Multi-Source Data Integration to Predict Well Performance: Eagle Ford Sweet Spot Mapping*

Beau Tinnin[1], Hector Bello[1], and Matthew McChesney[1]

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Abstract

Chemostratigraphy uses major, minor and trace element geochemistry to characterize, subdivide, and correlate strata. Traditionally within Pioneer's South Texas Asset Team, chemostratigraphy has been used primarily for geosteering horizontal wells (Eagle Ford and Austin Chalk) – either real time or post-drill to determine lateral placement with respect to a known target zone. These correlations are referenced back to geochemical signatures observed in pilot well(s).

After a comprehensive review, other applications of this geochemical dataset have been identified, most notably the ability to estimate Total Organic Carbon (TOC), paleoredox facies, and proxies for VClay in terms of carbonate-rich and clay-prone facies. Certain redox-sensitive trace metals such as molybdenum and nickel are concentrated in organic carbon-rich intervals of the Eagle Ford Formation. Using these trace metals, an estimation of TOC has been derived for certain key wells from Atascosa, Bee, DeWitt, Karnes, La Salle, Lavaca and Live Oak counties. In addition, using the enrichment or depletion of minor and trace elements relative to their crustal abundances, anoxic or oxic conditions may be inferred. This dataset was used to elucidate vertical and lateral paleoredox conditions and facies variability within the organic-rich Eagle Ford Shale and how that variability can affect well performance.

This geochemical dataset was integrated with geomechanical data to develop relationships for estimating the geochemical response from geomechanical properties, using multi-attribute transforms, neural network analysis, and principle component analysis. Based on these relationships, 3D volumes of specific geomechanical properties derived through pre-stack seismic inversion were used to propagate the geochemical data from wells into 3D volumes. This estimation of the geochemical response away from the wellbore using 3D surface seismic data provides a powerful means of improving the lateral resolution and predictive capabilities of the geochemical analysis.

TOC and the brittleness (VClay) of the Eagle Ford are two key performance drivers in Pioneer's 'sweet spot' acreage of DeWitt and Karnes counties. Well look backs in these counties have consistently shown that TOC and VClay can be correlated to well performance (Portis et al., 2013). Estimated TOC and brittleness from inorganic geochemistry within horizontal wells and the extension of this geochemical data to 3D

via relationships with geomechanical properties from seismic inversion provide another tool to evaluate variability as well as high-grading intervals within the Eagle Ford Formation across Pioneer's acreage position.

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AAPG GTW – Eagle Ford
February 25, 2014

Outline

PIONEER NATURAL RESOURCES

- Eagle Ford Shale production growth
- South TX regional framework
- Eagle Ford well performance drivers
  - VClay and TOC impact
- Elemental data and XRF
  - Elemental proxies
  - Mapping elemental data from cuttings
- Principle Component Analysis (PCA) of elemental data
  - Key elemental proxies for Eagle Ford
- Mechanical properties and seismic attributes
  - Inversion and mapping
  - Multi-attribute analysis
  - VClay and Mo volumes
- Sweet spot mapping
- Summary and conclusions

Boquillas Fm (Eagle Ford)
Big Bend National Park, TX

Eagle Ford Shale Production Growth

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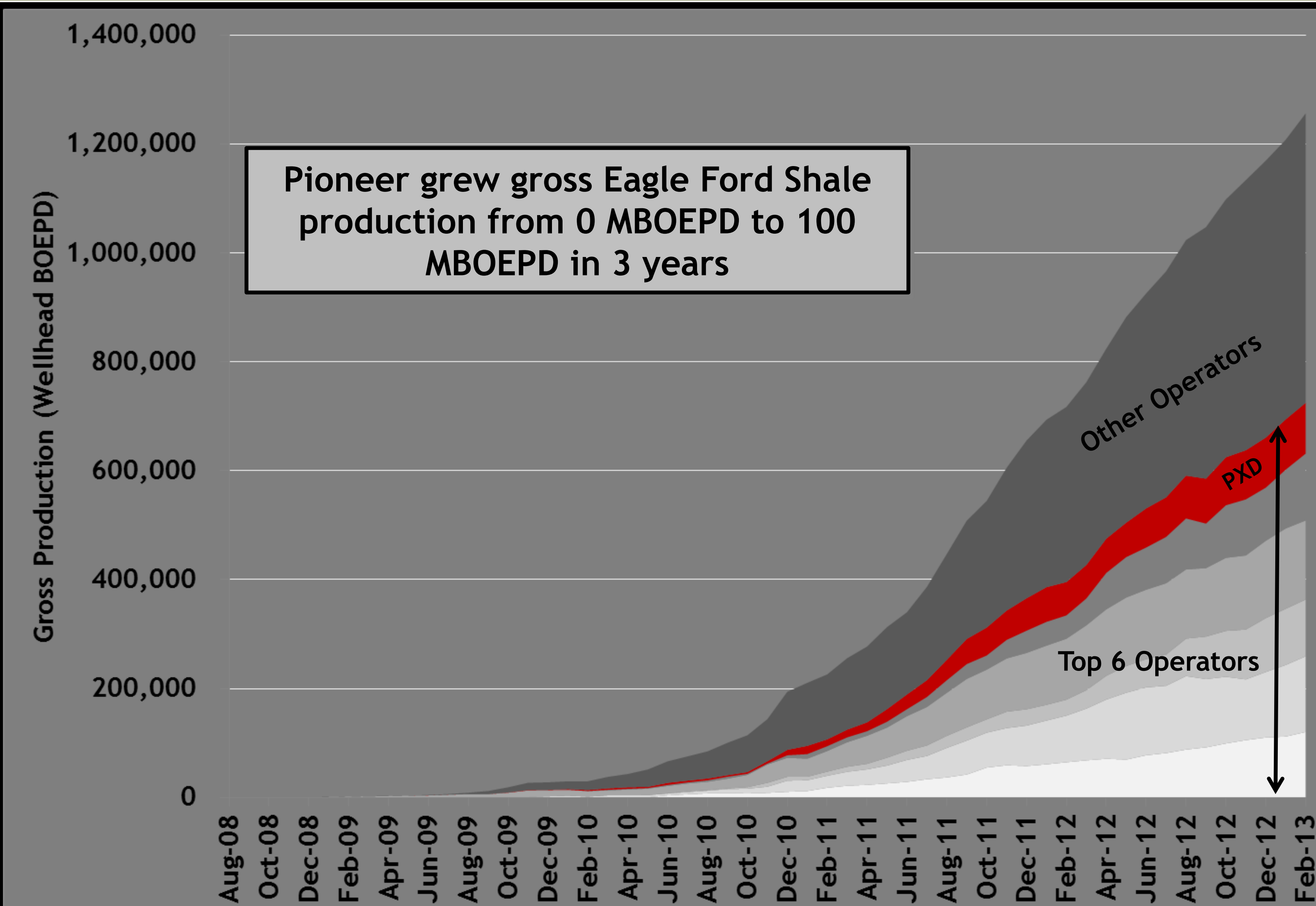

South Texas Regional Framework

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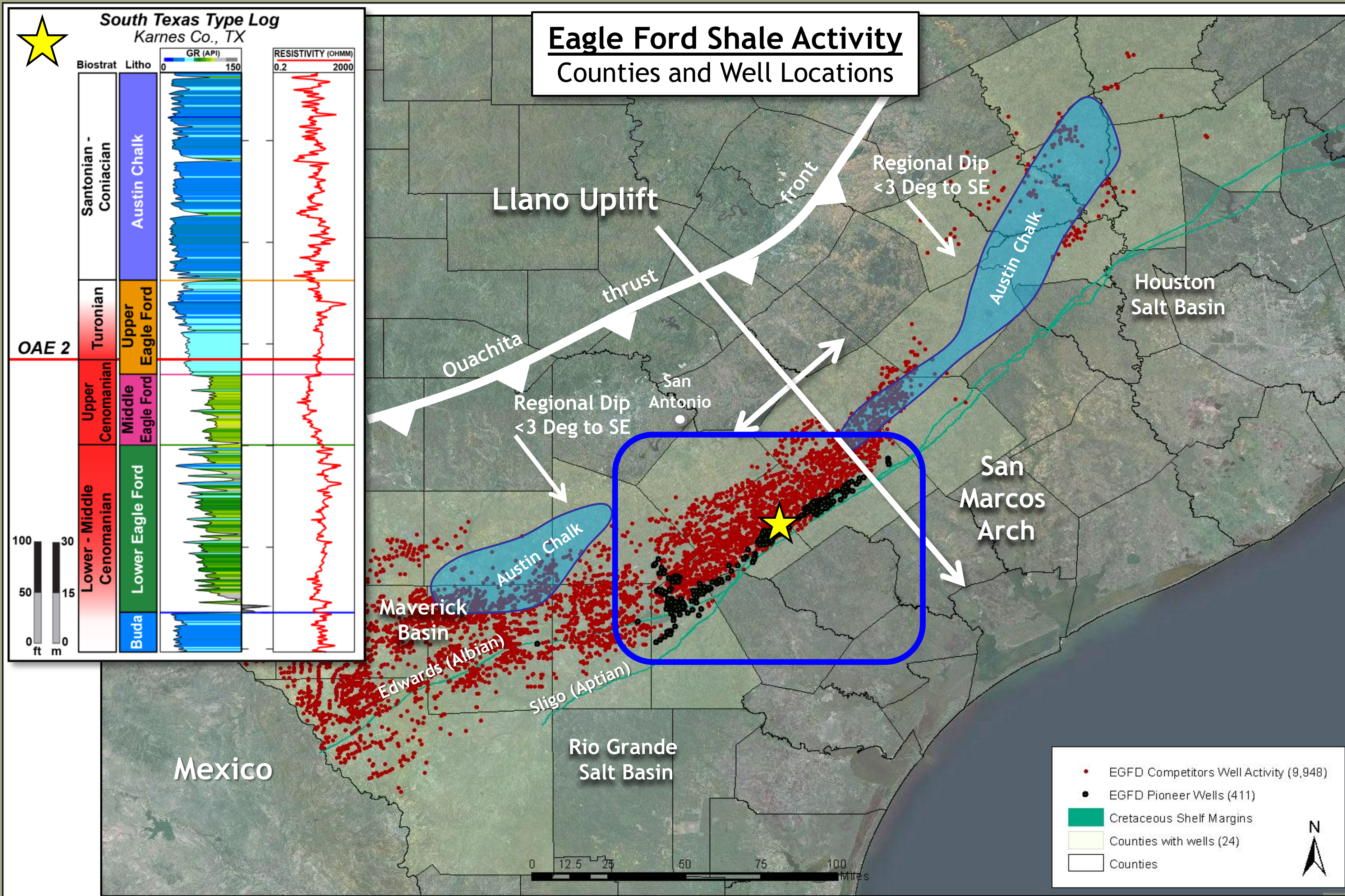

Eagle Ford Well Performance Drivers

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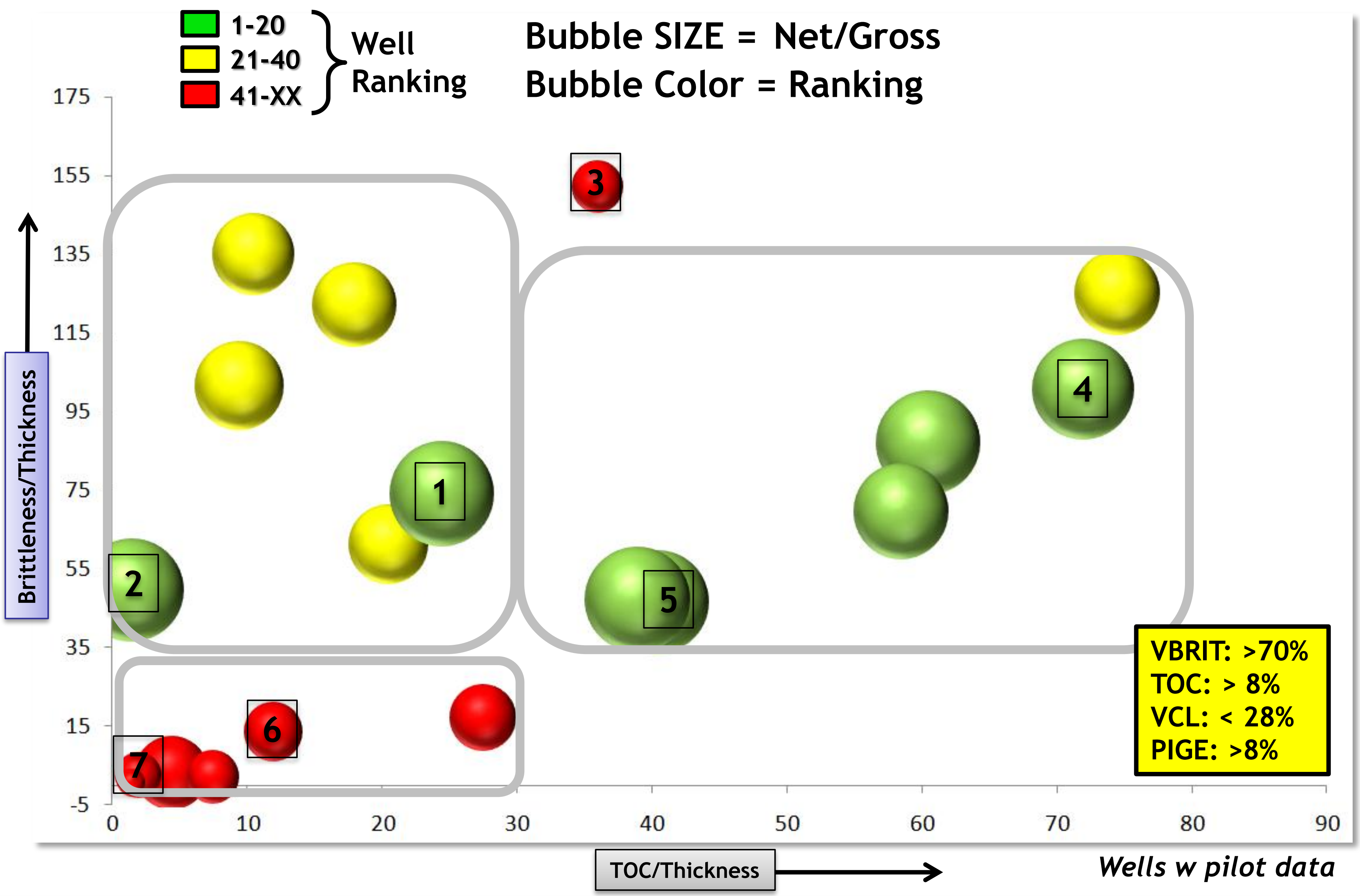

Facies Variability: VClay (Brittleness)

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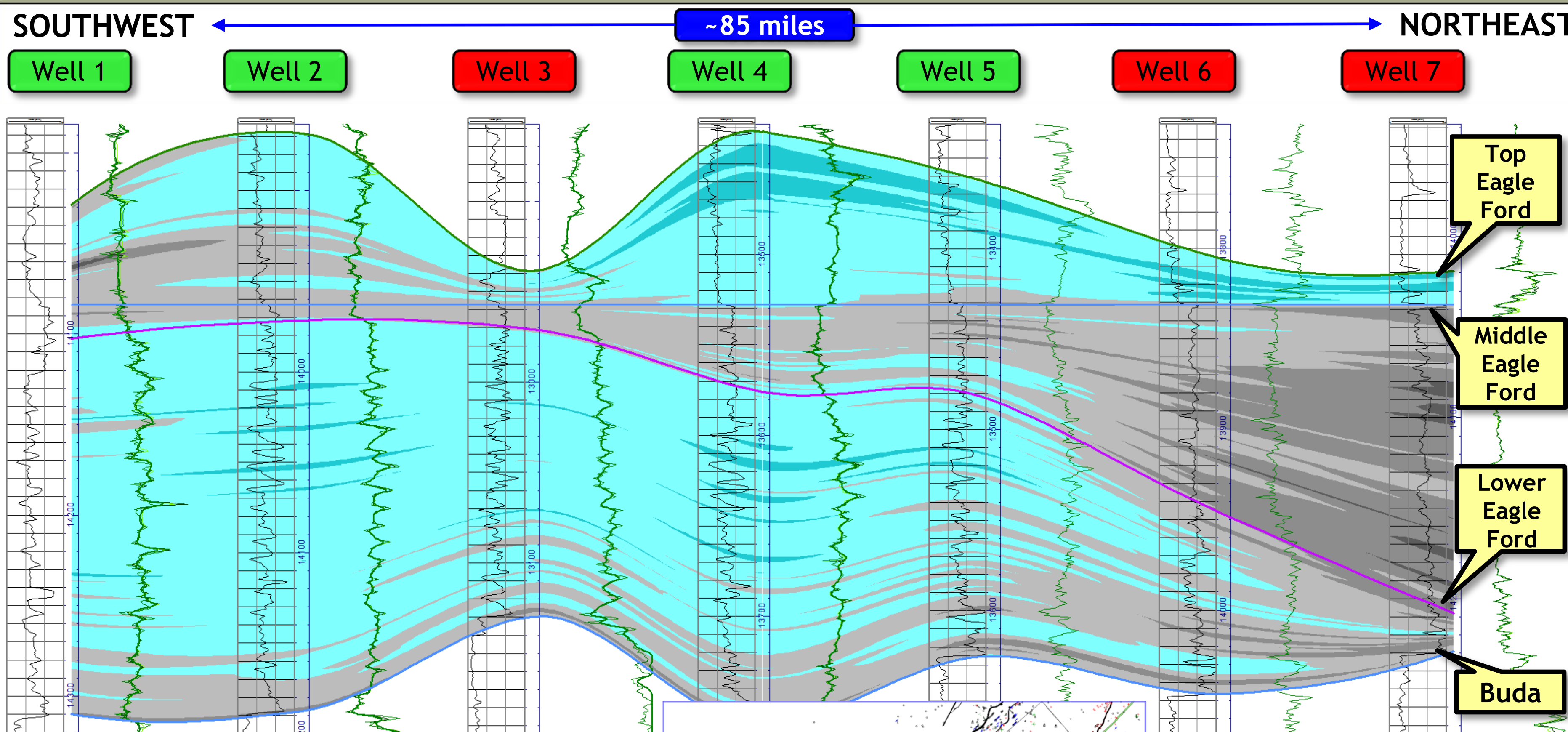
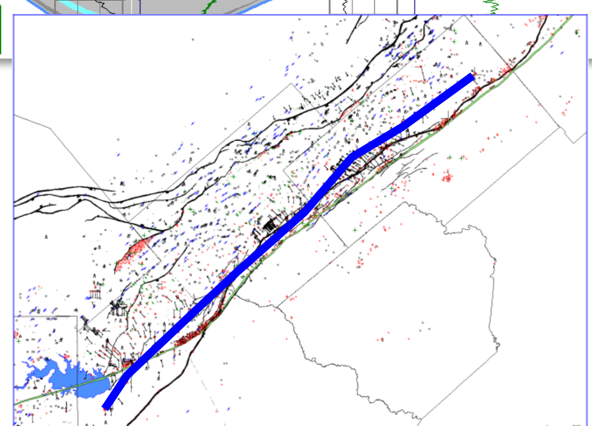


Clay Volume

- <15%
- >15%
- >30%
- >45%
- >60%

100 ft



- Better
- Average
- Poorer

Well Performance

Facies Variability: TOC (Kerogen)

