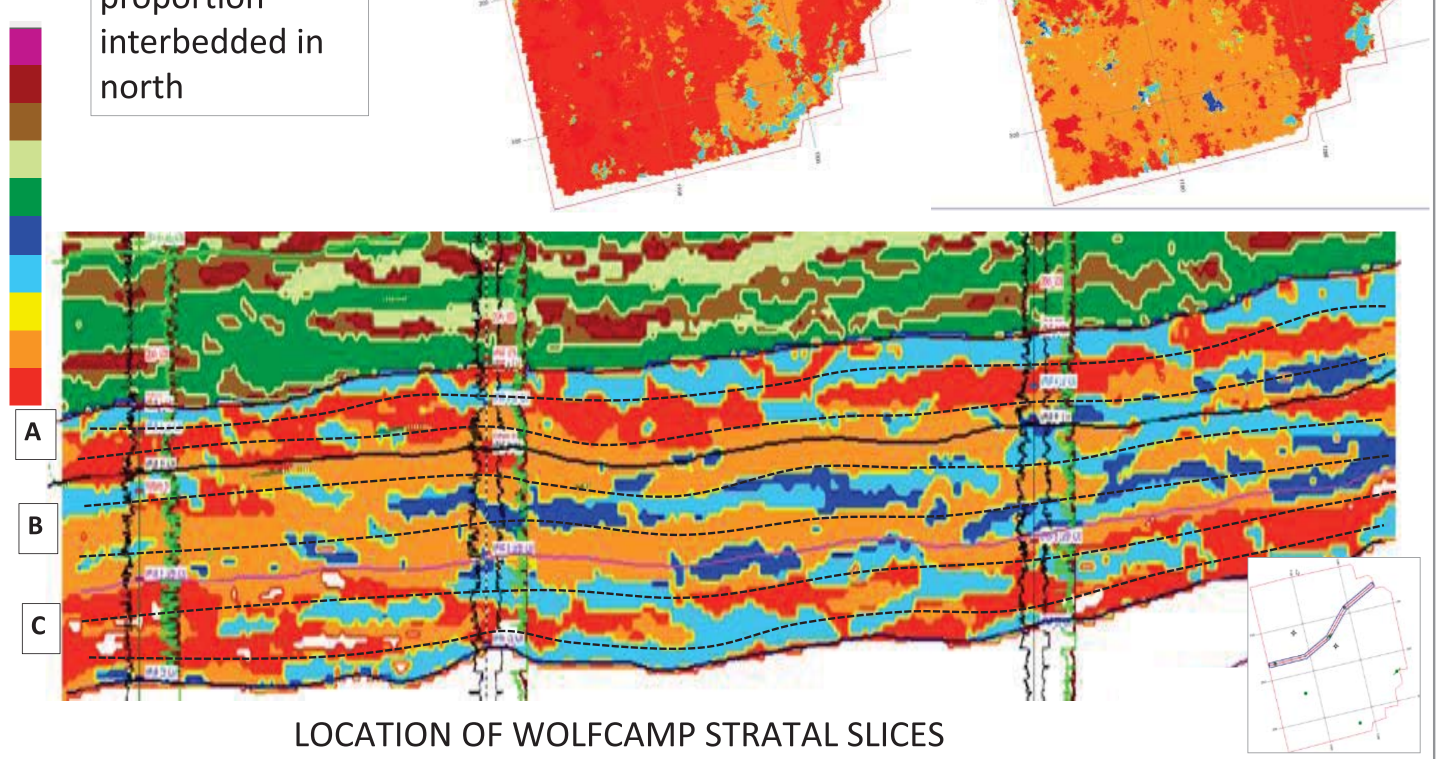


WFMP B—higher proportion of tight, wet carbonate debrites; oil-prone facies (siliceous mudrock) dominates in SE

