The Maturity of Organic-Rich Shales Using Micro-Impedance Analysis*

Kenechukwu Mba[1], Manika Prasad[2], and Michael L. Batzle[3]

Search and Discovery Article #40675 (2010)
Posted December 31, 2010

*Adapted from oral presentation at AAPG International Conference and Exhibition, Calgary, Alberta, Canada, September 12-15, 2010

[1]Petroleum Engineering, Colorado School of Mines, Golden, CO (kmba@mymail.mines.edu)
[2]Petroleum Engineering, Colorado School of Mines, Golden, CO
[3]Geophysics, Colorado School of Mines, Golden, CO

Abstract

Organic-rich shales (ORS) are the common source rock for most clastic reservoirs. The processes that are involved in how these shales generate extractable hydrocarbons from kerogen are fairly well understood. The maturity level of kerogens in organic-rich shales is presently determined by geochemical analysis of core samples. The maturity of shales at insitu conditions may be inferred from relationships between shale pressures, and downhole measurements from resistivity and sonic logs. The ability to determine maturity by the use of indirect measurements such as seismic is still the subject of research.

The study focus area is the Bakken Formation in the Williston Basin, North America whose organic-rich shales are proven hydrocarbon source rocks. Further study in the remote detection of maturity would be help in reducing exploration and development costs.

This study focuses on a method of predicting maturity of organic-rich shales by evaluation of their impedance micro-structure. Scanning acoustic microscopy is used to map the impedance of shale components. The impedance of these components is related to their elastic properties, and these components vary with maturity in the shales. Previous studies have been successful in relating shale velocities to porosity, and in detecting textural changes with maturity. In this study, direct qualitative relationships are shown between the impedance of shale samples, shale rock properties and maturity indicators, TOC and Transformation Ratio.

This study adds to current understanding of the maturity-based variations by using analysis from scanning acoustic microscopy, integrating measurements from geochemical analysis, and observations from downhole sonic measurements to develop relationships for relating impedance information from seismic data to organic shale maturity.

References

Prasad, M., A. Pal-Bathija, M. Johnston, M. Rydzy, and M. Batzle, 2002, Rock physics of the unconventional: The Leading Edge, v. 28/1, p. 34-38.

Price, L.C., T. Ging, T. Daws, A. Love, M. Pawlewicz, and D. Anders, Organic Metamorphism in the Mississippian-Devonian Bakken Shale North Dakota Portion of the Williston Basin, *in* J. Woodward, F.F. Meissner, and J.L. Clayton, (eds.), Hydrocarbon Source Rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists, p. 83-134.

Sonnenberg, S., and J.F. Sarg, 2009, The Bakken Petroleum System of the Williston Basin, From Unconventional Oil Resource Play: Web accessed 17 December 2010, Search and Discovery article #90090. http://www.searchanddiscovery.net/abstracts/html/2009/annual/abstracts/sonnenberg.htm?q=%2Btext%3Asonnenberg

The Maturity Of Organic-Rich Shales Using Micro-Impedance Analysis

AAPG ICE – Calgary, AB, Canada

SEPTEMBER 13-17, 2010

KENE MBA , MANIKA PRASAD, MIKE BATZLE

Colorado School of Mines

Presented by Rick Sarg

CONCLUSIONS

- **High silica + carbonate content results in high impedance shales.** No simple relationship between velocity, kerogen content, and maturity.
- **Horizontal lamination of clay and organic matter causes anisotropy.** This reduces with depth as shale 'hardens', and hydrocarbons are expelled.
- The combined **elastic modulus of kerogen + clay increases with increasing maturity**. Transformation ratio can be calculated from the Young's modulus as: TR = 0.0083*Young's Modulus - 0.0793
- **Increasing impedance with maturity** as hydrocarbons expelled, porosity reduced, and clay compacts. It may be possible to use impedance as a proxy for maturity.

PRESENTATION OUTLINE

- Study Objective and Motivation
- Background
- Results
    - Log Plots
    - QEMSCAN Mineralogy Imaging and Analysis
    - Nano-Indentation
- Conclusions

STUDY OBJECTIVES

- Determine the mineralogical control on the elastic properties of organic-rich shale.
- Determine the relationship between kerogen maturity and elastic properties of organic-rich shales in the Bakken Formation.