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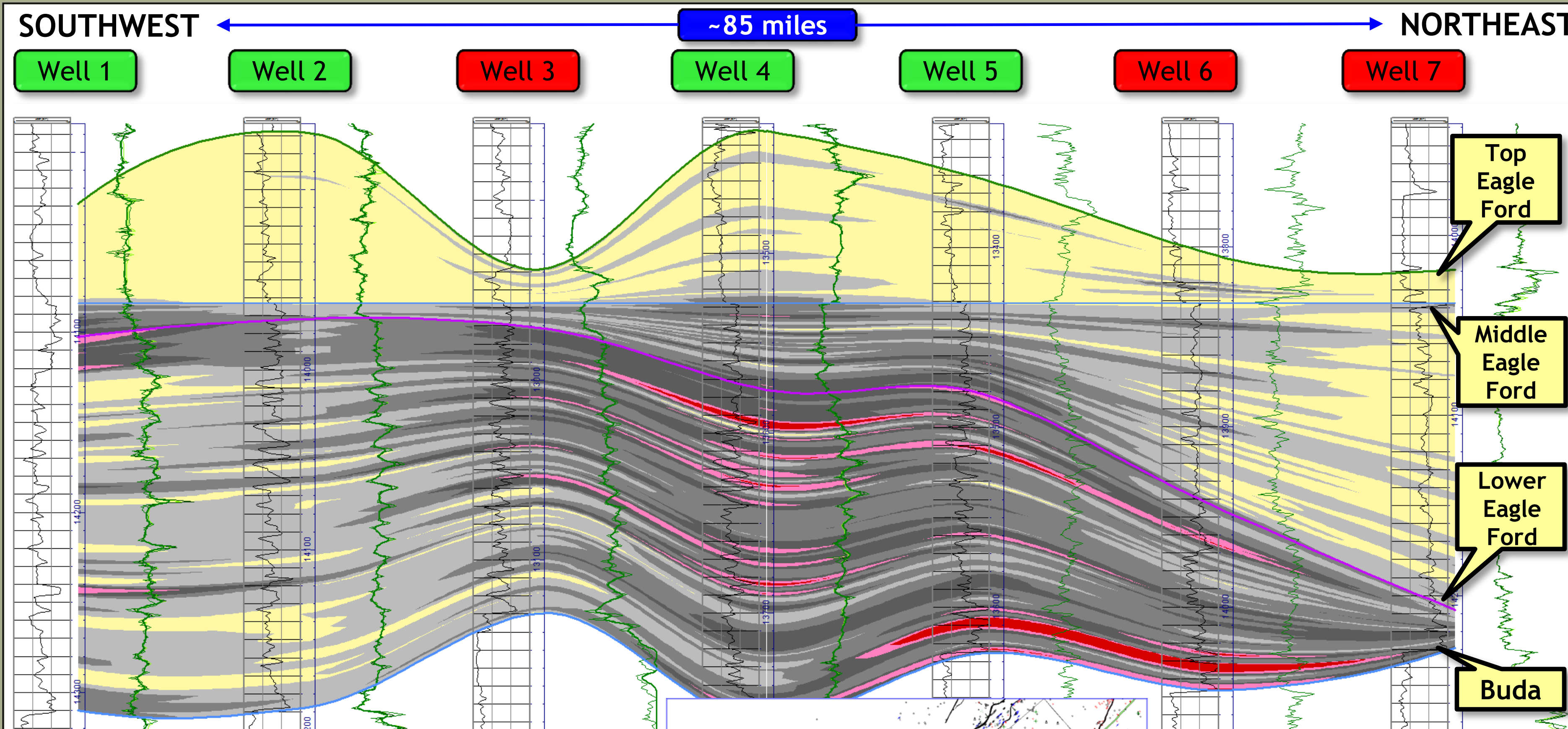
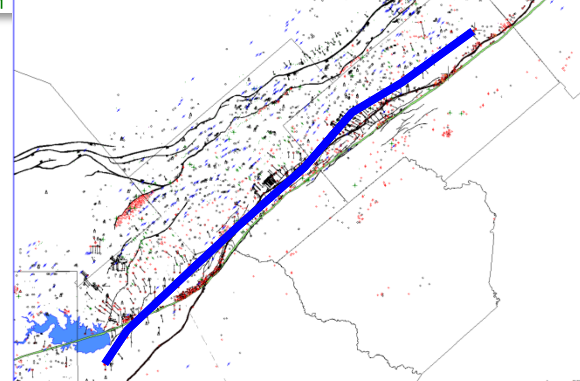


Kerogen Volume

- LEAN <2.5%
- >2.5%
- >5.0%
- >7.5%
- >10%
- >12.5%

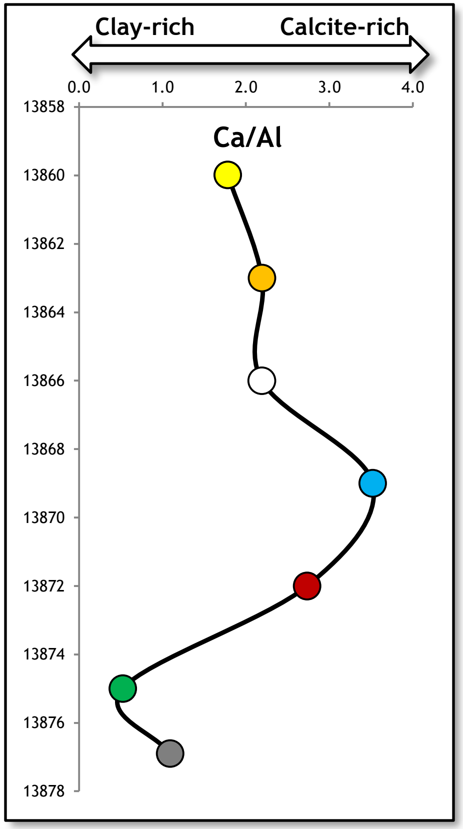


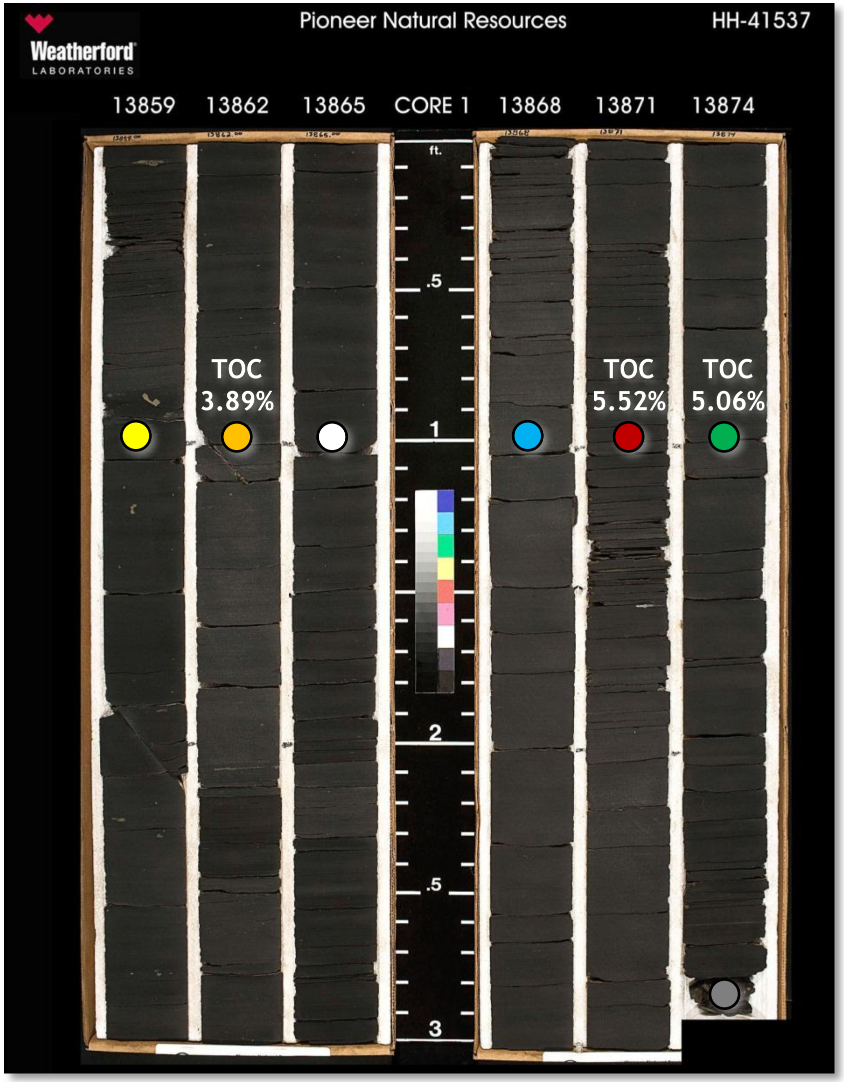
Well Performance

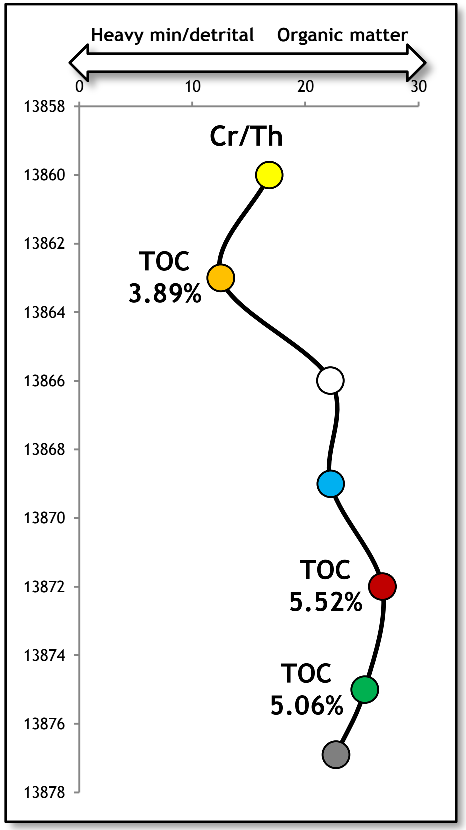
- Better
- Average
- Poorer

Chemostratigraphy

- Utilizes elemental geochemistry, from which mineralogy, depositional environment, and sediment source can be inferred and well-to-well correlations can be made and/or confirmed
- Very useful for evaluating rapid changes in what appear to be 'homogeneous' mudrocks







Elemental Data Derived using Hand Held XRF

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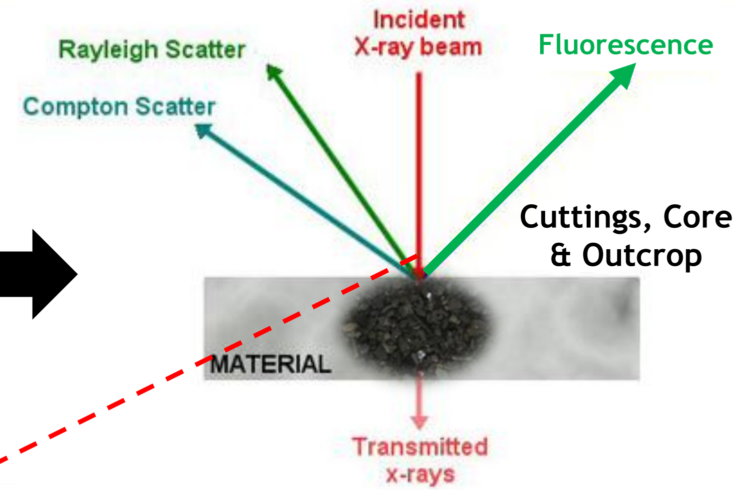
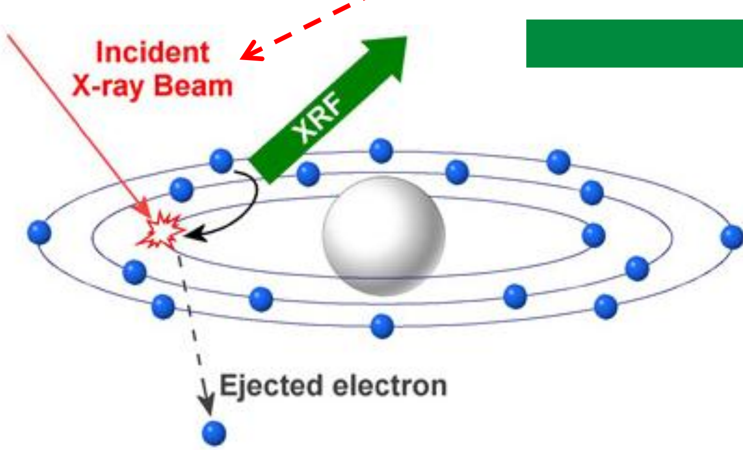
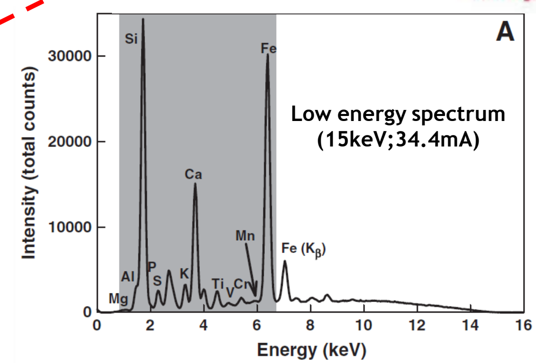
- Purchased Sept 2012 for $65,000
- To date STAT (South Texas Asset Team) have analyzed ~100 wells in house (vertical and horizontal wells)

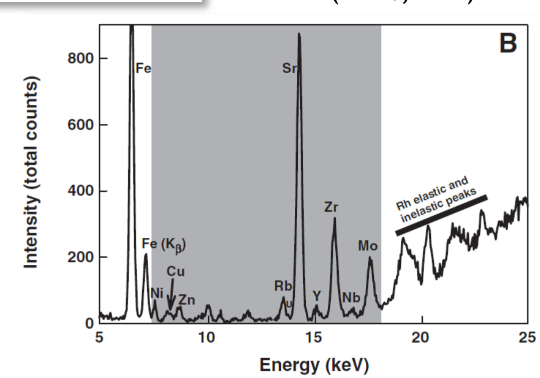






Elemental Data derived using X-Ray Fluorescence (XRF)

High energy spectrum (40keV;26mA)



Rowe et al. (2012)

Elemental Proxies

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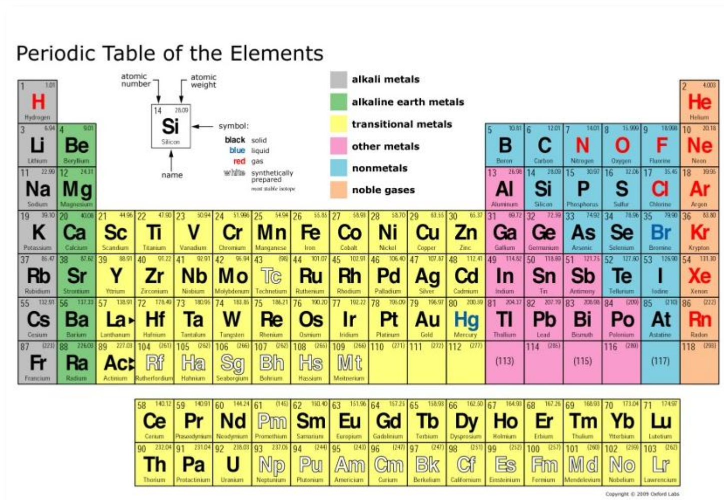

Oxford Labs

Nutrient rich
- P

Clay
- K
- Th
- Rb
- Nb
- Pb
- Al
- Si

Organic matter
- Cu
- Zn
- Cr
- Mo
- S
- U
- Ni

Carbonate
- Ca
- Mg
- Sr

Detrital
- Ti
- Zr

Redox
- Fe
- As
- Sb
- Co

Quartz = $\underline{\mathbf{Si}}O_2$

Calcite = $\underline{\mathbf{Ca}}CO_3$

Dolomite = $(Ca,\underline{\mathbf{Mg}})_2\,(CO_3)_2$

Kaolinite = $\underline{\mathbf{Al}}_2Si_2O_5(OH)_4$

Illite = $(K,H_3O)(\underline{\mathbf{Al}},Mg,Fe)_2(Si,\underline{\mathbf{Al}})_4O_{10}\,[(OH)_2,(H_2O)]$

Chlorite = $(Mg,Fe)_3(Si,\underline{\mathbf{Al}})_4O_{10}(OH)_2\cdot(Mg,Fe)_3(OH)_6$

Smectite = $(Na,Ca)_{0.33}(\underline{\mathbf{Al}},Mg)_2(Si_4O_{10})(OH)_2\cdot nH_2O$

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Wedephol, 1971; Brumsack, 2006; Tribovillard et al., 2006

Hand Held XRF Data – Pilot & Lateral

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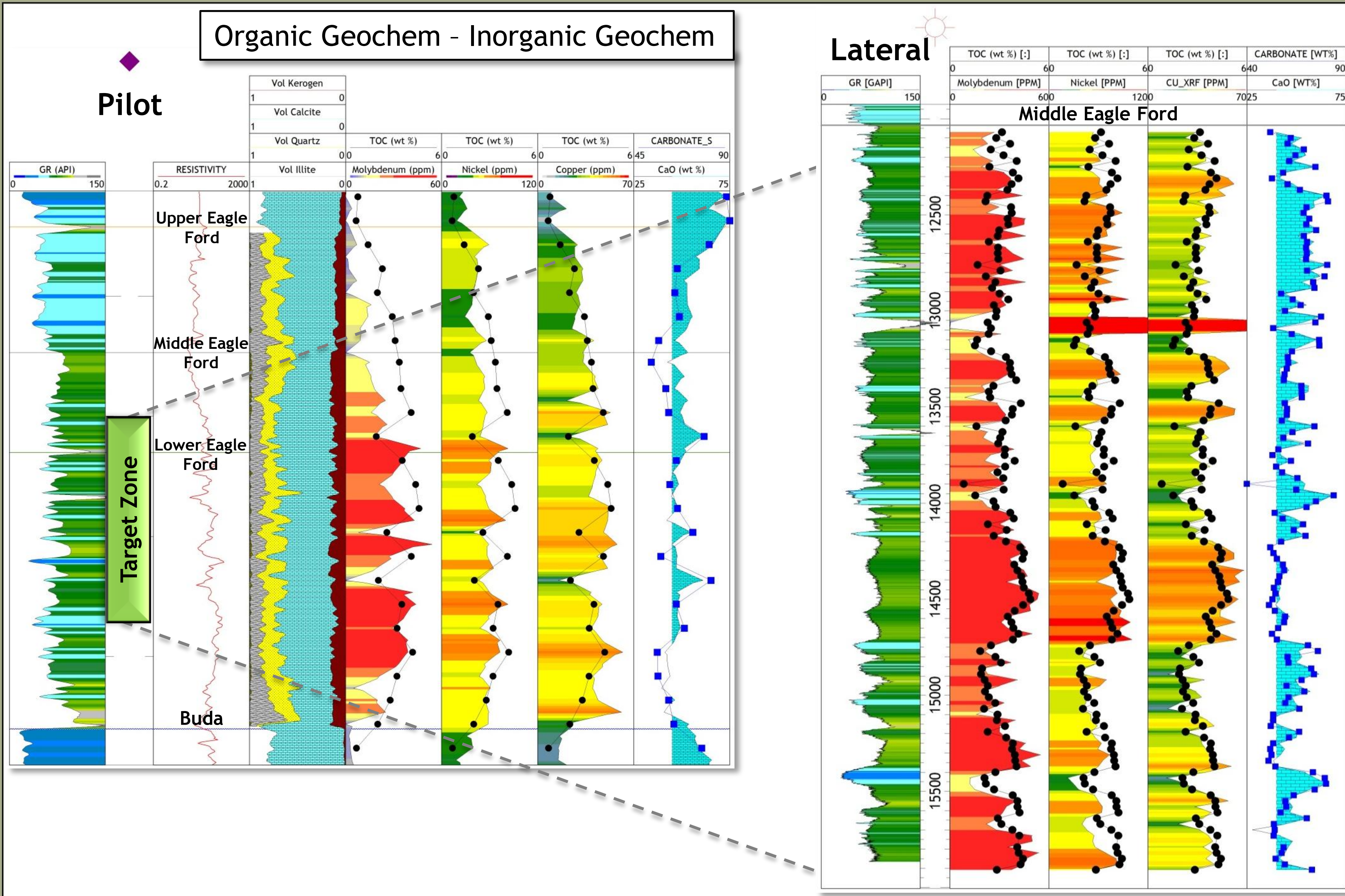

Paleoredox Facies - Strike (SW to NE)