LMR Facies Distribution WFMP C



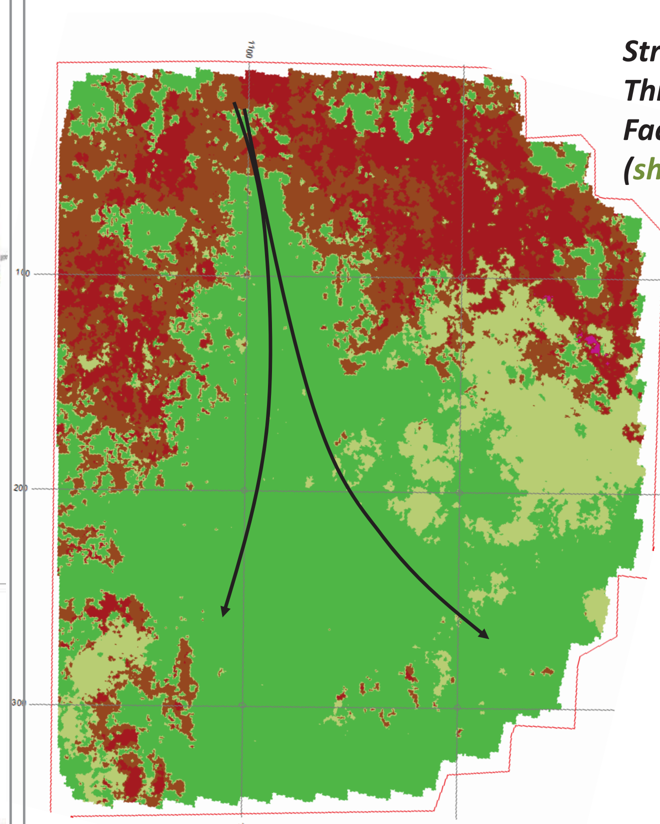
WFMP C—high proportion of oil-prone facies; significant debrite proportion interbedded in north