GOAL

- To establish relationships that would be useful in predicting organic-rich shale maturity from elastic properties.

MOTIVATION

- Shale hydrocarbon systems have emerged as major contributors to the global hydrocarbon resource base.
- Current methods for determining maturity are typically localized to near wellbore areas, and may not be representative (sweet spot drilling) of regional trends.
- Existing models that relate maturity to petrophysical data are empirical.
- Lack of physical explanations for maturity affects on petrophysical data.

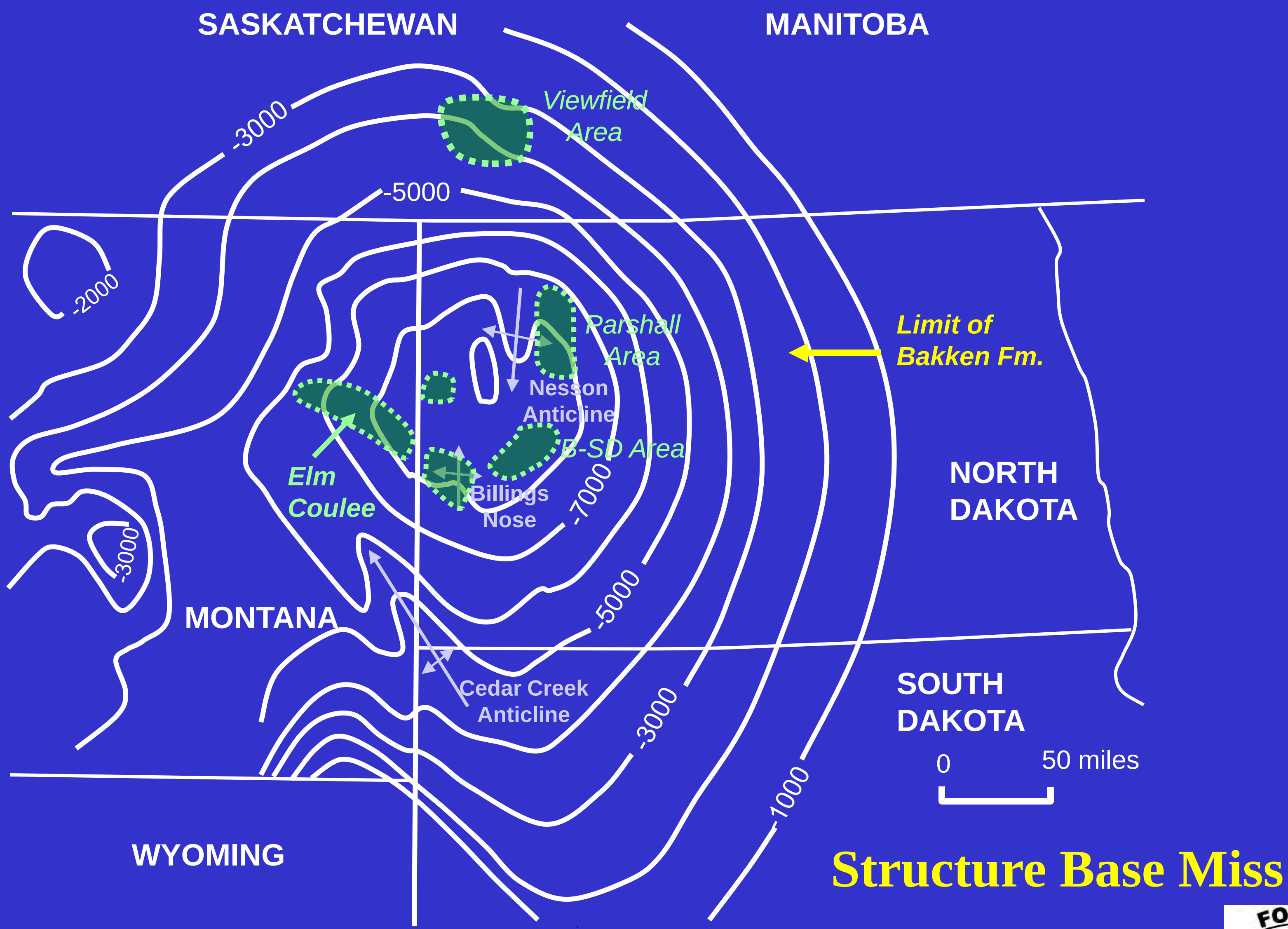
COLORADOSCHOOLOFMINES
EARTH ENERGY ENVIRONMENT