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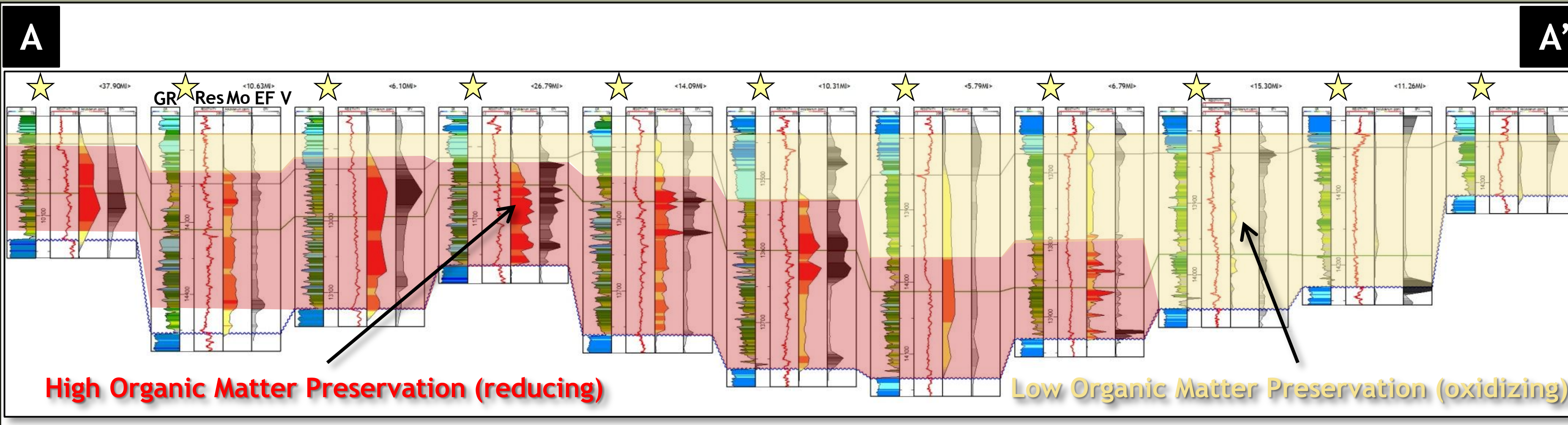
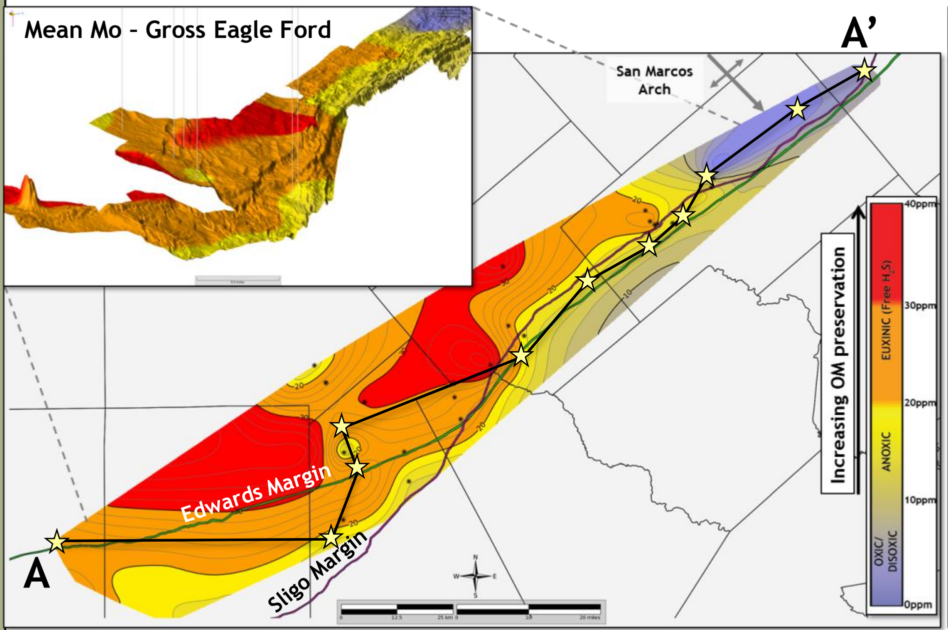
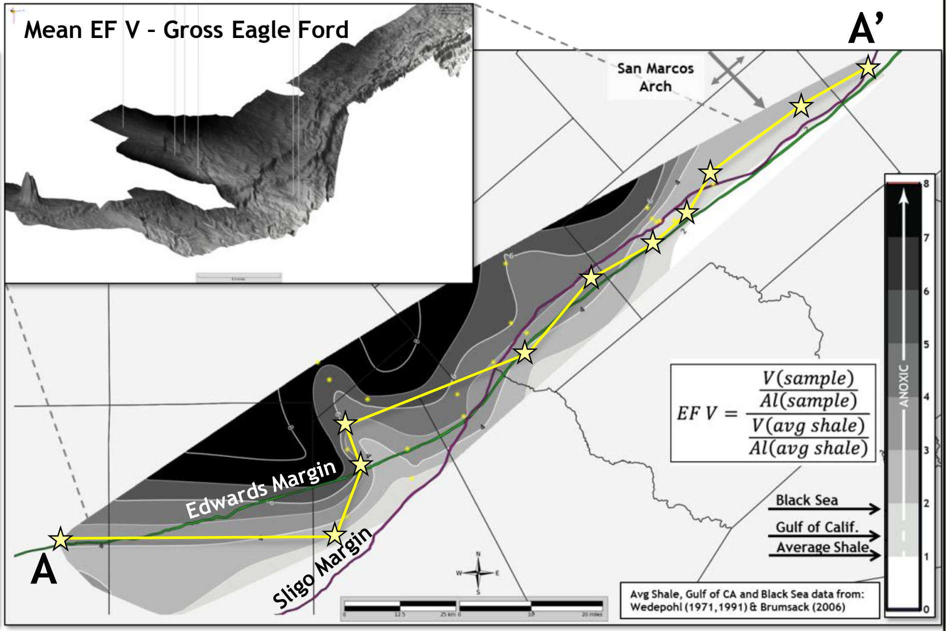




Eagle Ford Mean Molybdenum (Mo)



Eagle Ford Mean EF Vanadium (EF V)

Paleoredox Facies - Strike (SW to NE)

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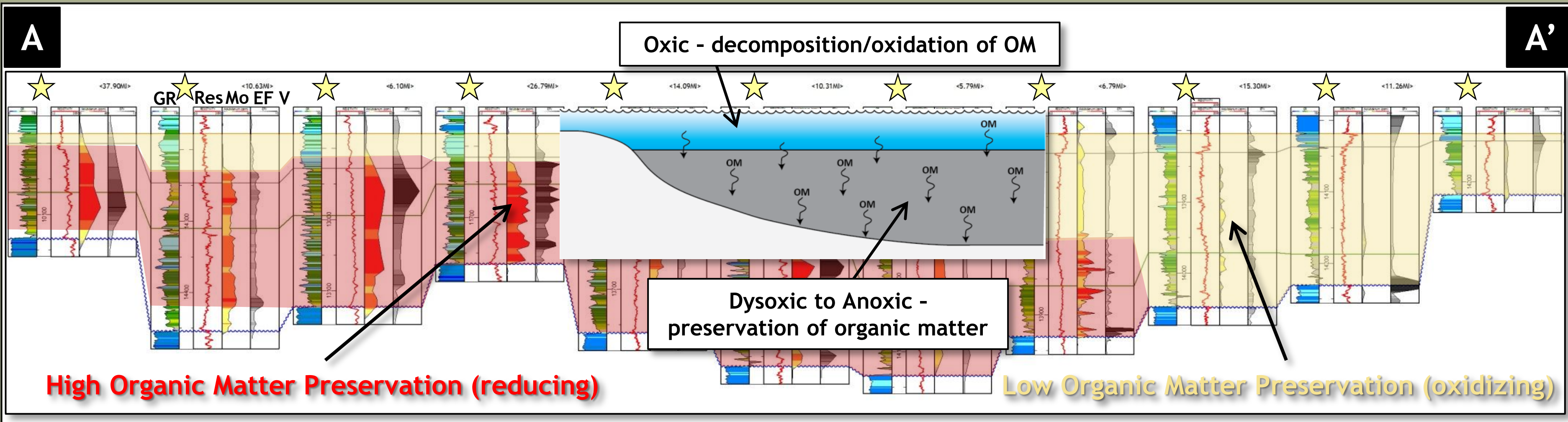
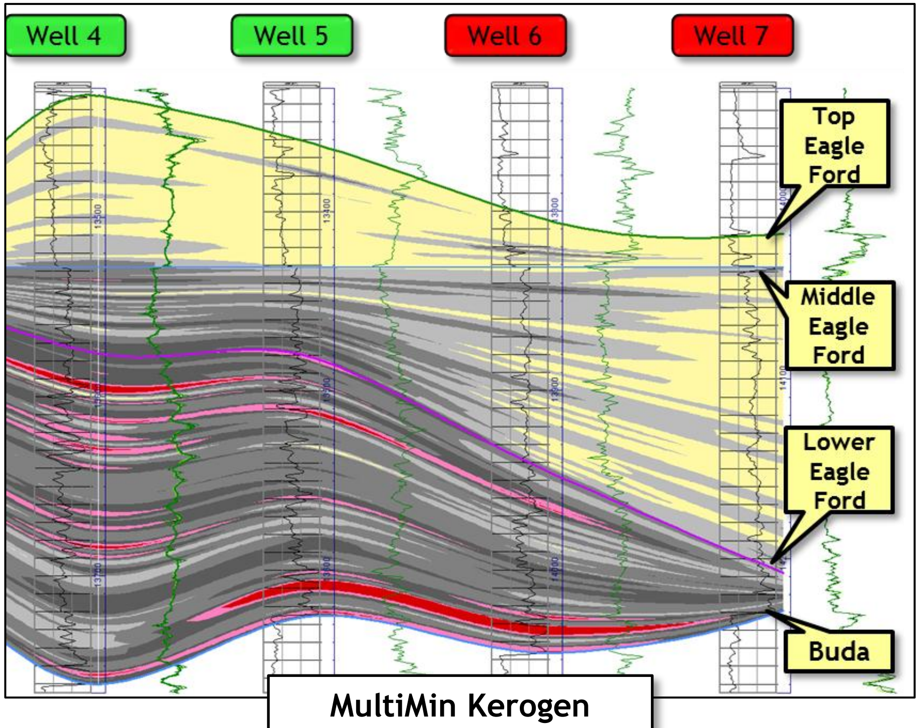
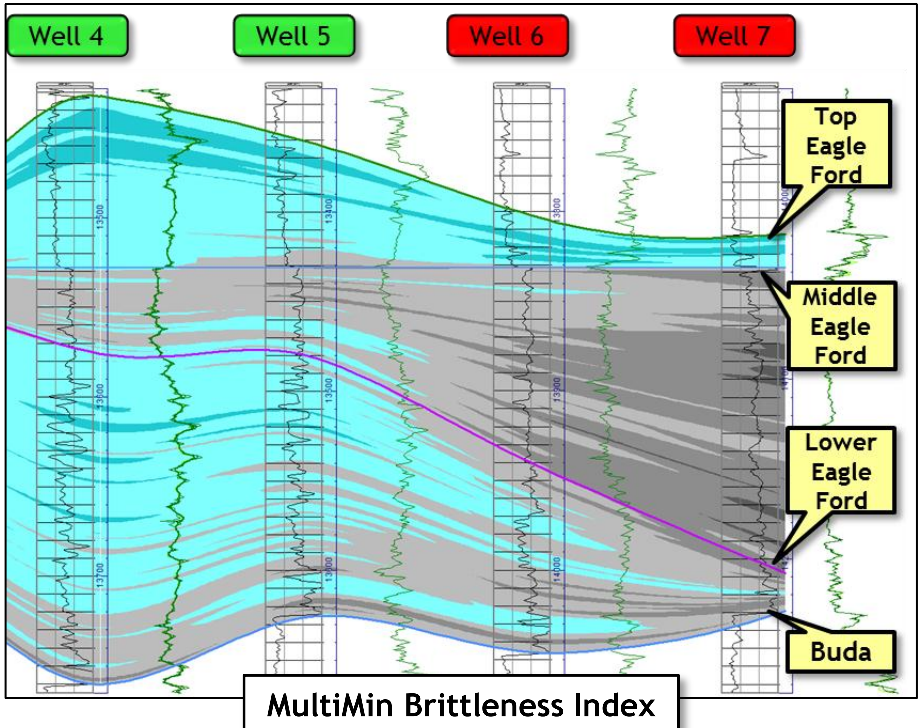
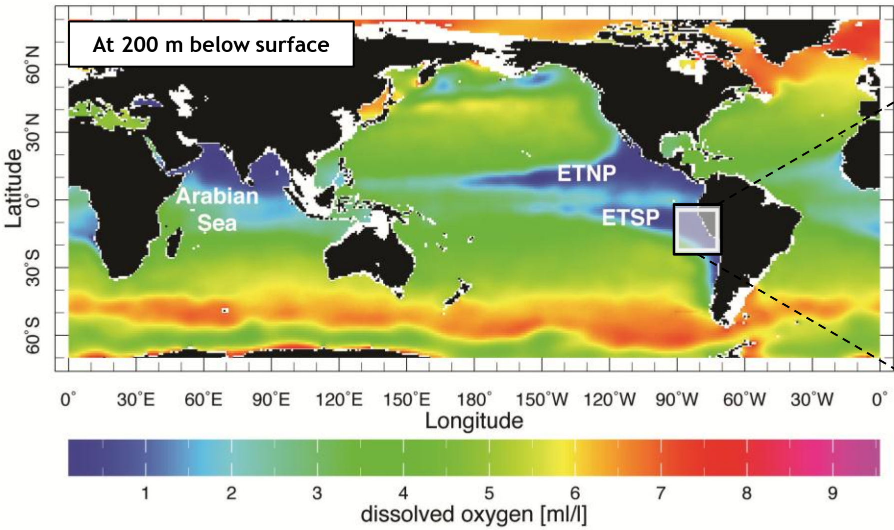






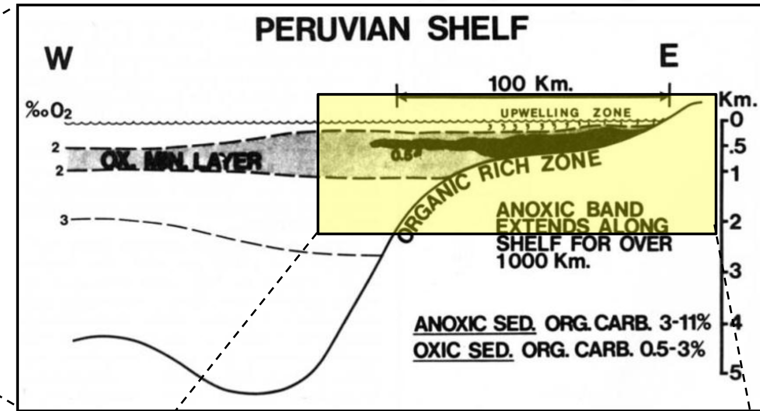
Oxygen Minimum Zone

Oxygen Minimum Zone (OMZ) is an oxygen-depleted layer of water, usually in 200 to 1000 meters water depth

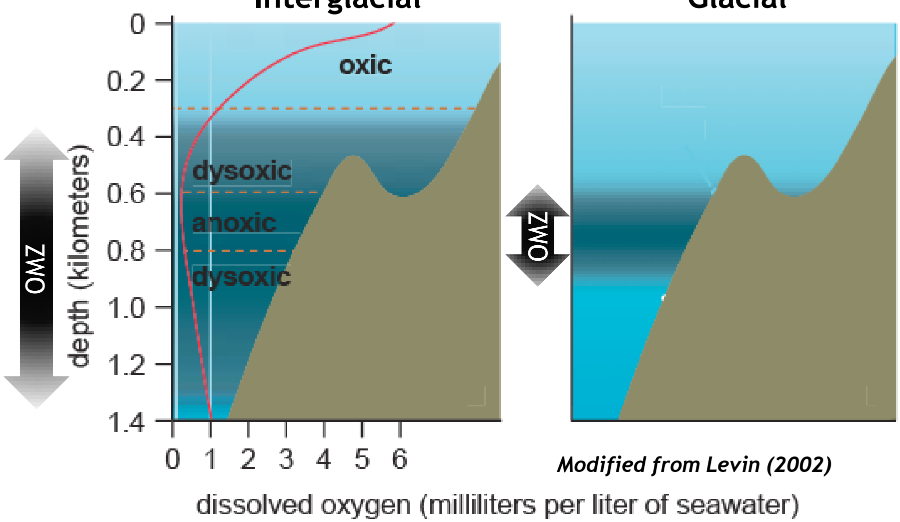


http://iridl.ldeo.columbia.edu/, IRI/LDEO Climate Data Library, Columbia University

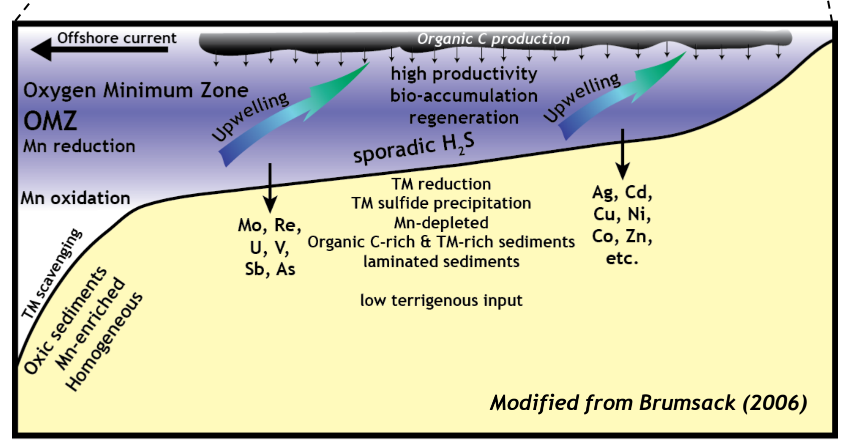
Anoxia caused by upwelling



Demaison and Moore (1980)



Modified from Levin (2002)



Modified from Brumsack (2006)

Oxygen Minimum Zone

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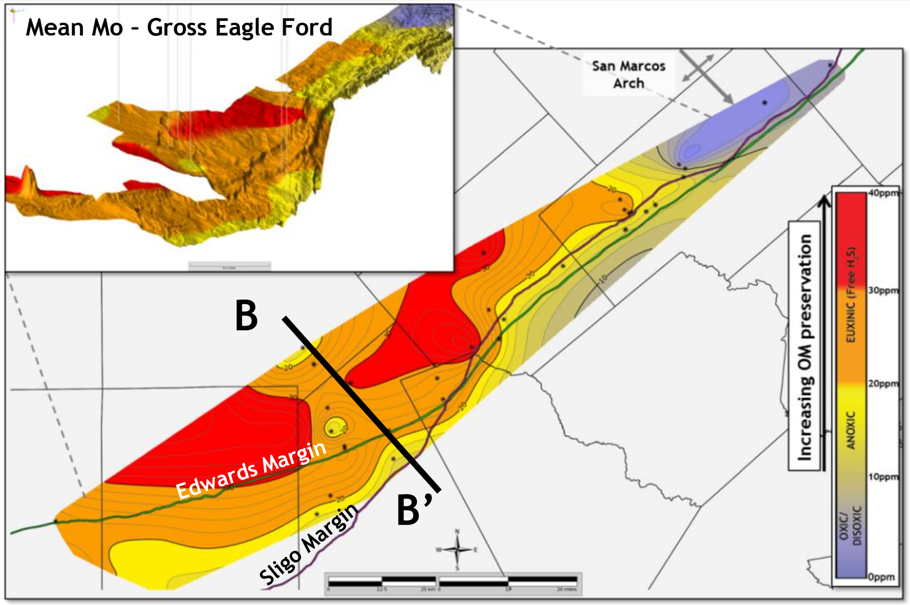

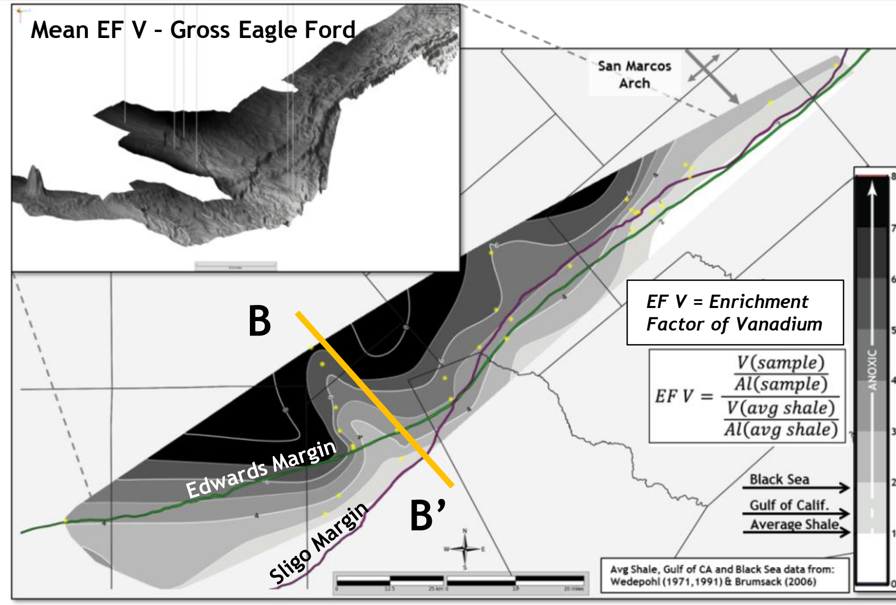

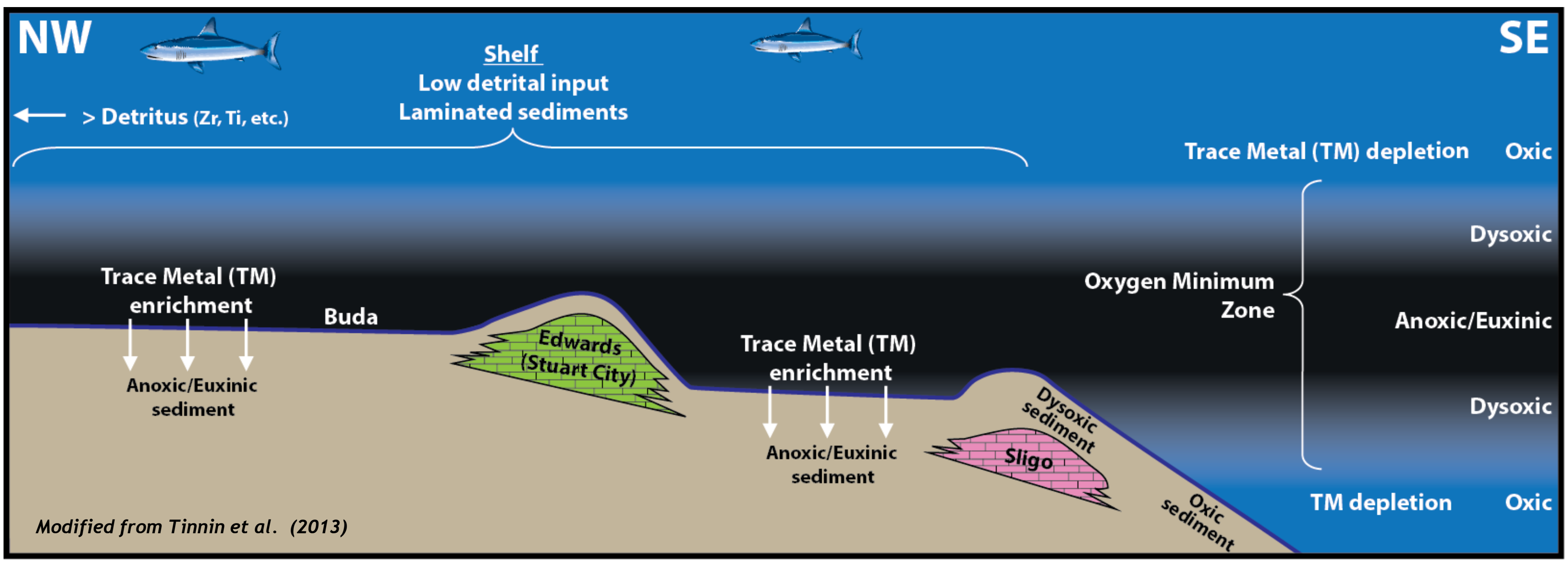

Rock Fracability (Brittleness)