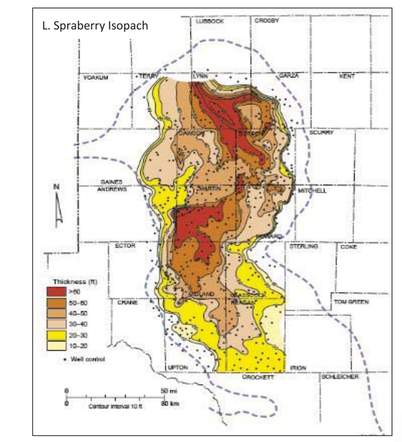
LOCATION OF WOLFCAMP STRATAL SLICES

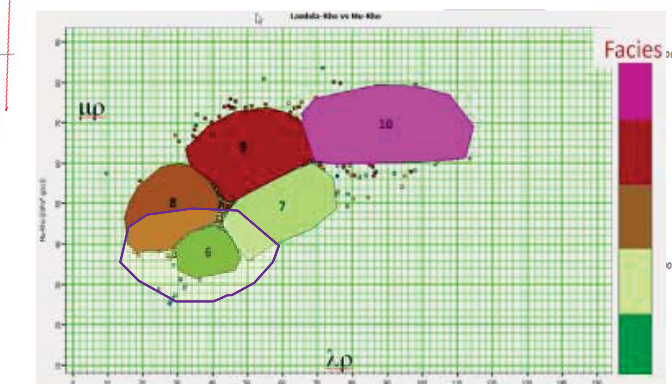
Lower Spraberry

LMR FACIES DISTRIBUTION WITHIN BASIN ARCHITECTURE

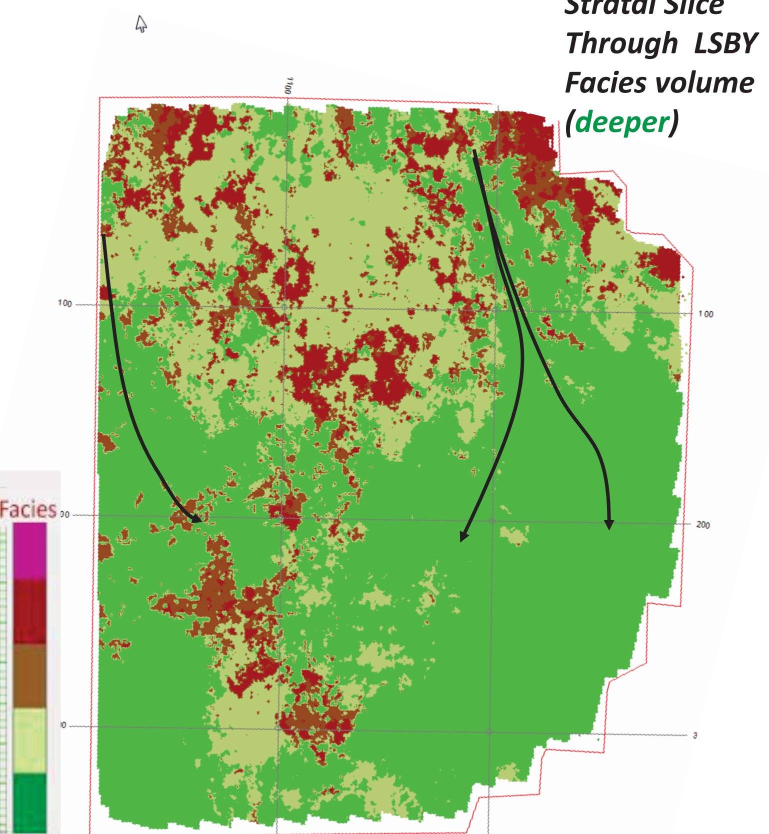


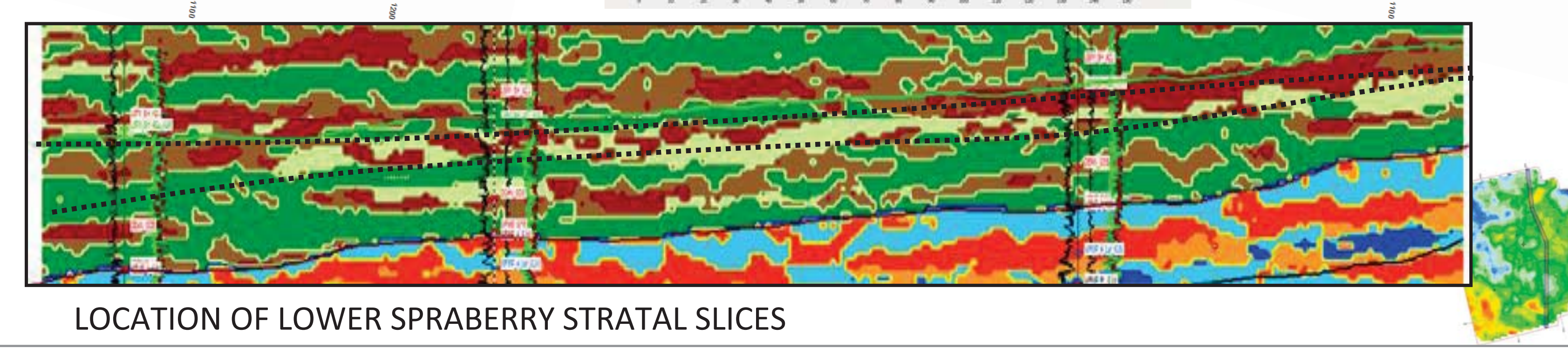
Stratal Slice Through LSBY Facies volume (shallower)





Stratal Slice Through LSBY Facies volume (deeper)





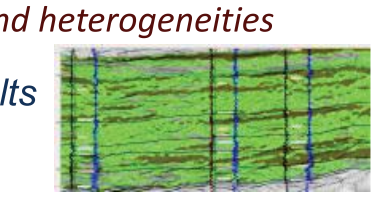
LOCATION OF LOWER SPRABERRY STRATAL SLICES

- LMR Facies 6—dominant in distal and basin center
- LMR Facies 7, 8, 9 —northerly sediment input, increasingly dominated by debris flows and turbidites; more proximal facies

INVERSION INTEGRATION WITH GEOMECHANICS

OVERALL CONNECTION WITH MECHANICAL ROCK PROPERTIES & HYDRAULIC FRACKING

ROCK FABRIC : *Hydraulic fracture growth controlled by rock properties and heterogeneities*



- ROCK STIFFNESS (Brittleness/Stiffness) => *deliverable from inversion results*
- VARIATION OF LAMINATED MUDROCK FACIES
- GEOMETRIC NATURE OF PORE GEOMETRY AND POROSITY
- NATURAL FRACTURES (stiffness variability and layer thickness in the stratigraphy can control)

FAULTING

- HYDRAULIC FRACTURE GROWTH AFFECTED BY FAULTING
- STRESS FIELD VARIATION AROUND FAULTING

The Net Fracture Pressure (ISIP - $P_{closure}$): Provides Insight into Induced Fracture Complexity *(SPE 162814)*