CENTER FOR ROCK ABUSE
Squeezing Rocks since 1994

Notes by Presenter: Point out after the first bullet that shale play exploration and developments are typically technologically challenging, since their tight permeability requires higher well density than conventional clastic reservoir plays and expensive multi-stage fracture jobs are frequently required prior to production.The economics for development are thus challenged, so it is necessary to have a really good idea of individual field reserves. The current methods are restricted to near wellbore and so aerially limited.

BACKGROUND

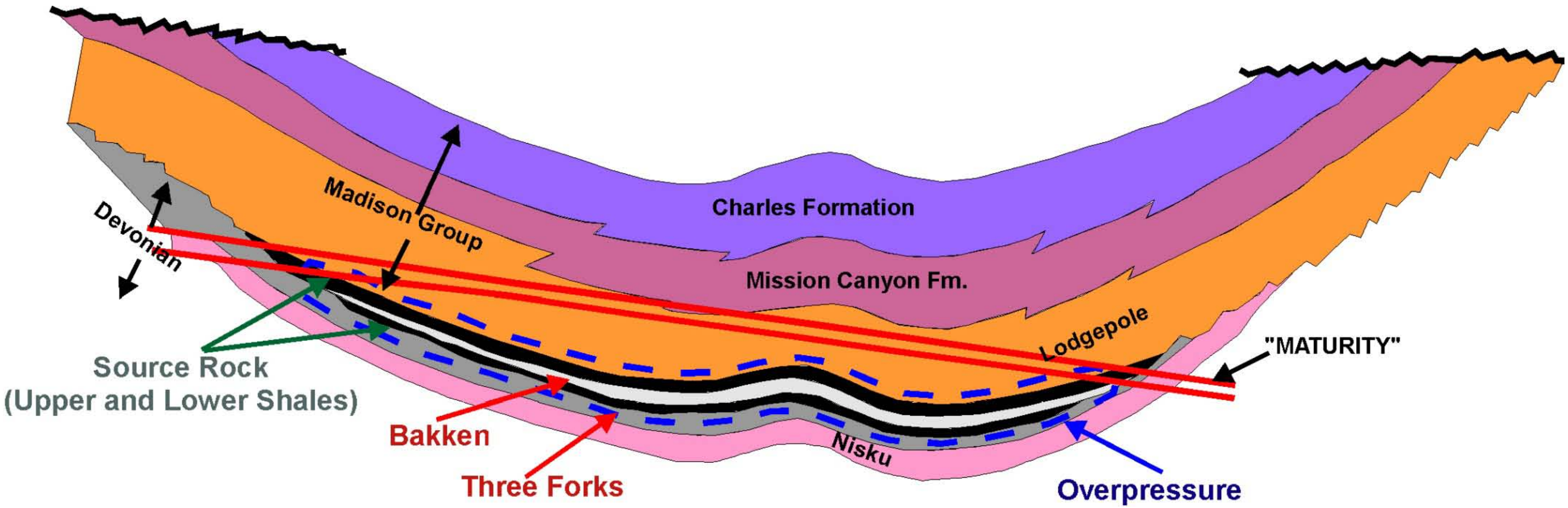
STUDY AREA: LOCATION AND GEOLOGIC OVERVIEW