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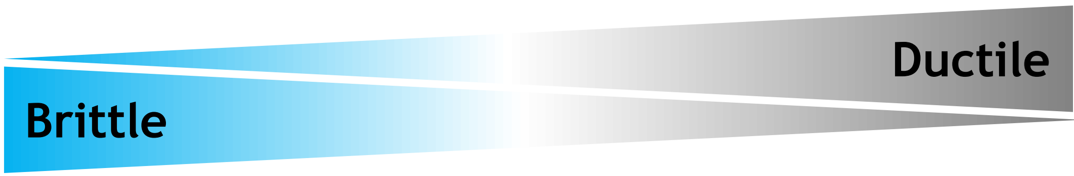
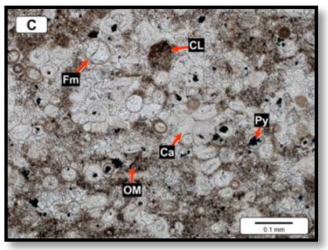
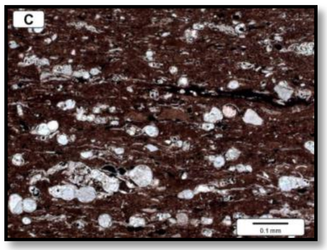
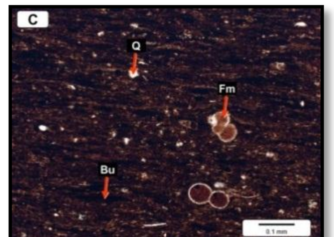
$$\text{Brittleness Index (BI)} = \frac{\text{Quartz} + \text{Dolomite} + \text{Calcite}}{\text{Quartz} + \text{Dolomite} + \text{Calcite} + \text{Clay}}$$

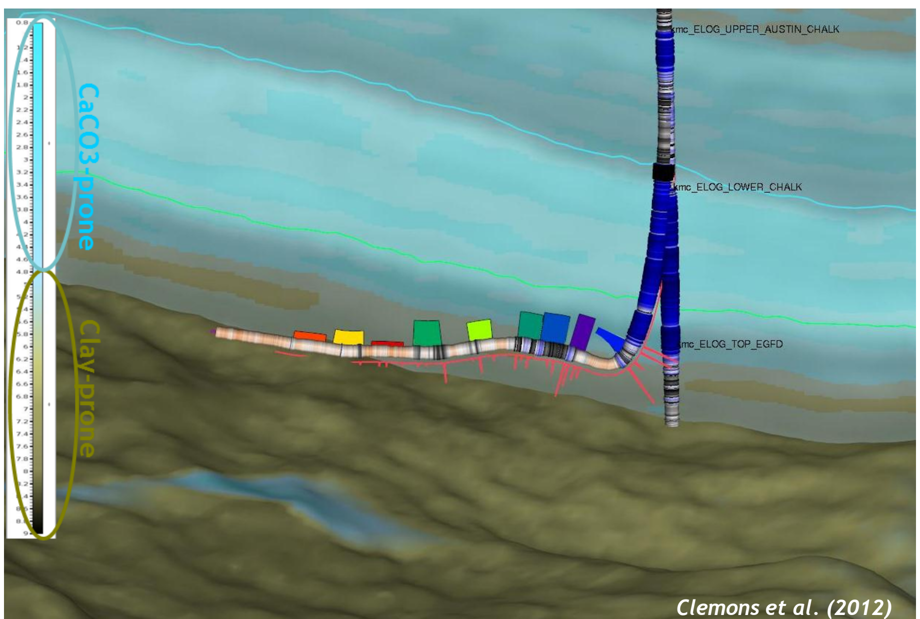
Wang and Gale (2009)



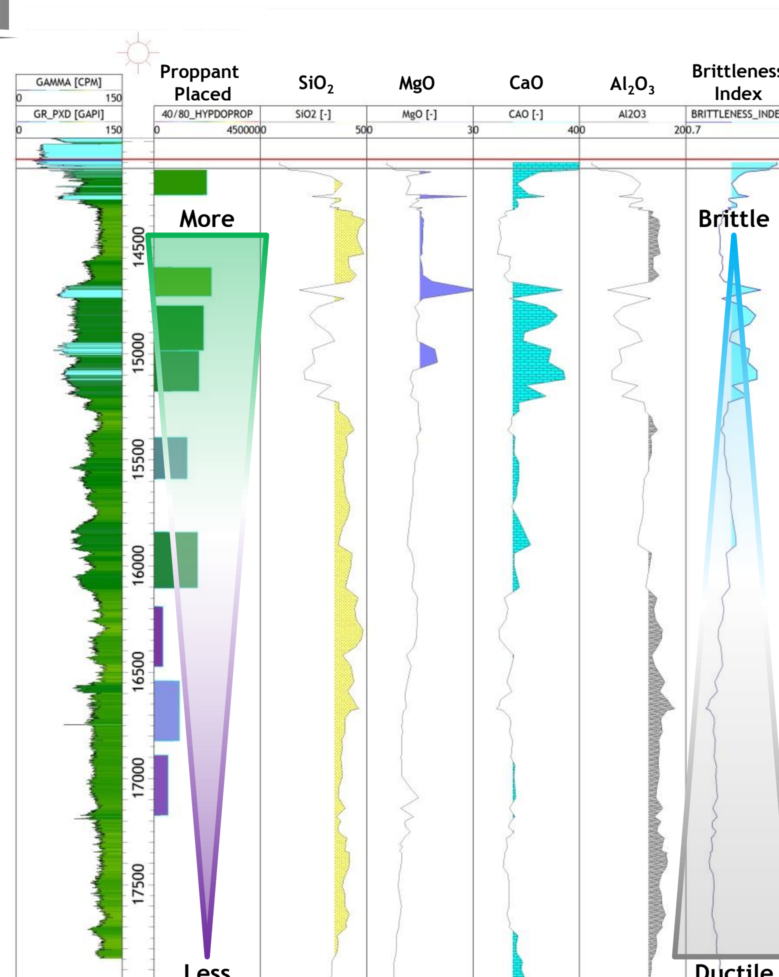








Clemons et al. (2012)



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Big Bend National Park, TX

Elemental Proxies

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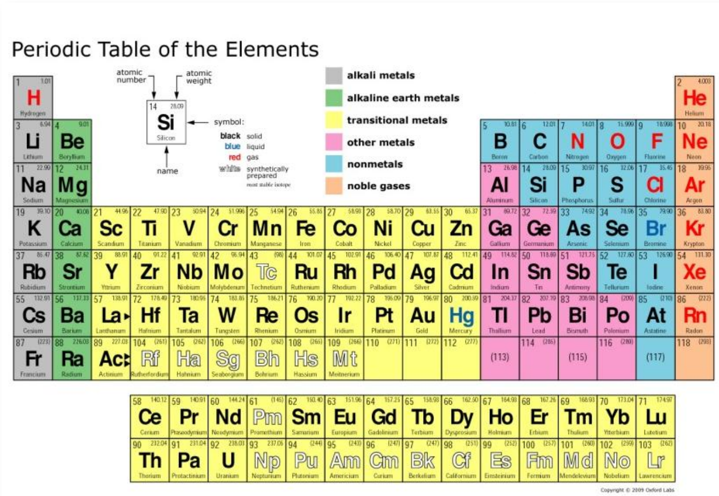

Oxford Labs

Nutrient rich
- P

Organic matter
- Cu
- Zn
- Cr
- **Mo**
- S
- U
- **Ni**

Redox
- Fe
- As
- Sb
- Co

Carbonate
- **Ca**
- Mg
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Clay
- K
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- **Al**
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Choice of Elemental Proxies

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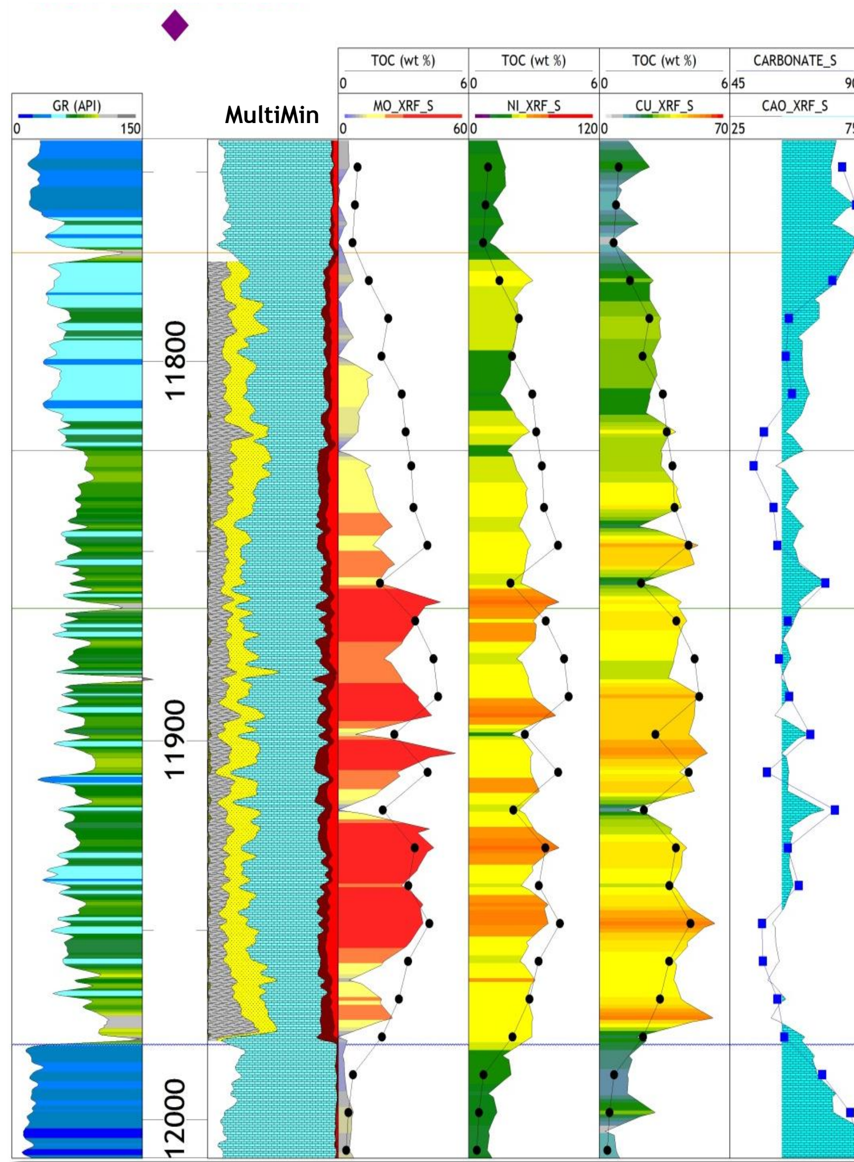
PCA Analysis using Elemental Data

- Calculate and interpret different element concentrations using XRF data from well cuttings samples.
- Identify elements that correlate with rock properties in order to better define target windows in zones with poor data control. Kerogen, Vclay, etc.
- Perform Principal Component Analysis (PCA) over a set of identified key elements from the hand held XRF data. Interpret matrix correlations, eigenvalues, contribution, etc.
- Proceed with multi-source data integration using the most appropriate elemental proxies for rock properties



XRF Data from Well Samples

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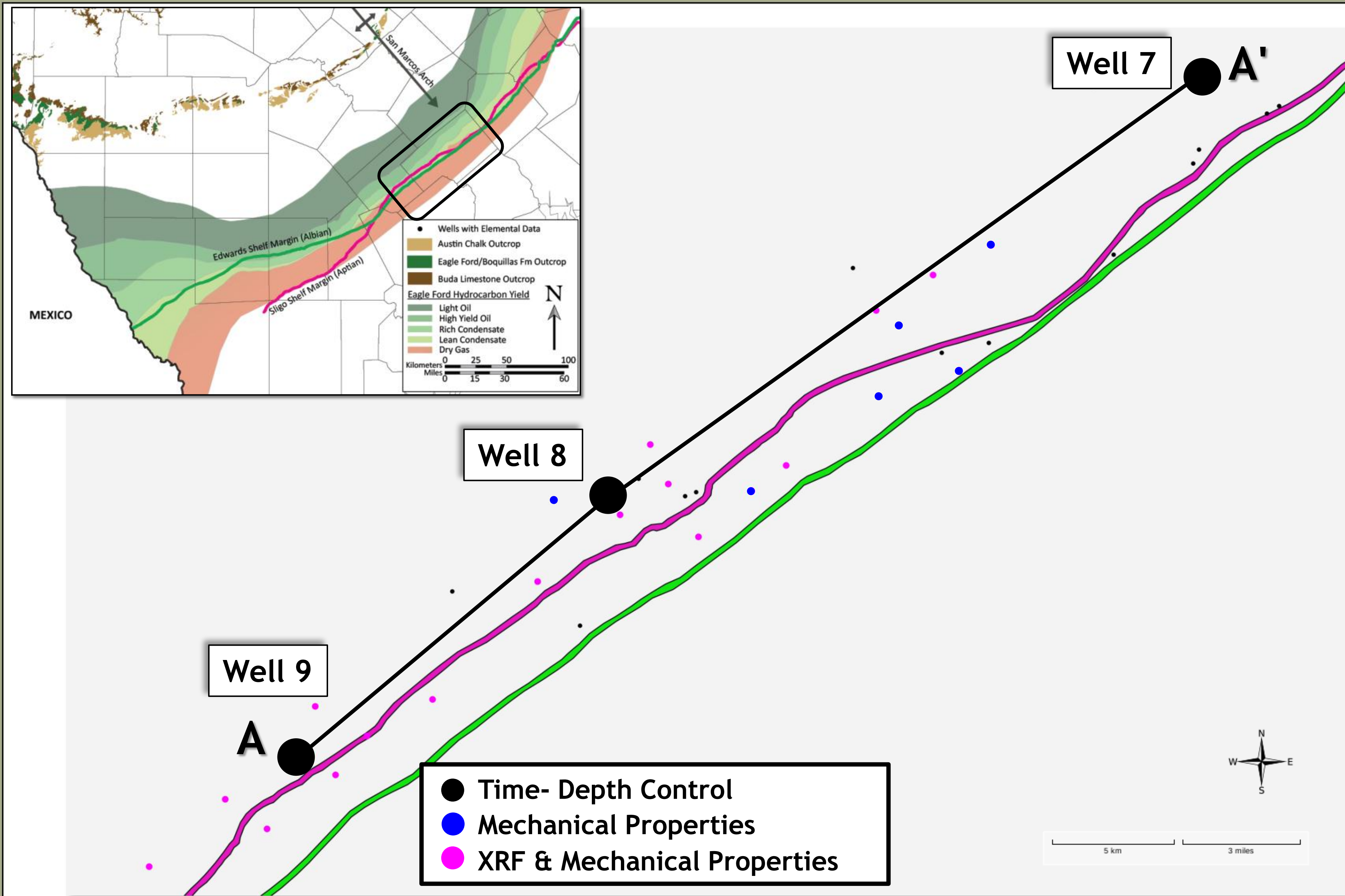
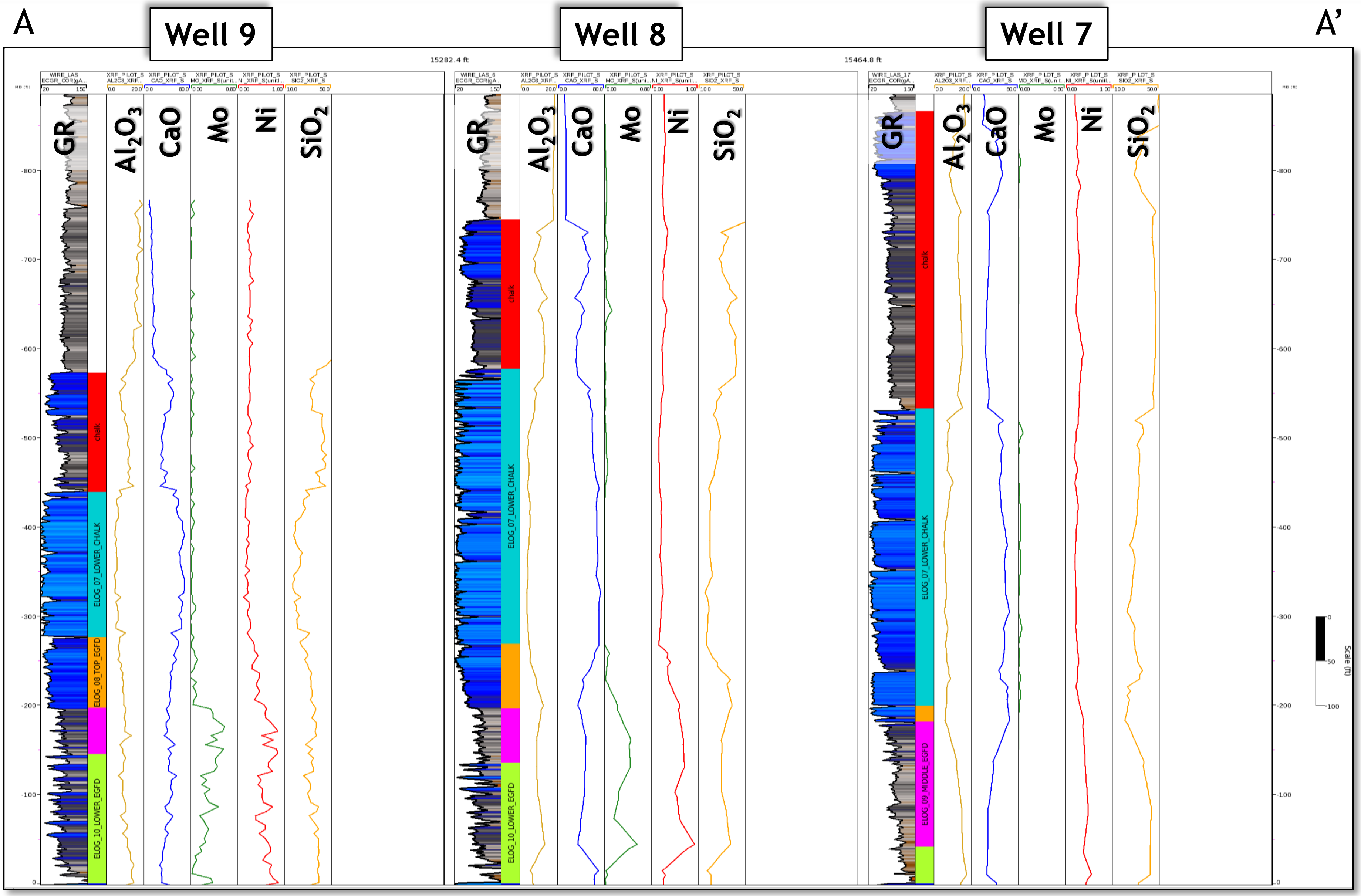


XRF Data from Well Samples



Analysis Matrix: Correlations

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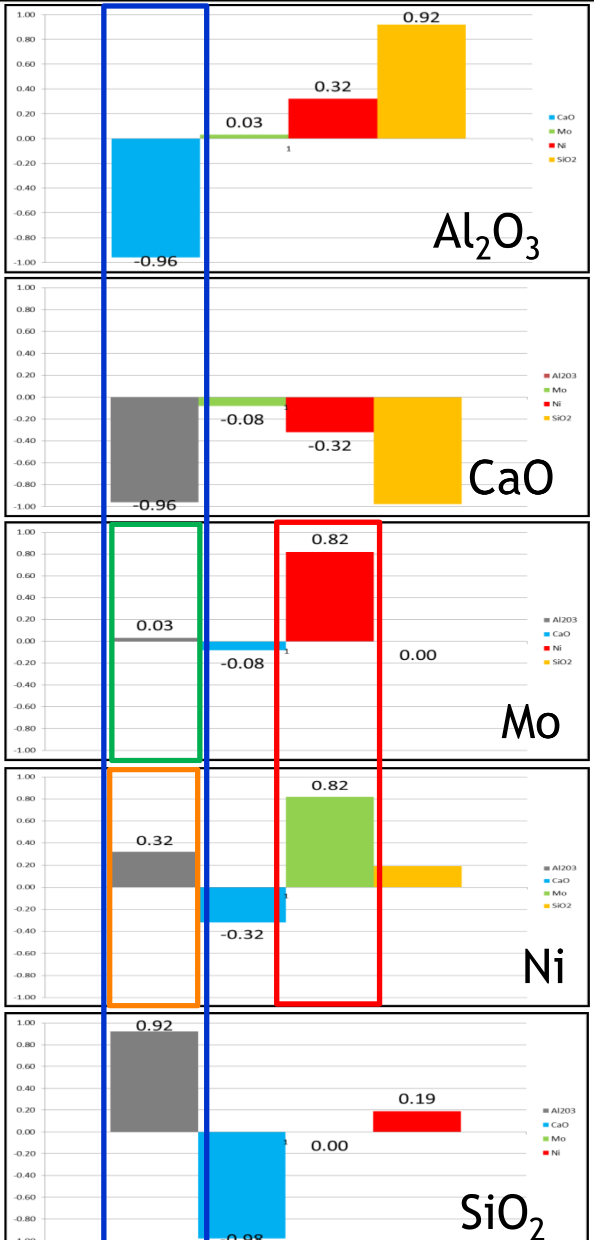
	Clay	Brittle	Organic Matter		
	Al203	CaO	Mo	Ni	SiO2
Al203	1.00	-0.96	0.03	0.32	0.92
CaO	-0.96	1.00	-0.08	-0.32	-0.98
Mo	0.03	-0.08	1.00	0.82	0.00
Ni	0.32	-0.32	0.82	1.00	0.19
SiO2	0.92	-0.98	0.00	0.19	1.00