DECIPHERABLE FROM 3D SEISMIC

- Tectonic Setting (strike-slip, normal faulting, compressional)
- Fracture density (rock fabric) and anisotropy
- Stress anisotropy and the differential stress
- Mechanical stratigraphy
- Laminated fabric associated with certain lithofacies

- Facies classifications (Wolfcamp and Spraberry) calculated from the 3D volume map out into reasonable stratigraphic configurations.
- Technique can extract additional lithofacies information from existing 3D seismic data via prestack inversion calibrated with petrophysics parameters.
- Closure pressure (minimum horizontal stress) and rigidity may also be estimated from the 3D volume.

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PreStack Inversion Results and Analysis -- Integration With Lithofacies, Pressures, Horizontal Well Control and Production

INVERSION INTEGRATION WITH GEOMECHANICS

CALCULATION OF MINIMUM HORIZONTAL STRESS (closure pressure)

- Frackable (what's it take to break it?)
- Frac containment (vertically & horizontally)

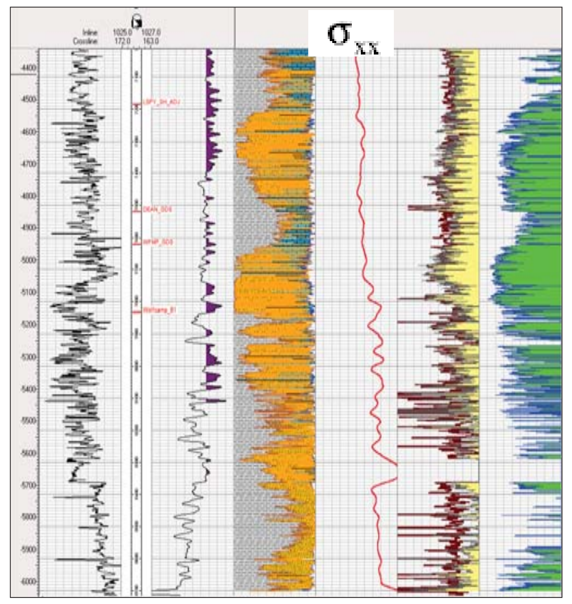
Assuming P_p is 5500 PSI *(Shaochuan & Zoback 2015)* e_{xx}=.00011 e_{yy}=.00011

$$\sigma_{xx} = \frac{\nu}{1-\nu}\left[\sigma_{zz} - B_V P_p\right] + B_H P_p + \frac{E}{1-\nu^2}\left(\epsilon_{xx} + \nu\epsilon_{yy}\right)$$

TECTONIC STRAIN

Can be used as "calibration knobs" tied to DFITS, image logs

Horizontal stresses don't follow simple gradient; variability with lithology and elastic properties *(Herwanger, Bottrill & Mildren, 2015; UTReC 2172545)*

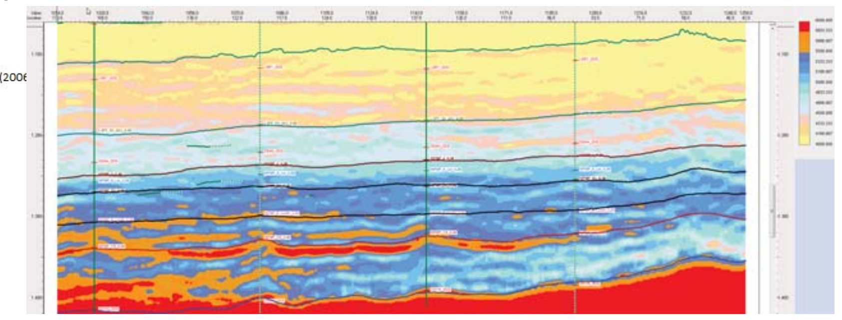


Reformulated to accommodate LR and MR

$$\sigma_{xx} = \frac{\lambda}{\lambda+2\mu}\left[\sigma_{zz} - B_V P_p + \frac{2\mu}{\nu}\left(\epsilon_{xx} + \nu\epsilon_{yy}\right)\right] + B_H P_p$$