COLORADO SCHOOL OF MINES
EARTH ENERGY ENVIRONMENT

CENTER FOR ROCK ABUSE
Squeezing Rocks since 1994

Bakken Petroleum System



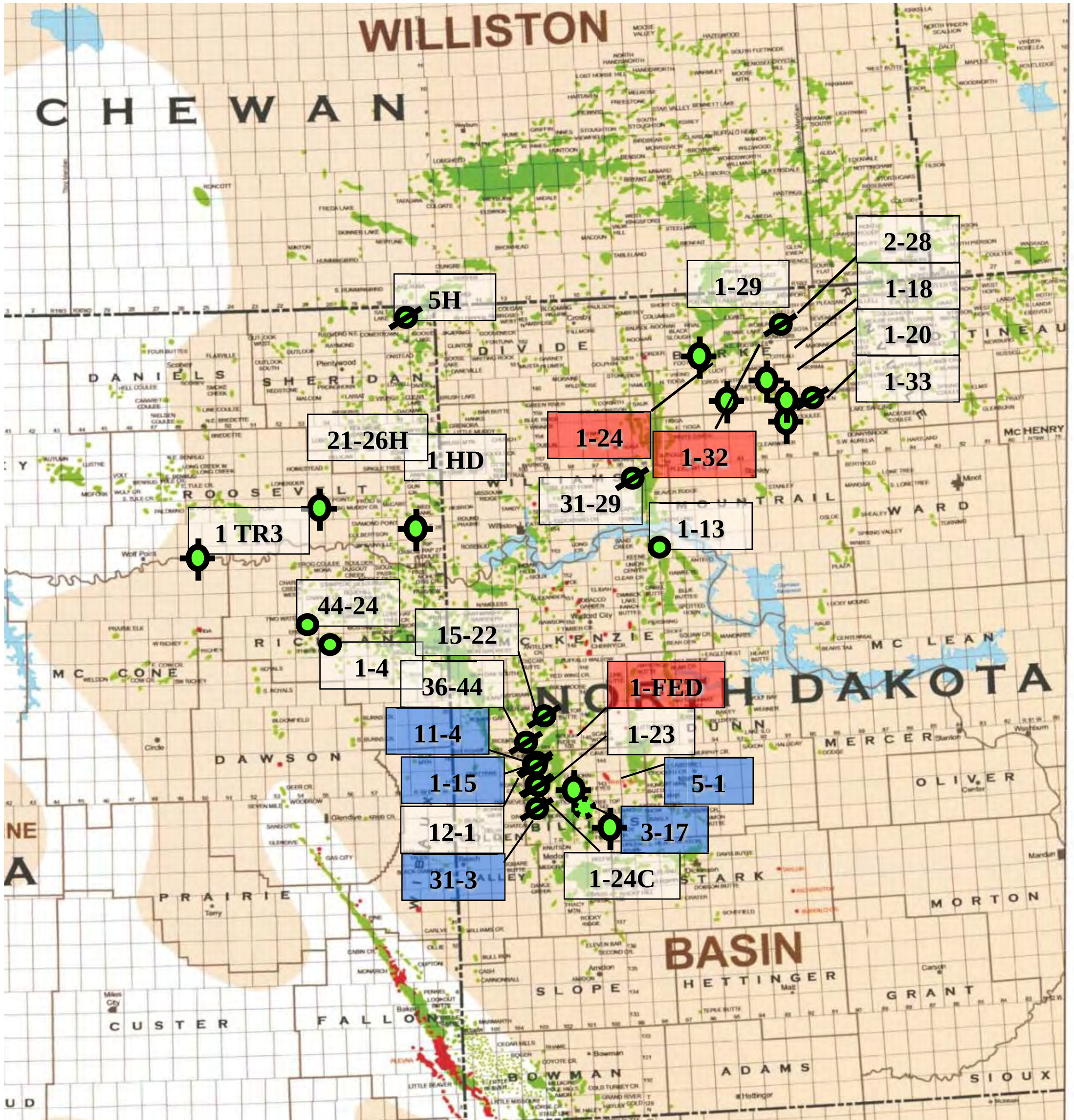
Reservoirs:
Middle Bakken & Three Forks

Source Beds:
Upper & Lower Bakken Shales

“what was made in the Bakken, stayed in the Bakken PS”