- SiO_2 is strongly correlated with Al_2O_3 and CaO is strongly anti-correlated with Al_2O_3
- Mo has almost no correlation with Al_2O_3
- Mo and Ni do have a fairly strong correlation
- Ni also exhibits some correlation with Al_2O_3



Eigenvalues & Component Variables

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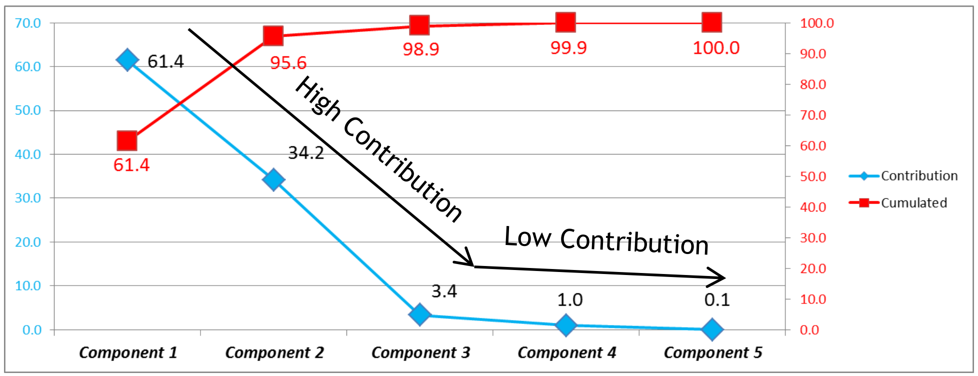
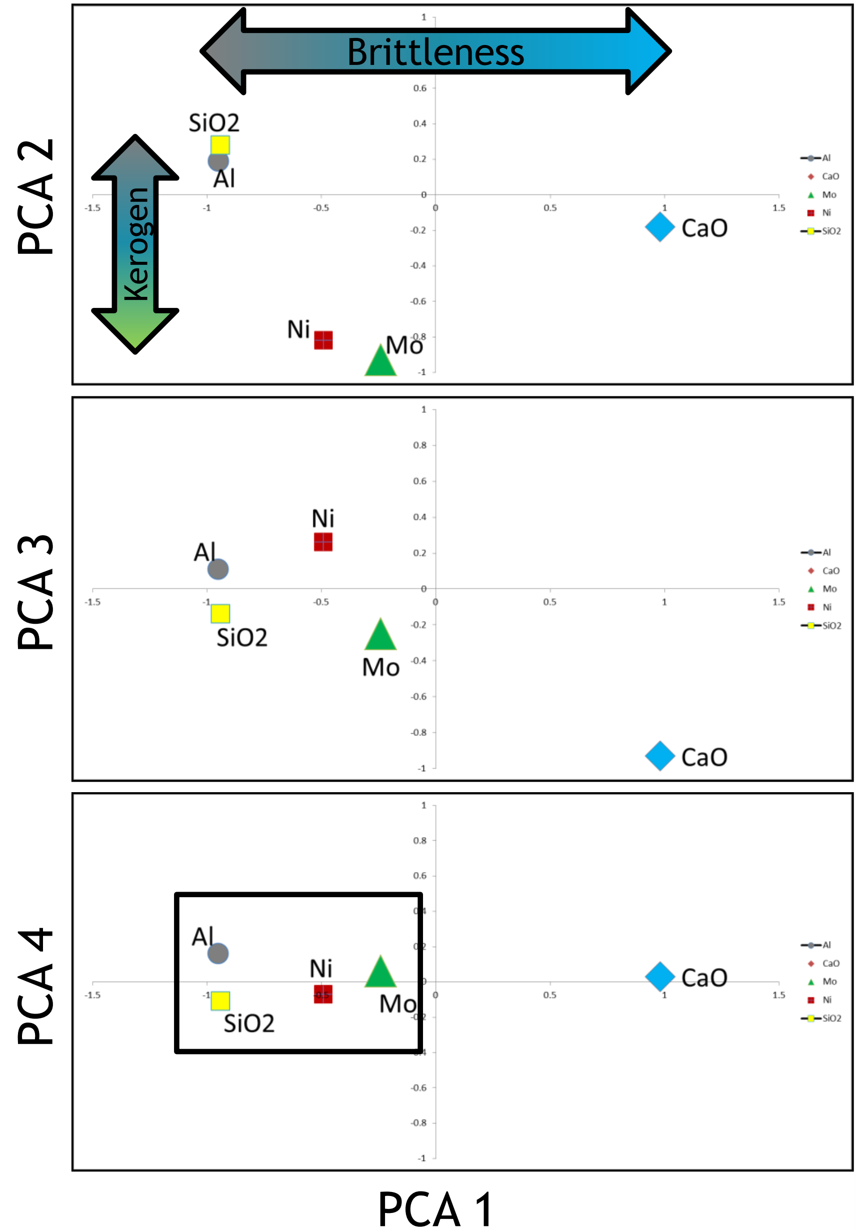
	Eigen Values	Contribution	Cumulated
Component 1	3.1	61.4	61.4
Component 2	1.7	34.2	95.6
Component 3	0.2	3.4	98.9
Component 4	0.1	1.0	99.9
Component 5	0.0	0.1	100.0

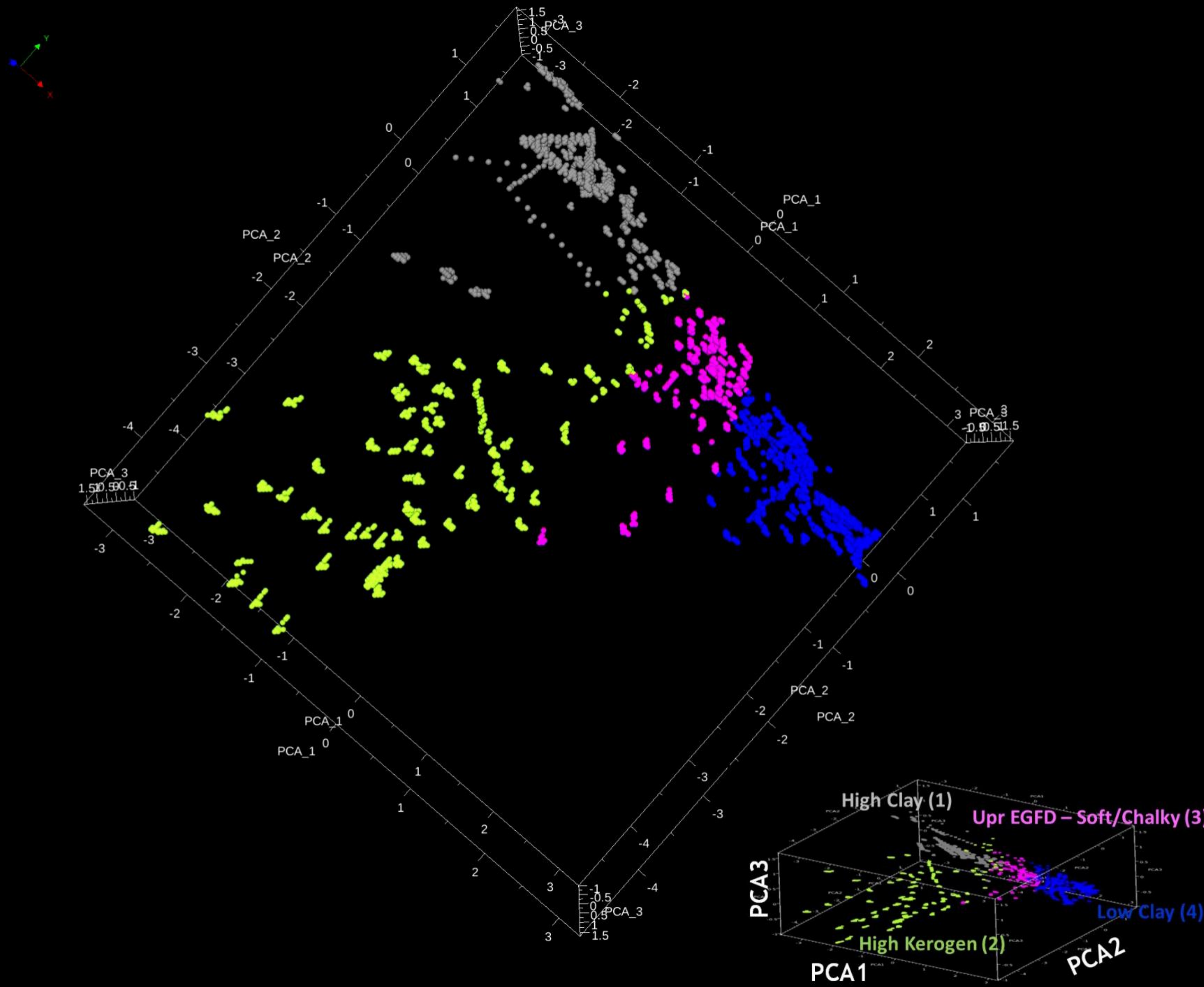


Eigenvalues

	Component 1	Component 2	Component 3	Component 4
Al	-0.95	0.19	0.11	0.16
CaO	0.98	-0.18	-0.93	0.03
Mo	-0.24	-0.93	-0.25	0.061
Ni	-0.49	-0.82	0.26	-0.07
SiO2	-0.94	0.28	-0.139	-0.11

4 Components cumulate 99.9% of the data

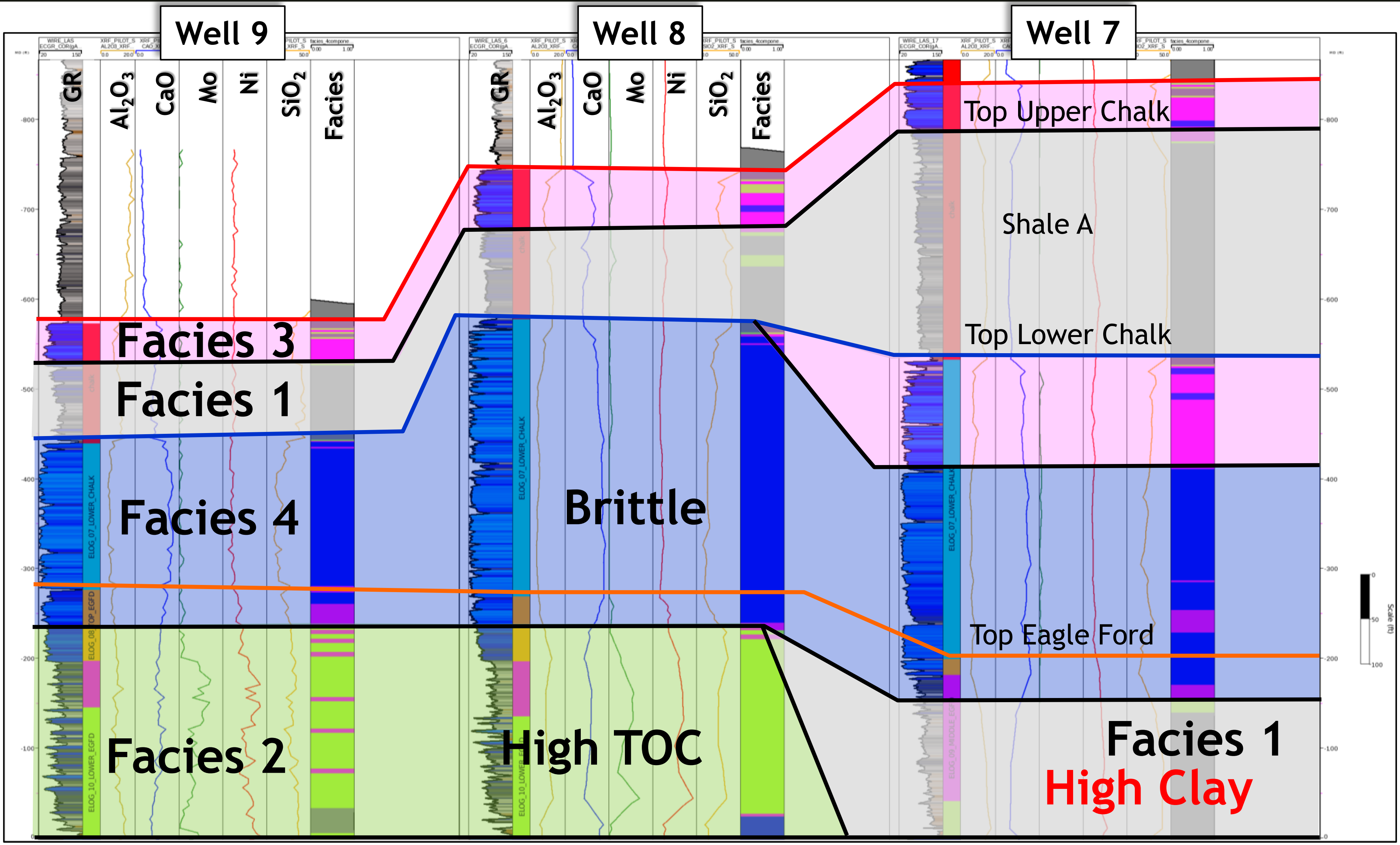




PCA_1
PCA_2
PCA_3
High Clay (1)
Upr EGFD – Soft/Chalky (3)
PCA3
Low Clay (4)
High Kerogen (2)
PCA1
PCA2