OVERBURDEN STRESS; PORE PRESSURE; STRAIN IN X; STRAIN IN Y; PORE PRESSURE; VERTICAL POROELASTIC CONSTANT; VERTICAL POROELASTIC CONSTANT

GOODWAY, VARSEK & ABACO (2006)



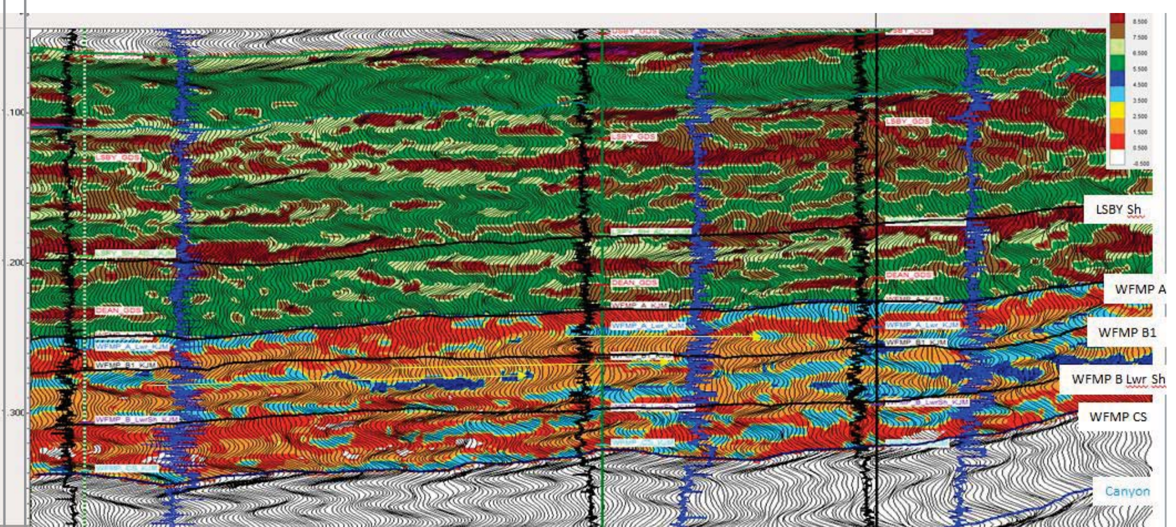
VOLUME ESTIMATED CLOSURE PRESSURE

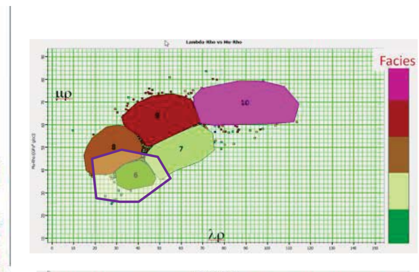
HORIZONTALS DRILLED IN THE WOLFCAMP AND LOWER SPRABERRY WITHIN THE 3D AREA

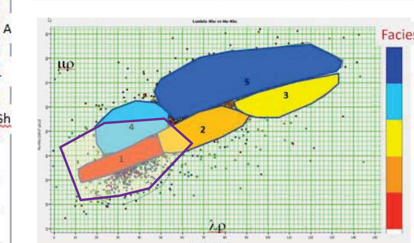
WFMP (16) AVE 286 BOPD
AVE 768 BWPD (71% water cut)

LSBY (10) AVE 306 BOPD
AVE 1089 BWPD (75% water cut)

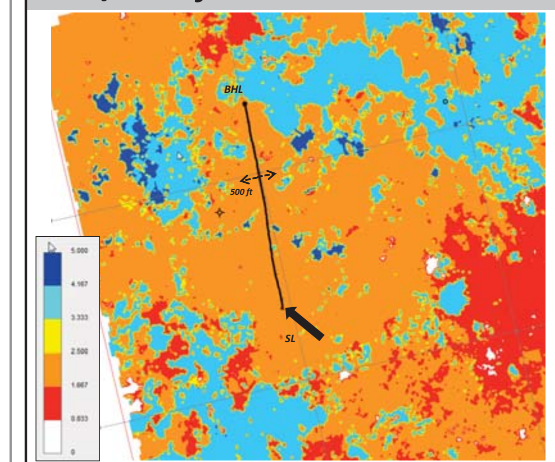
- Best reservoir rock are mudstones with higher siliceous content and porosity; lower carbonate content, higher oil saturation.
- Carbonate debris flows are tight, brittle, wet.