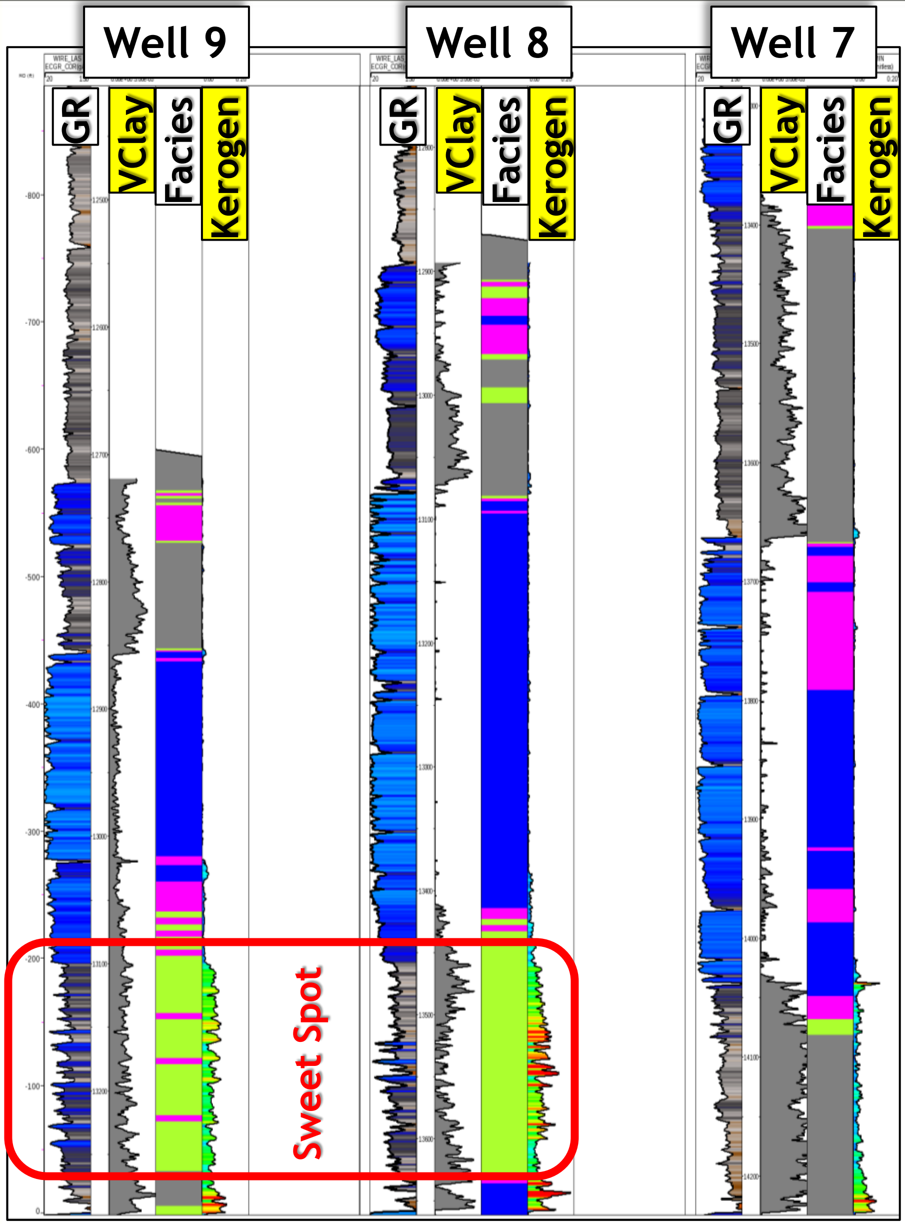
Facies Logs & Geology

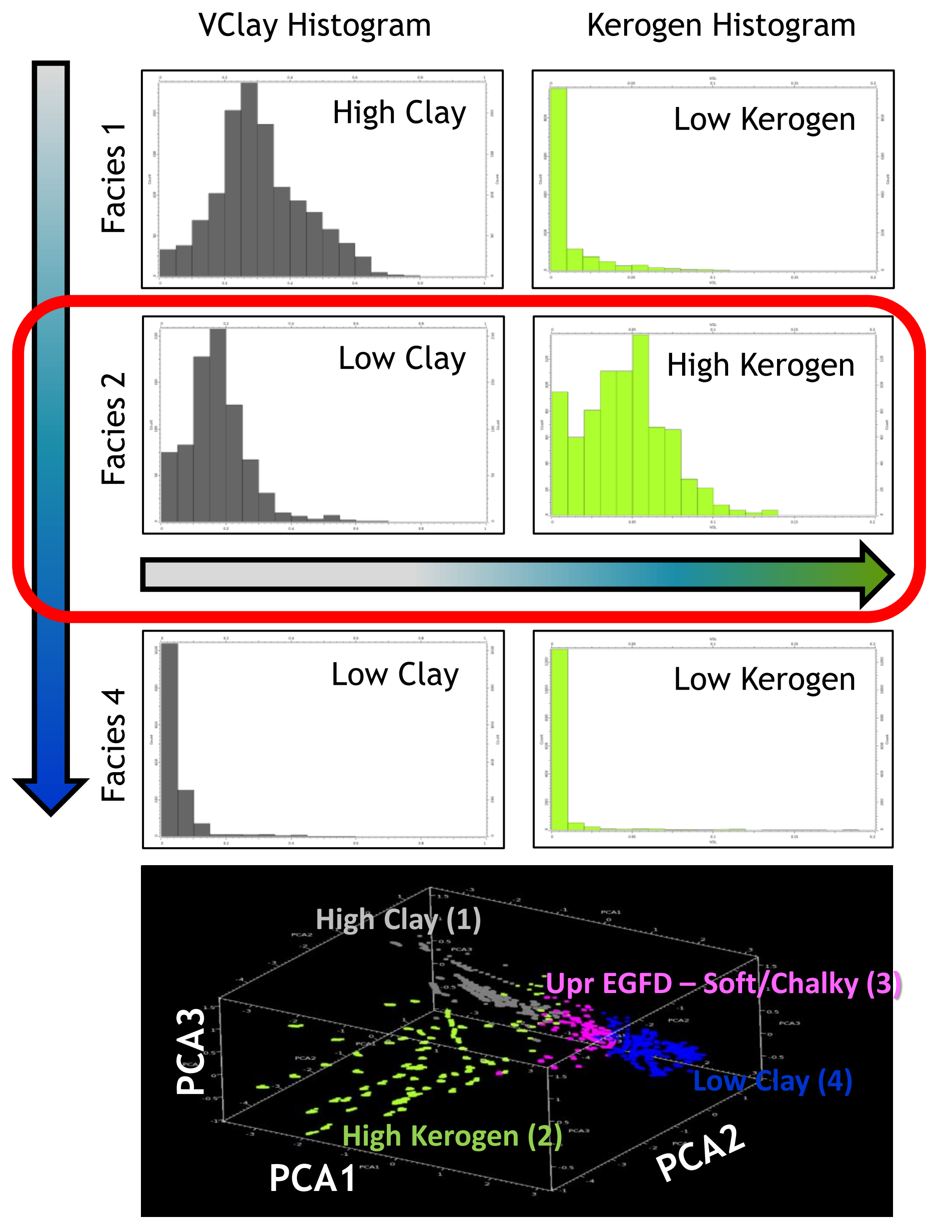
PIONEER NATURAL RESOURCES



Relationship with Petrophysical Interpretation

PIONEER NATURAL RESOURCES





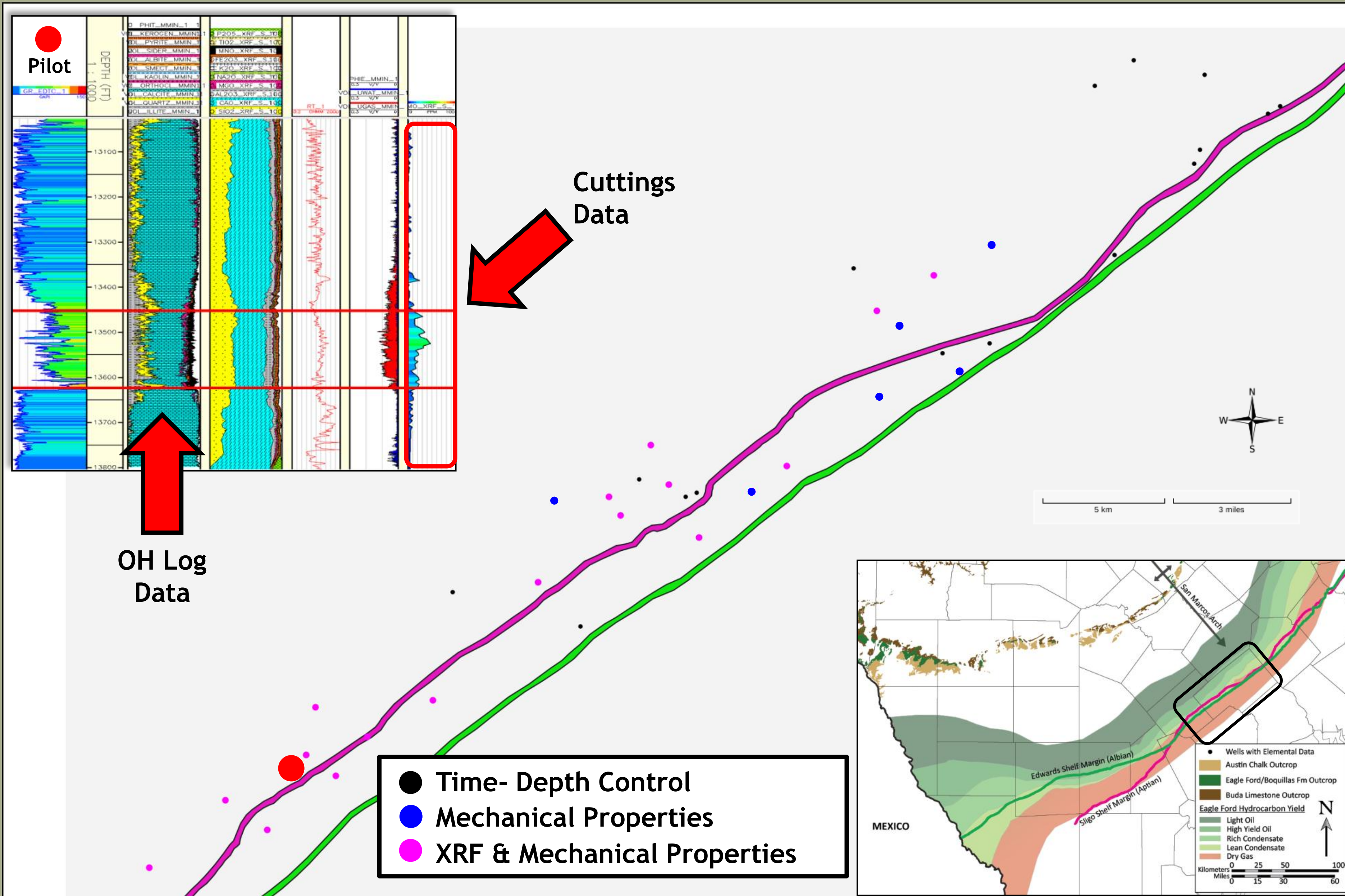
Outline

PIONEER
NATURAL RESOURCES

- Eagle Ford Shale production growth
- South TX regional framework
- Eagle Ford well performance drivers
  - VClay and TOC impact
- Elemental data and XRF
  - Elemental proxies
  - Mapping elemental data from cuttings
- Principle Component Analysis (PCA) of elemental data
  - Key elemental proxies for Eagle Ford
- **Mechanical properties and seismic attributes**
  - Inversion and mapping
  - Multi-attribute analysis
  - VClay and Mo volumes
- Sweet spot mapping
- Summary and conclusions

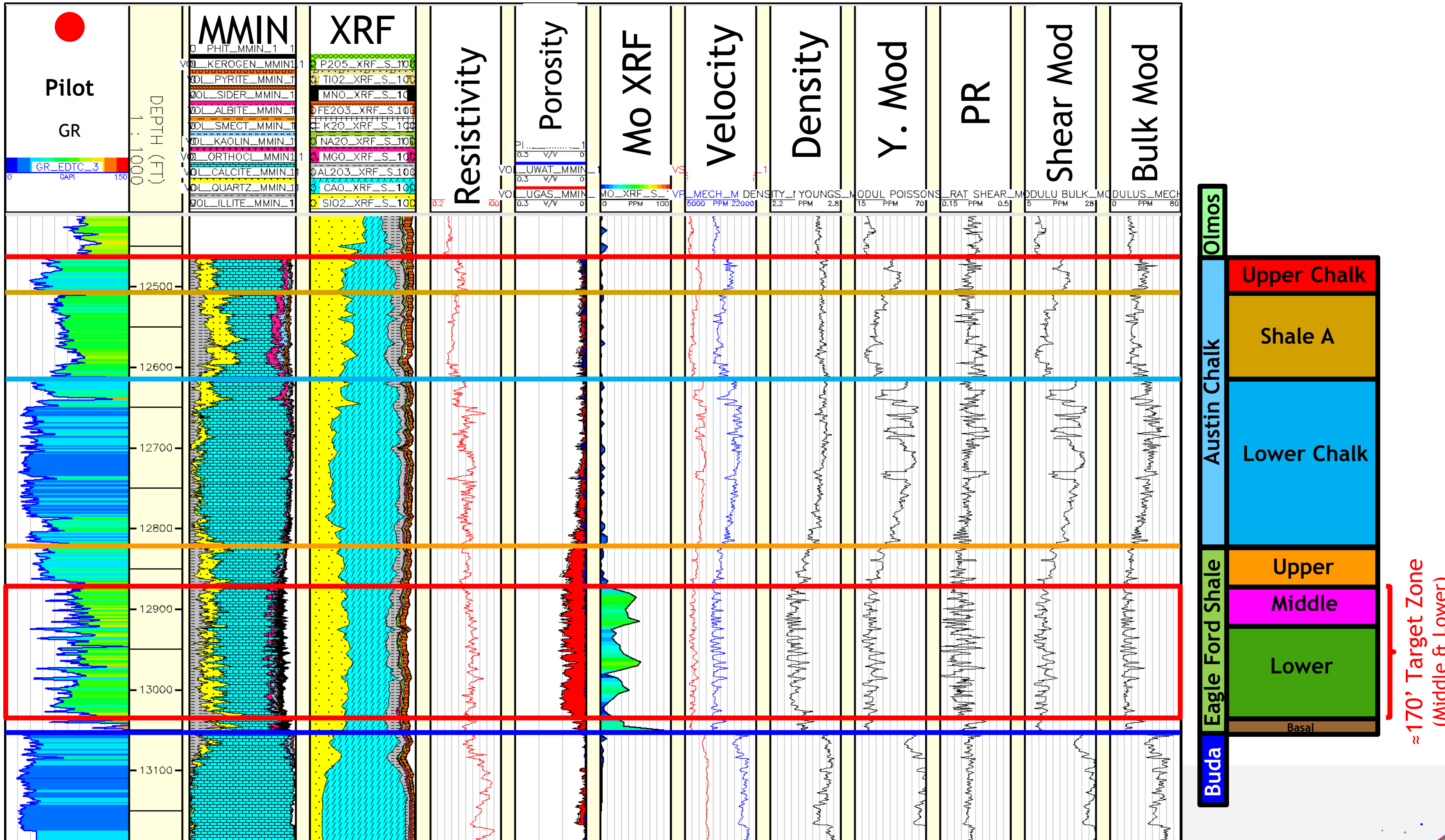
Sweet Spot Mapping: Seismic and Wells

PIONEER NATURAL RESOURCES



Integrating OH Logs and Cuttings

PIONEER NATURAL RESOURCES

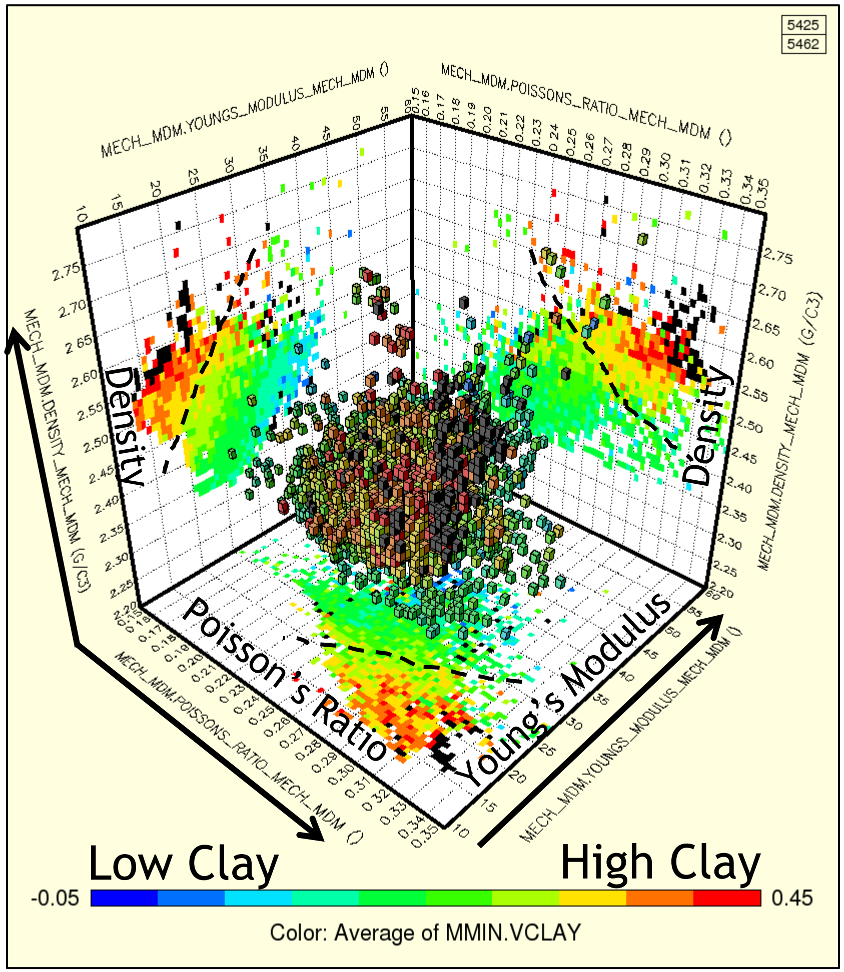


Sweet spot identification is based on mechanical properties and high Mo from XRF data.

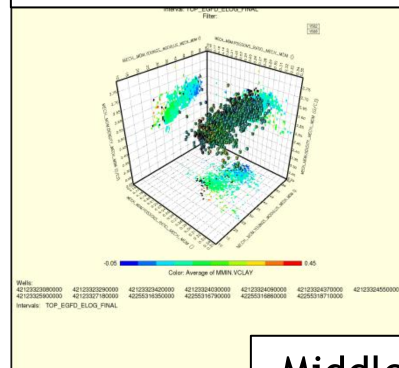
Rock Properties vs. Clay Content

PIONEER
NATURAL RESOURCES

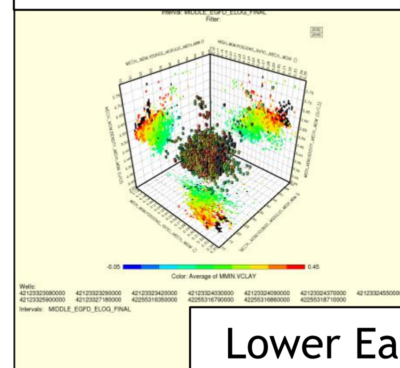
Middle & Lower Eagle Ford Shale Mechanical Properties Colored by VClay



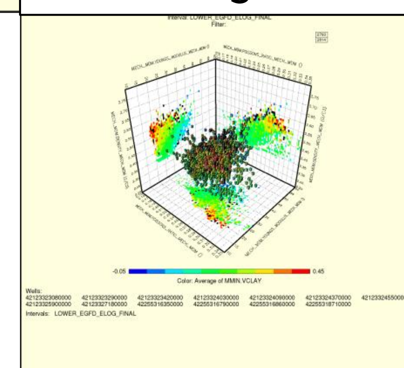
Upper Eagle Ford



Middle Eagle Ford



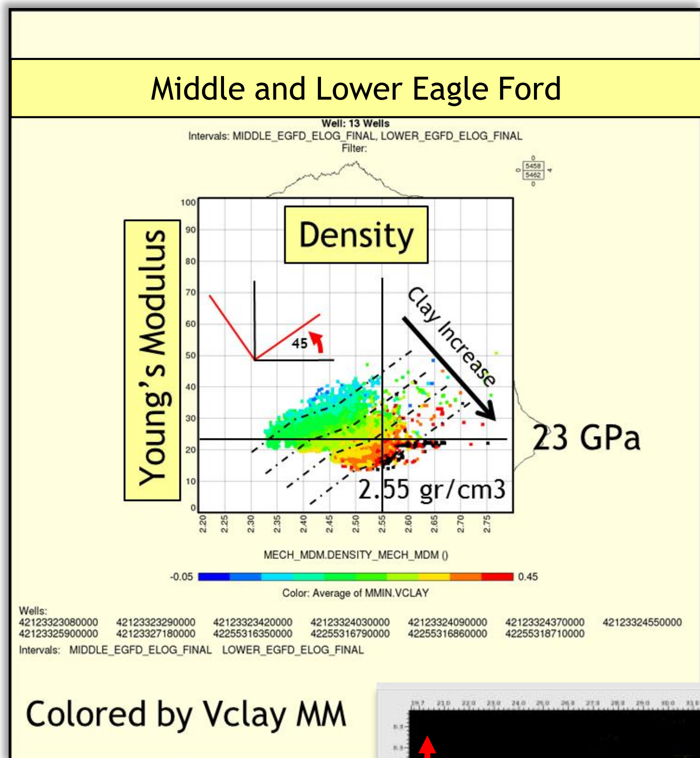
Lower Eagle Ford

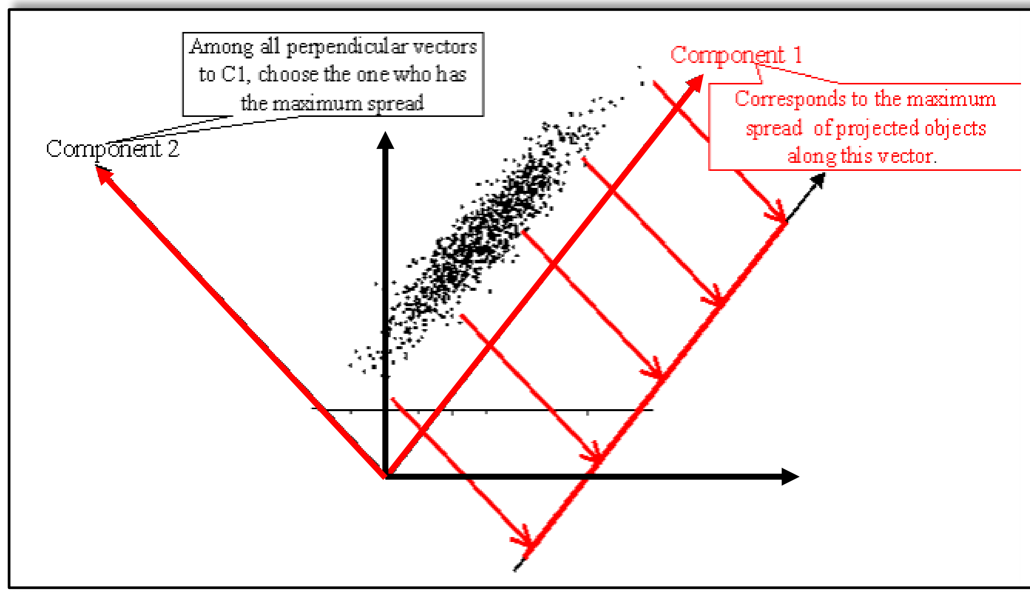


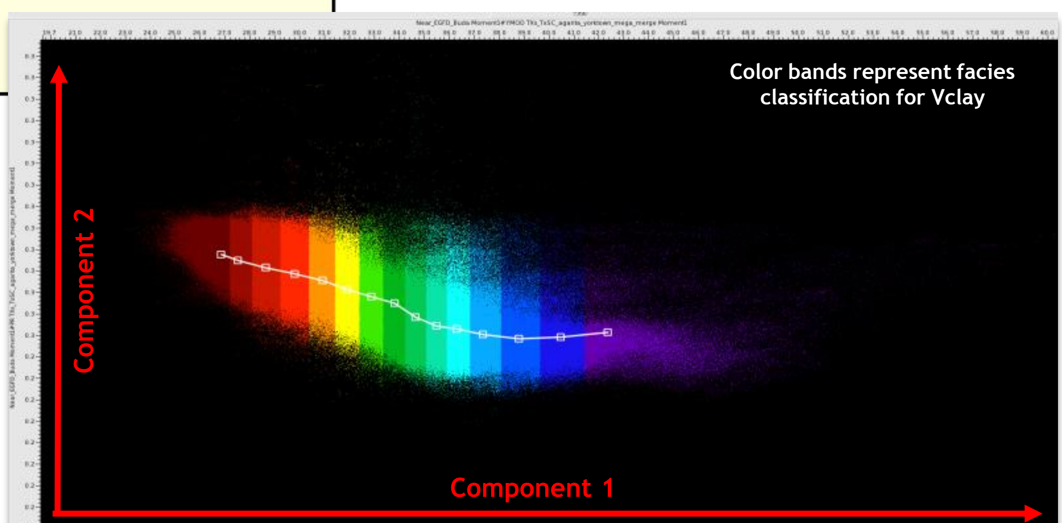
Variation can not be mapped with a single attribute