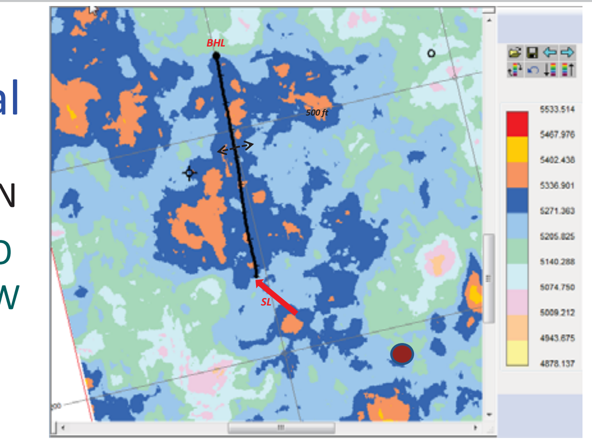


LMR/Lithofacies Zones: MAP VIEW



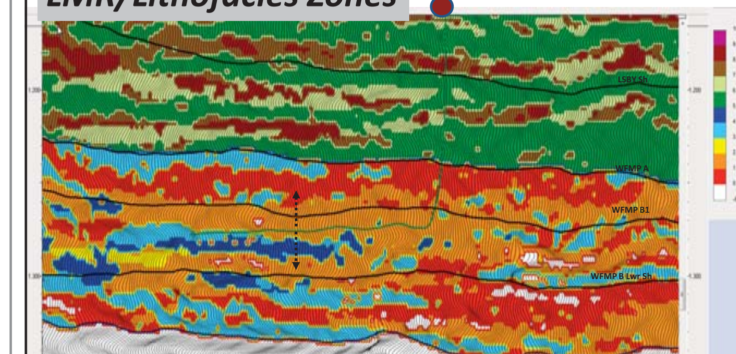
WFMP Horizontal
CUM PRODUCTION
102,913 BO
428,623 BW
148 MCFG

Estimated Closure Pressure: MAP VIEW



- Put the well bore in the most oil prone facies
- Pressure variability along and around the well bore (connection potential within oil prone facies)

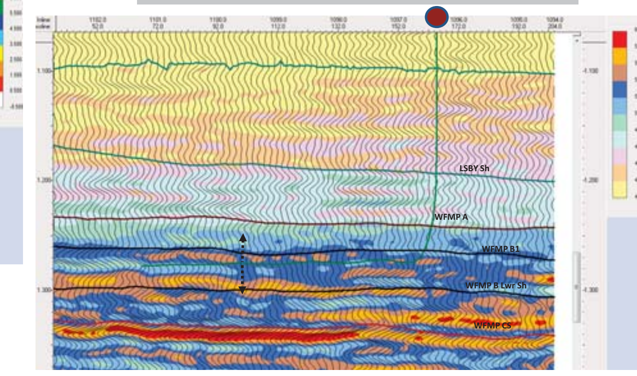
LMR/Lithofacies Zones



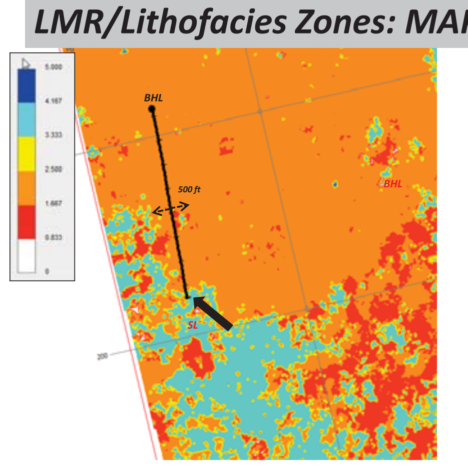
- Drilled in LMR facies 2, - 4, 5 close by
- Relatively brittle section
- Wellbore sandwiched between higher pressure zones
- Is higher water cut associated with zone 5?