PCA Multi-Attribute Mapping

PIONEER
NATURAL RESOURCES

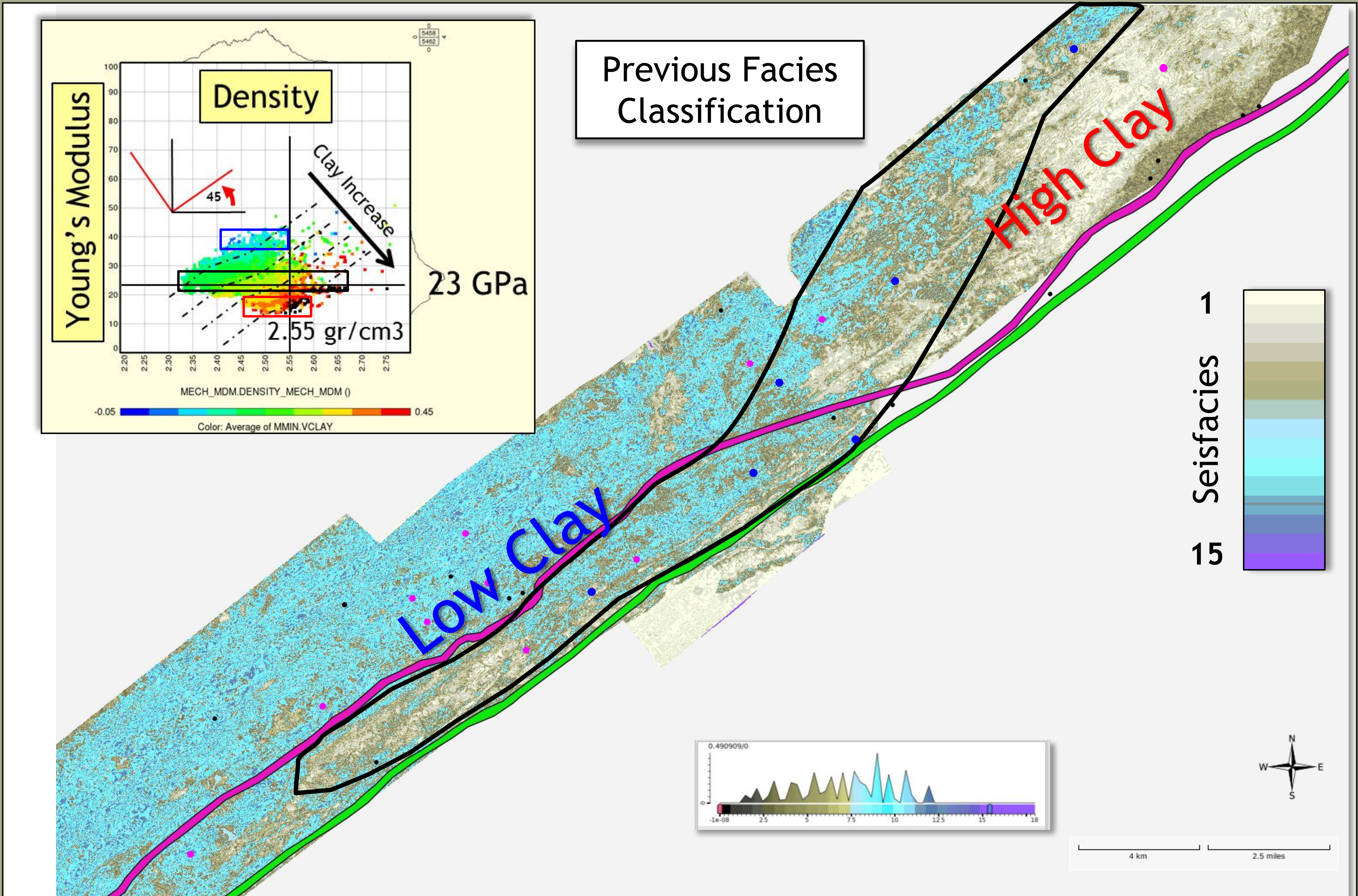




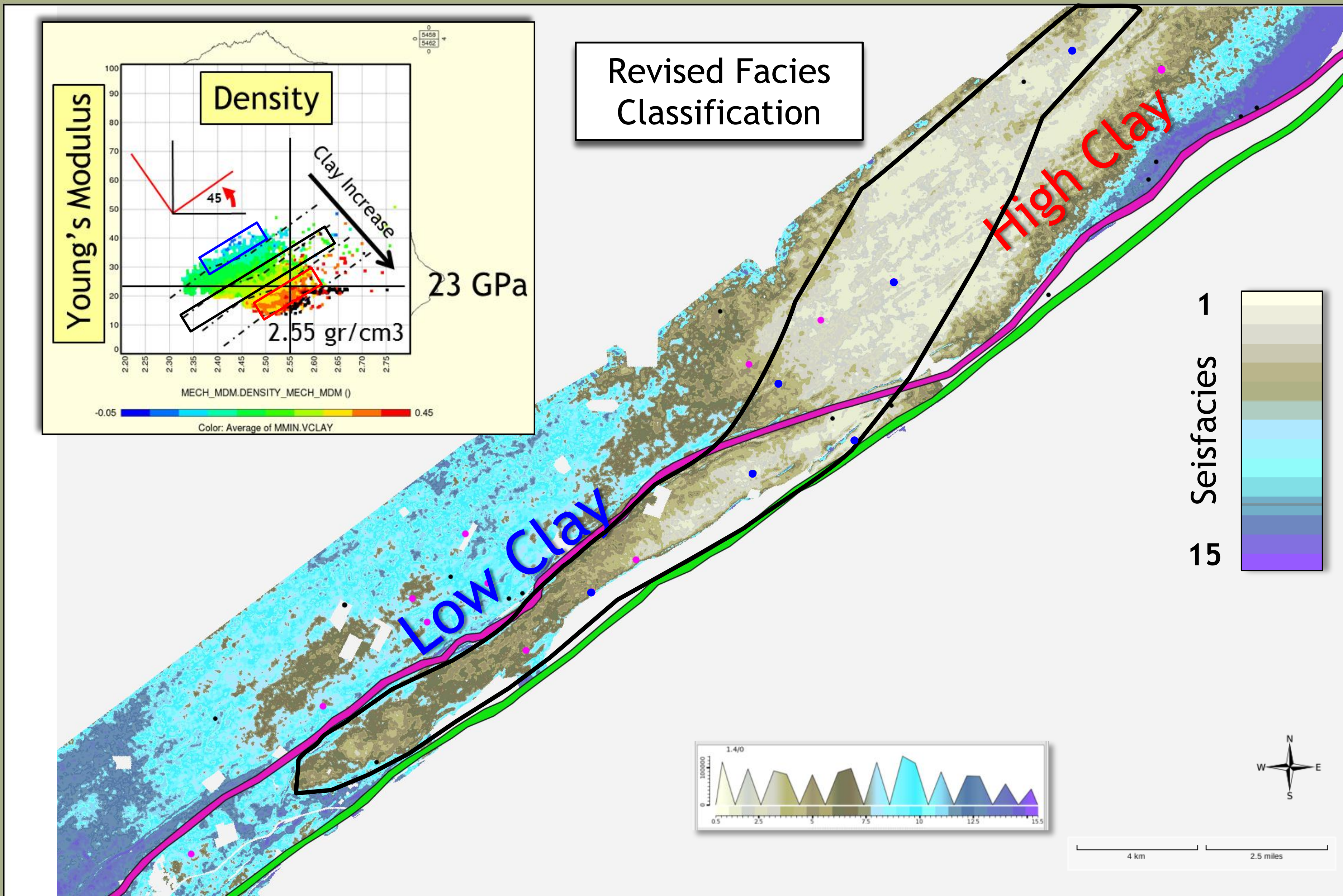


Impact on Seismic Facies Classification

PIONEER NATURAL RESOURCES



Impact on Seismic Facies Classification



Seismic Facies Map – VClay

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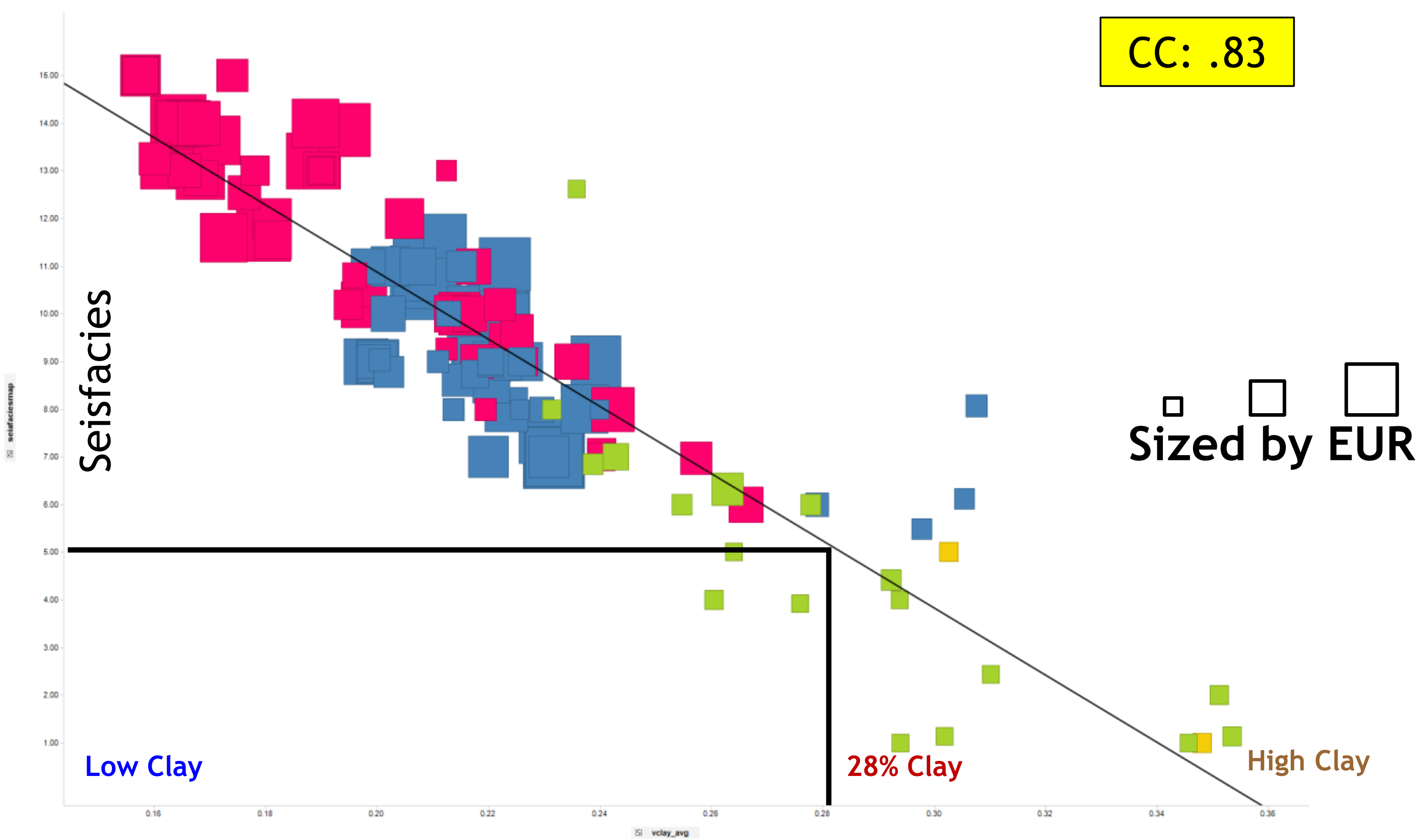
NATURAL RESOURCES

Data Relationships (Linear Regression)

Y (numerical)	X (numerical)	p-value	FStat	RSq	R	Df	n
seisfaciesmap	vclay_avg	1.42E-048	601.62	0.83	-0.91	120	122

Data table:
Data Relation...

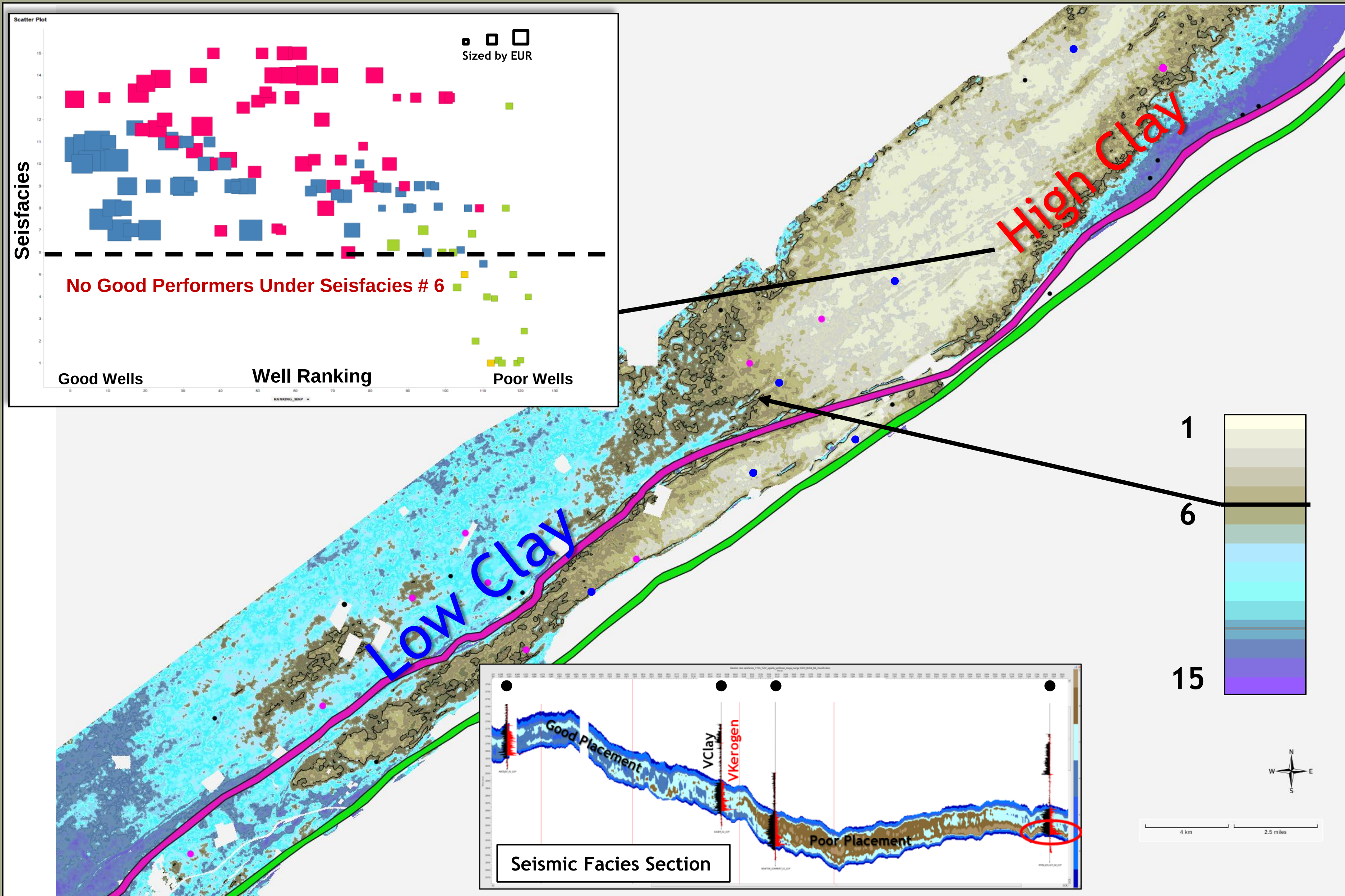
Data Relationships (Details)