Approx 400 ft

Estimated Closure Pressure

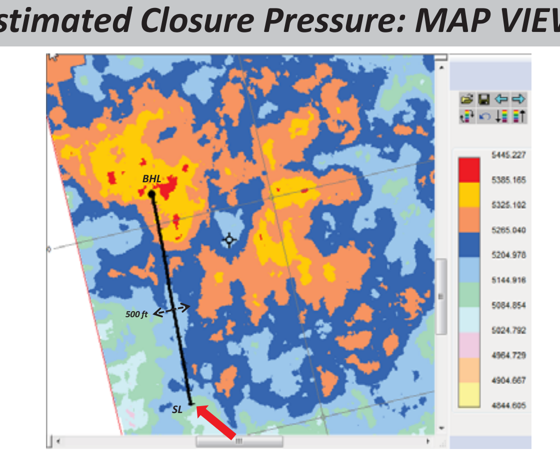


LMR/Lithofacies Zones: MAP VIEW

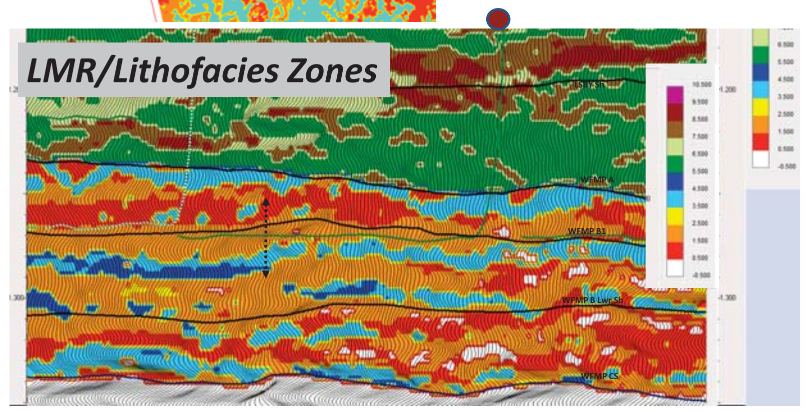


WFMP Horizontal
CUM PRODUCTION
92,000 BO
230,000 BW
59 MCFG

Estimated Closure Pressure: MAP VIEW



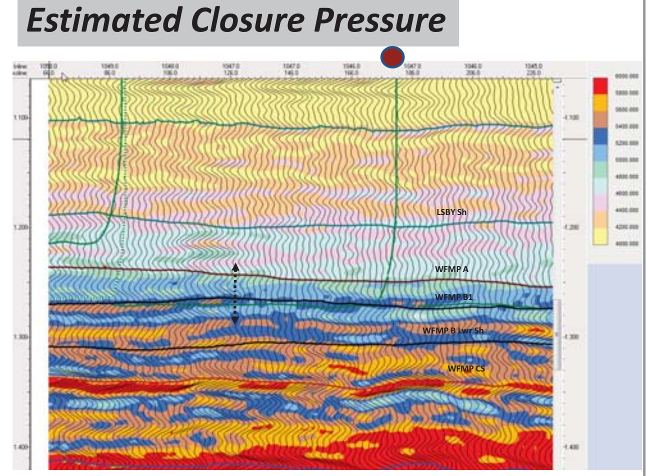
LMR/Lithofacies Zones



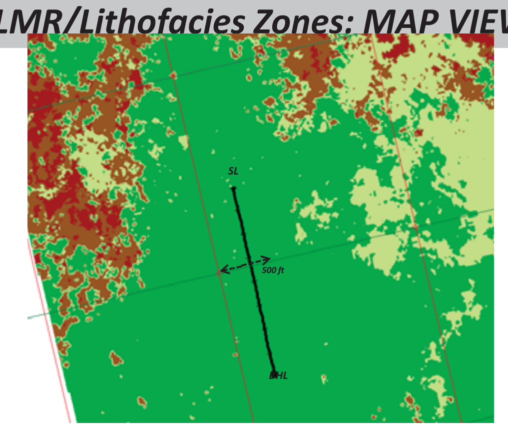
- Drilled in LMR facies 2
- Relatively brittle section
- Wellbore sandwiched between higher pressure zones

Approx 400 ft

Estimated Closure Pressure

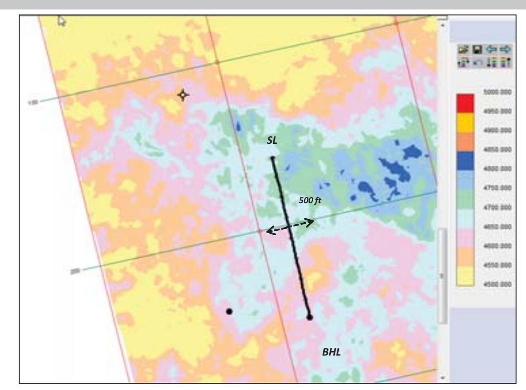


LMR/Lithofacies Zones: MAP VIEW

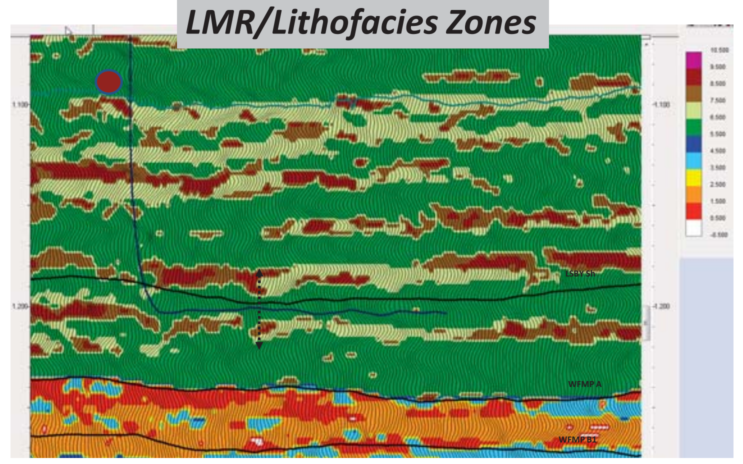


LSBY Horizontal
CUM PRODUCTION
218,176 BO
807,312 BW
237 MCFG

Estimated Closure Pressure: MAP VIEW

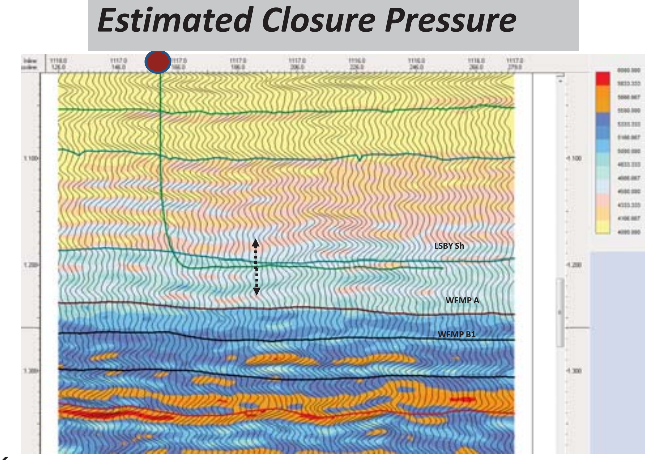


LMR/Lithofacies Zones



- Drilled in higher porosity zone 6, laminated siliceous mudrock
- Relatively brittle section
- Wellbore sandwiched between higher pressure zones

Estimated Closure Pressure



Approx 400 ft

SUMMARY

- Wolfberry classified facies volumes calculated from petrophysically-derived lithofacies fields allow direct 3D mapping of oil-prone facies.
- Wolfberry lithofacies and geomechanical properties can be mapped to define/choose horizontal well locations and trajectories ahead of drilling.
- Geomechanical parameters may also be defined from inversion results.
- Petrophysics must drive classification of inversion results into mappable key facies. This workflow may be extended to include commonly calculated shale logs.
- Seismic inversion is dependent on reliable seismic amplitude data
  - ❑ Processing and data preparation critical
- Seismic horizons keyed to well ties and seismic geometries critical at outset
  - ❑ Poststack seismic inversion useful for interpreting sequence-scale detail
  - ❑ Prestack seismic inversion augments stratigraphic architecture and facies distribution at sub-sequence scale
- Seismic data (with its typically large areal extent and high spatial sampling) provides the canvas for a multidisciplinary data integration once it is mined for reservoir properties (eg, inversion) and geomodel characteristics.

- Petrophysics drives classification of prestack inversion results into mappable lithofacies.
- Better production occurs in conjunction with higher proportions of best-quality rock (laminated siliceous mudstone in the Wolfcamp case) are encountered by the borehole.
- Pressure variability provides higher connection potential and may also be calculated from the prestack inversion.

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