VClay

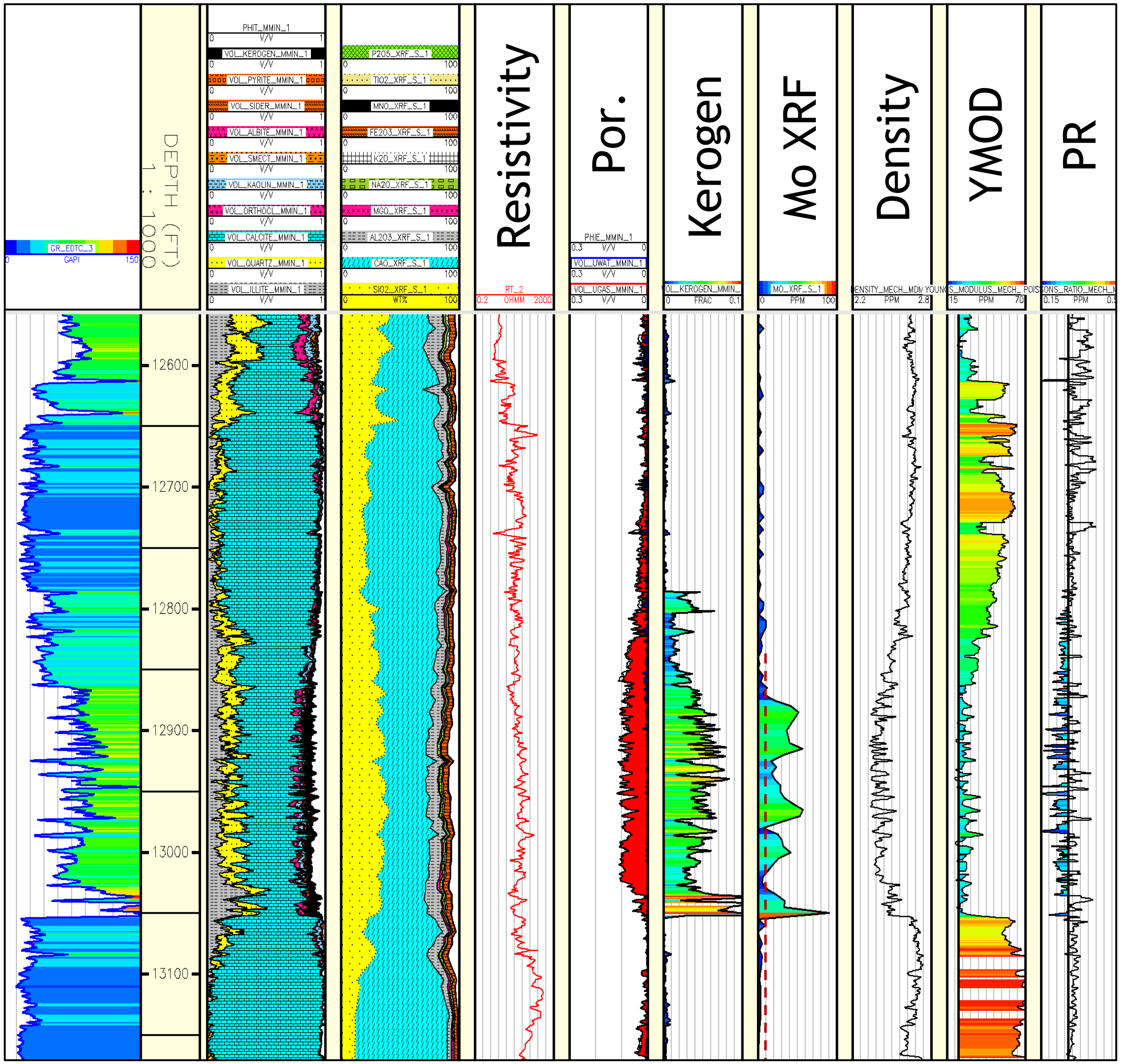
Seismic Facies Map – PCA Mapping

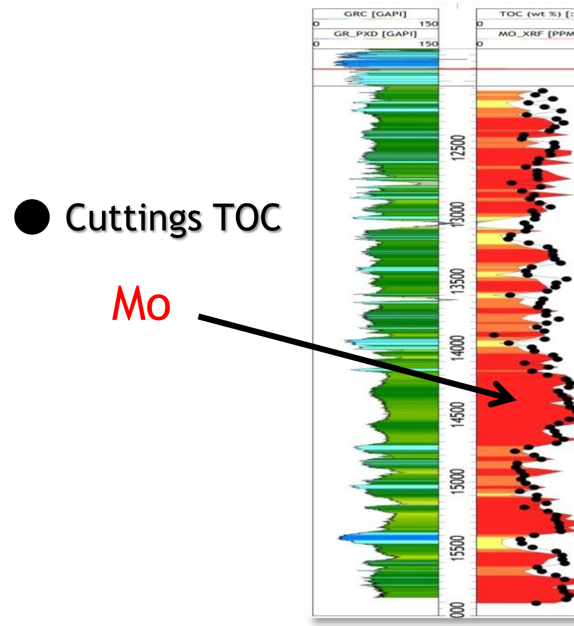
PIONEER NATURAL RESOURCES

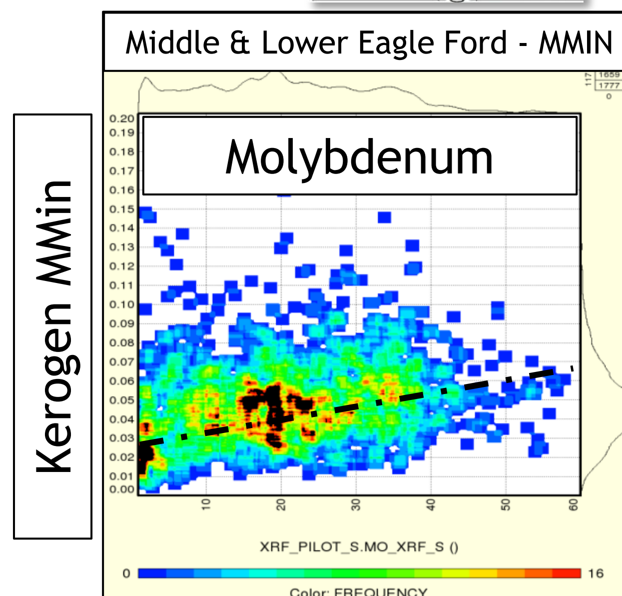


Molybdenum and TOC

PIONEER
NATURAL RESOURCES

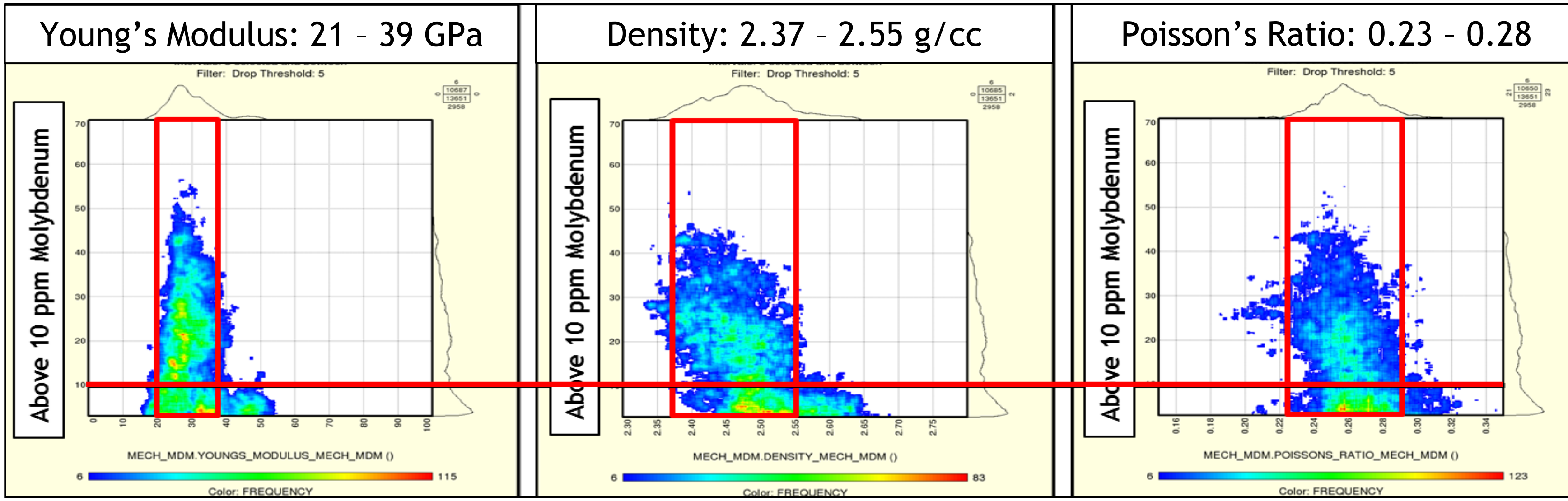


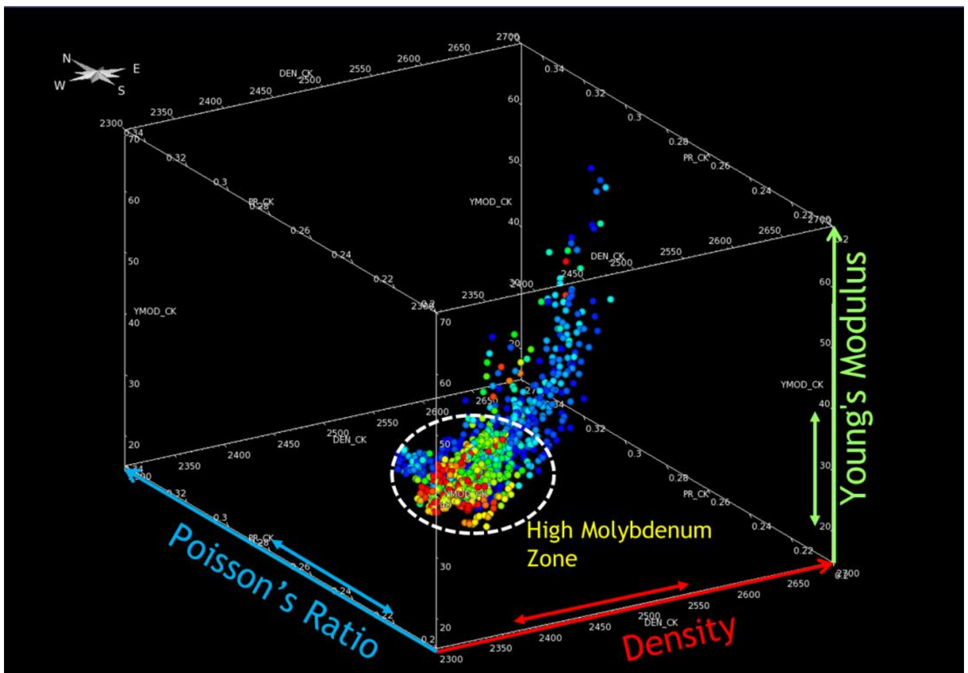




10 ppm Mo or ~3% TOC

Molybdenum vs. Mechanical Properties



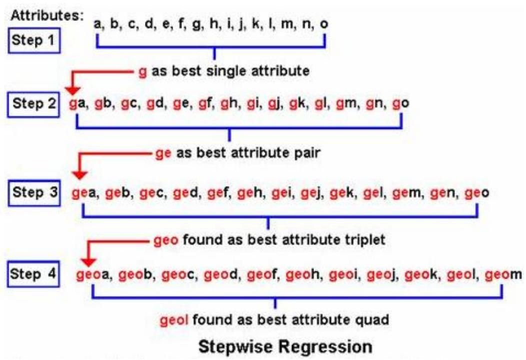


Analysis of 25 wells suggests that high Mo zones (Mo > 10 ppm) are confined to specific rock property ranges.

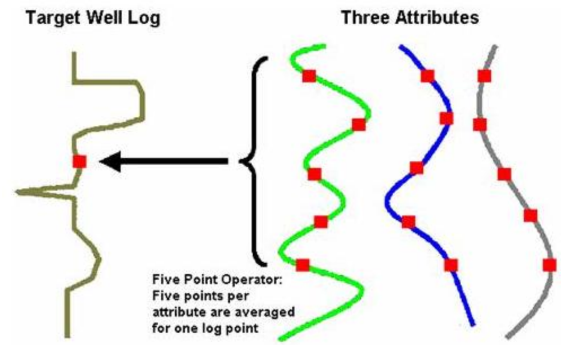
EMERGE: Multi-Attribute Regression

PIONEER NATURAL RESOURCES

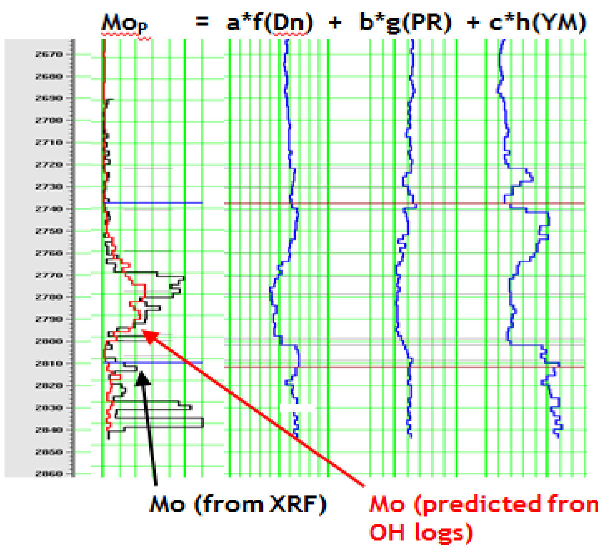
EMERGE determines the best combination of independent attribute curves for prediction of a desired target curve via stepwise regression

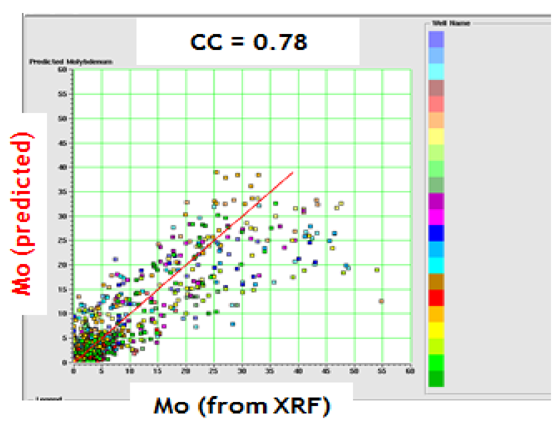


The independent attribute curves are then combined using a weighted sum to predict the desired target curve



The predicted curves are then compared to the actual target curves in order to assess error and robustness of the prediction





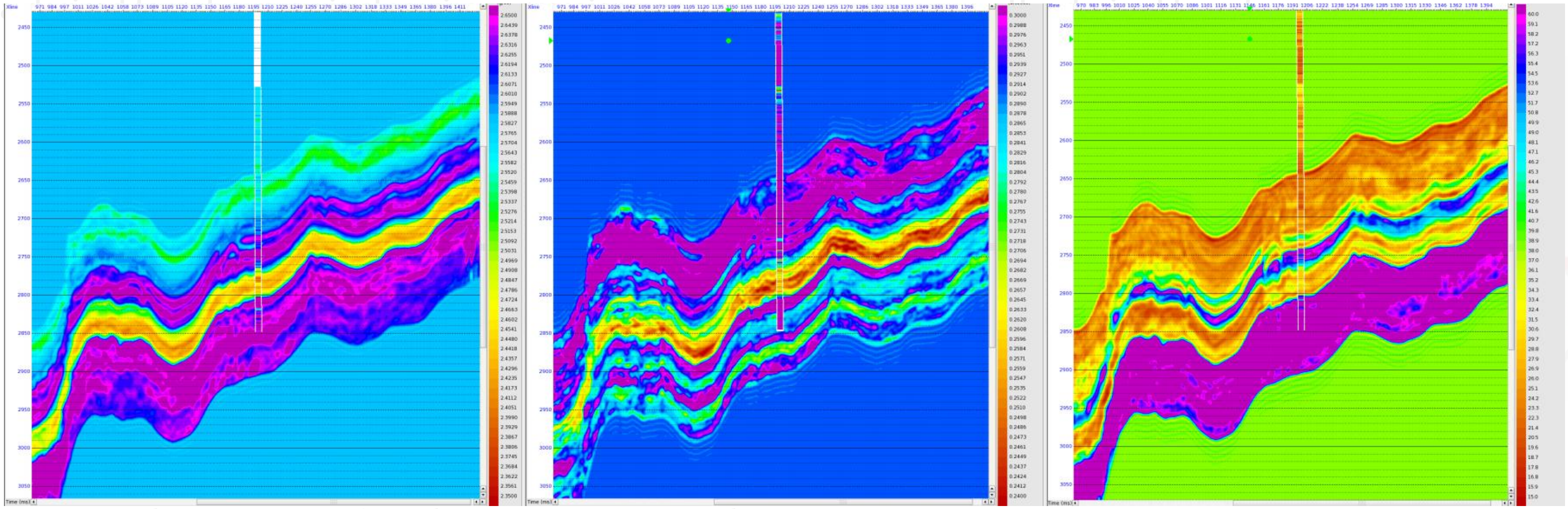
The predicted Mo curves from the OH log mechanical properties Density, Poisson's Ratio, and Young's Modulus had a CC = 0.78 with the measured Mo curves from Hand Held XRF and an average error of ~7 ppm.

Hampson-Russell CGG

Multi-Attribute Regression

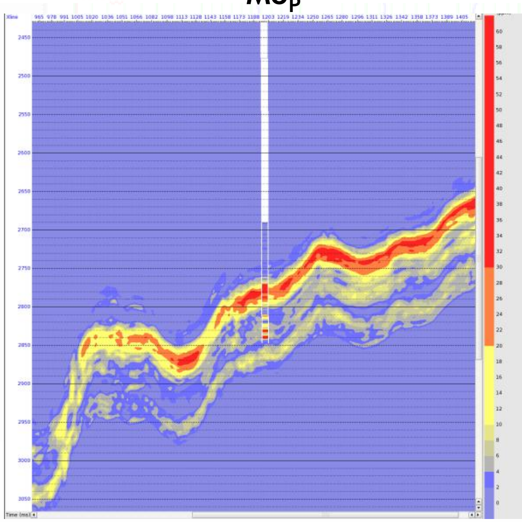
PIONEER NATURAL RESOURCES

After the analysis with the OH logs confirmed that Mo from HH XRF could be predicted from the mechanical properties, the process was repeated with the seismic inversion results in order to produce a 3D volume of Molybdenum

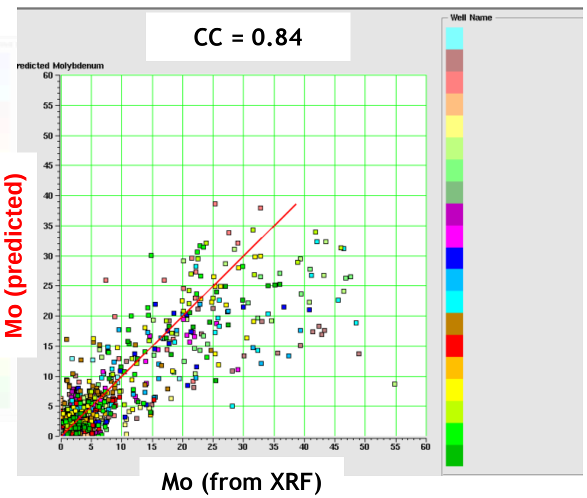


a*f(Dn) + b*g(PR) + c*h(YM)

= Mo_P



The predicted Mo curves from the seismic inversion mechanical properties Density, Poisson's Ratio, and Young's Modulus had a CC = 0.84 with the measured Mo curves from Hand Held XRF and an average error of < 6 ppm.



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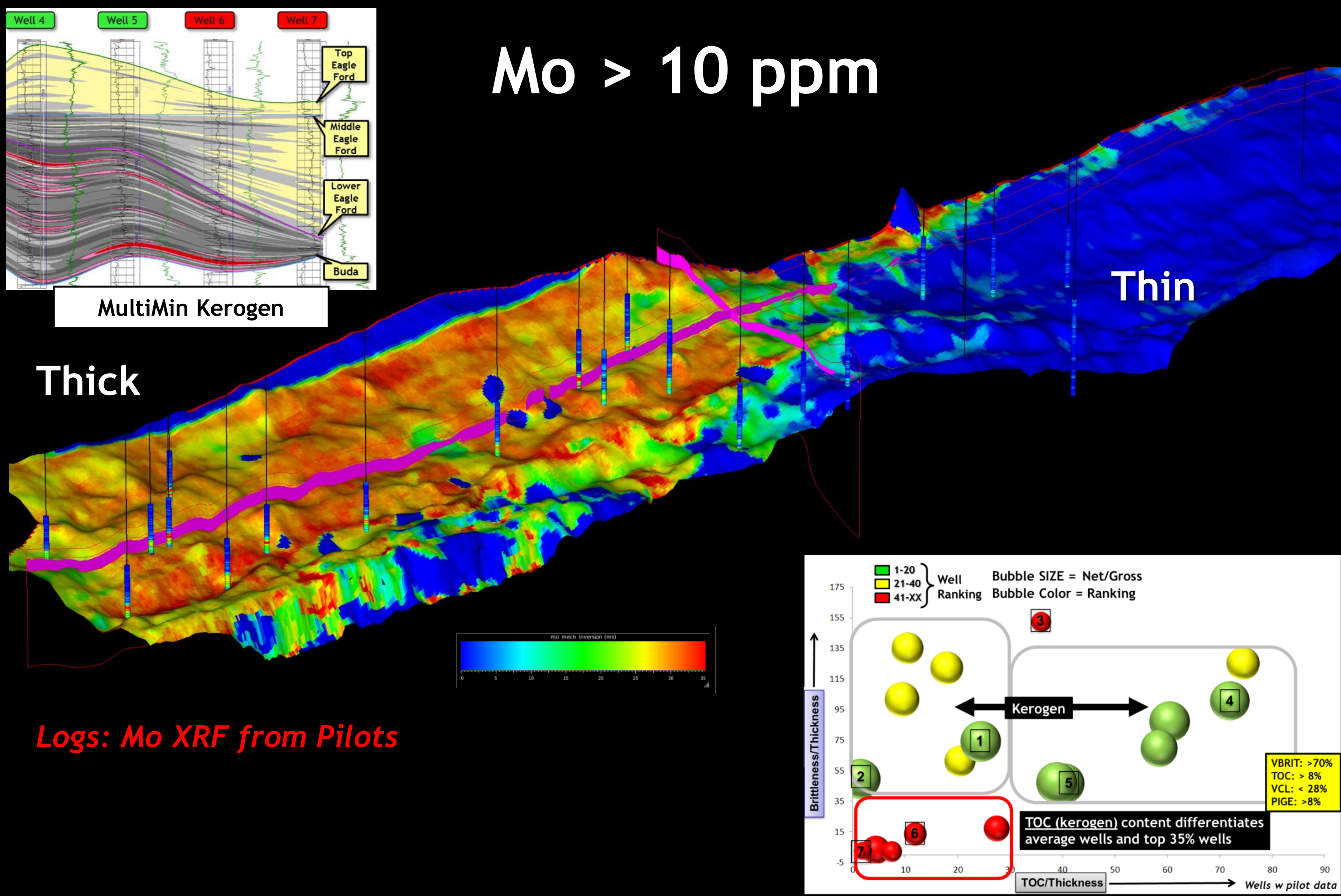
Boquillas Fm (Eagle Ford)
Big Bend National Park, TX

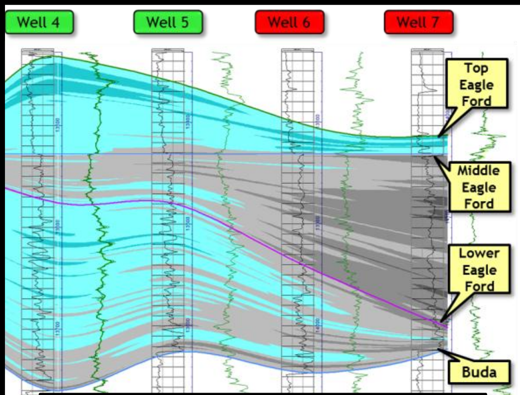
Molybdenum Sweet Spot Zone (Mo > 10 ppm ≈ 3% TOC)

PIONEER NATURAL RESOURCES



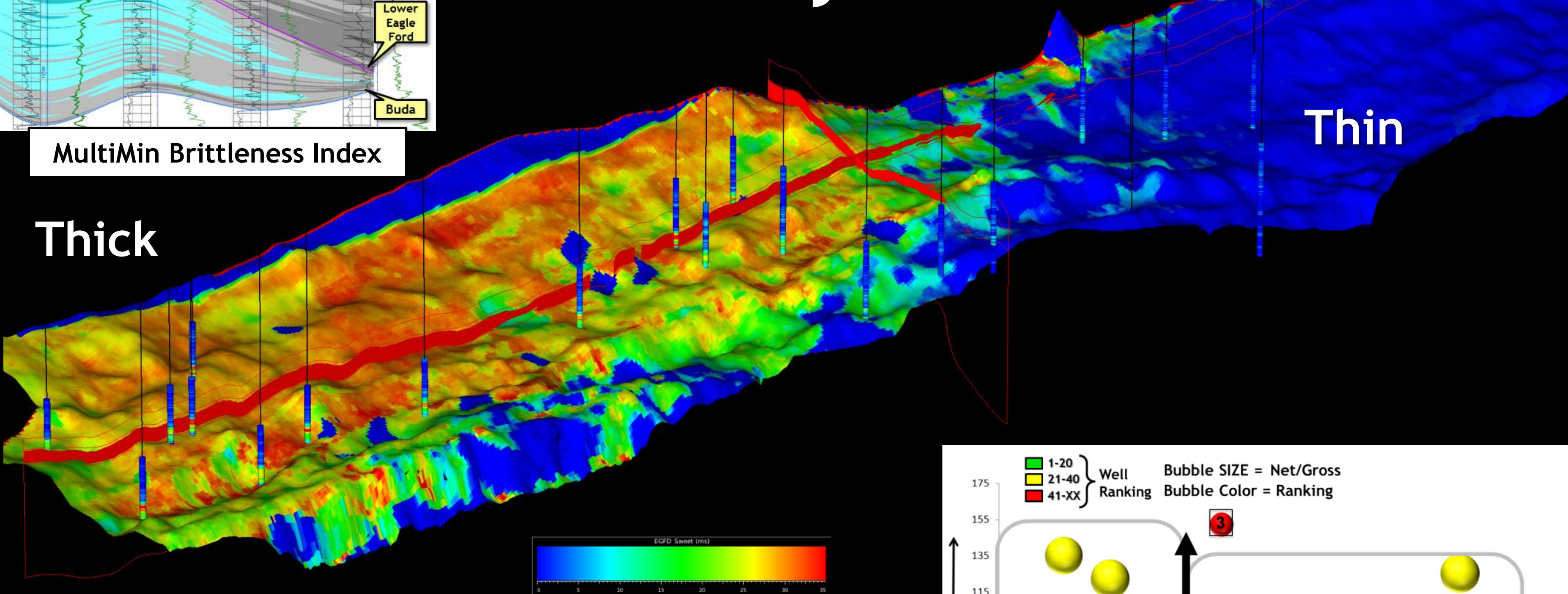
Eagle Ford Sweet Spot: TOC (Mo) and Rock Properties

PIONEER NATURAL RESOURCES

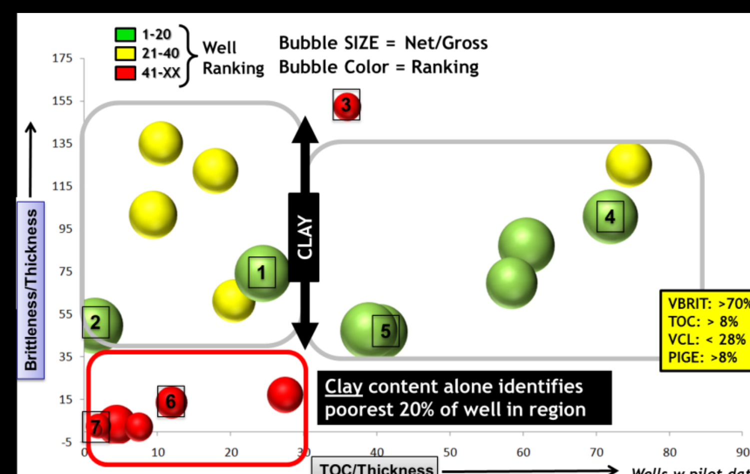


MultiMin Brittleness Index

Mo > 10 ppm & VClay < 30%



Logs: Mo XRF from Pilots



Summary and Conclusions

PIONEER NATURAL RESOURCES

- Within our northeastern acreage position the main performance drivers are VClay (brittleness) and organic content
- Elemental data from hand held XRF can be used as proxies for petrophysical parameters; for this area Mo serves as a good proxy for TOC and Al_2O_3 serves as a good proxy for VClay
- Principal Component Analysis of the elemental data shows interesting and expected relationships between the elements; notably Mo and Al_2O_3 have no correlation
- Mechanical properties (Young's Modulus, Poisson's Ratio and Density) can be used to discriminate VClay and TOC (using Mo as a proxy)
- Inversion of seismic data allows for the extension of these mechanical properties to 3D volumes
- Previous studies have been limited to pilot open hole logs with ~11,000 feet of available data
- An extension of this analysis through the use of XRF data from lateral wells as proxies for petrophysical data increases the available data to ~400,000 feet