STUDY AREA: LOCATION MAP OF SAMPLES USED

- Producing Oil Well
- Dry Oil Well
- P & A
- Status Not Found



UPPER SHALES

- 11-4 FEDERAL
- 1-15 GRAHAM USA
- 31-3 SHORT FEE
- 3-17 TOC MEE USA
- 5-1 THOMPSON UNIT

LOWER SHALES

- 1-32 MERTES
- 1-FEDERAL DG
- 1-24 CITGO-CHAMBERS

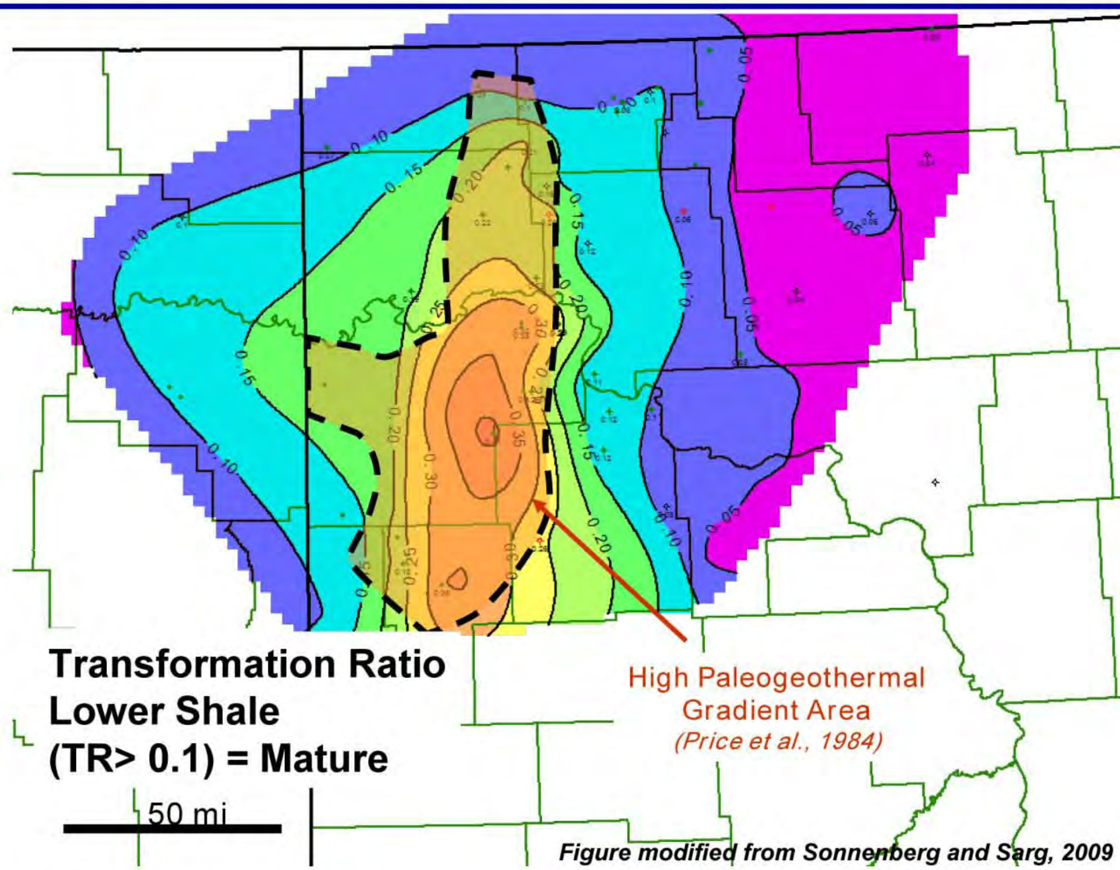
CONVENTIONAL MATURITY DETECTION

- Geochemical Composition (Pyrolysis)
    - S1, S2, S3 and the maximum temperature at S2 (TMax)
    - Total Organic Carbon (TOC) and Hydrogen Index (HI)
    - Calculated – Transformation Ratio (TR) and S1/TOC

$$TR = \left[\frac{SI}{S1 + S2} \right] x\, 100\%$$

- TOC from Wireline Logs (Resistivity, Sonic, Density Logs)
    - Schmoker (density)
    - Passey (Δlog R)
- Wireline Log vs Depth Relationships

REGIONAL MATURITY BANDS FROM PYROLYSIS



- Contouring of core sample TR used to delineate maturity in the Bakken
- Area inside dashed polygon has low S2 values, implying higher maturity

COLORADO SCHOOL OF MINES
EARTH ▲ ENERGY ▲ ENVIRONMENT

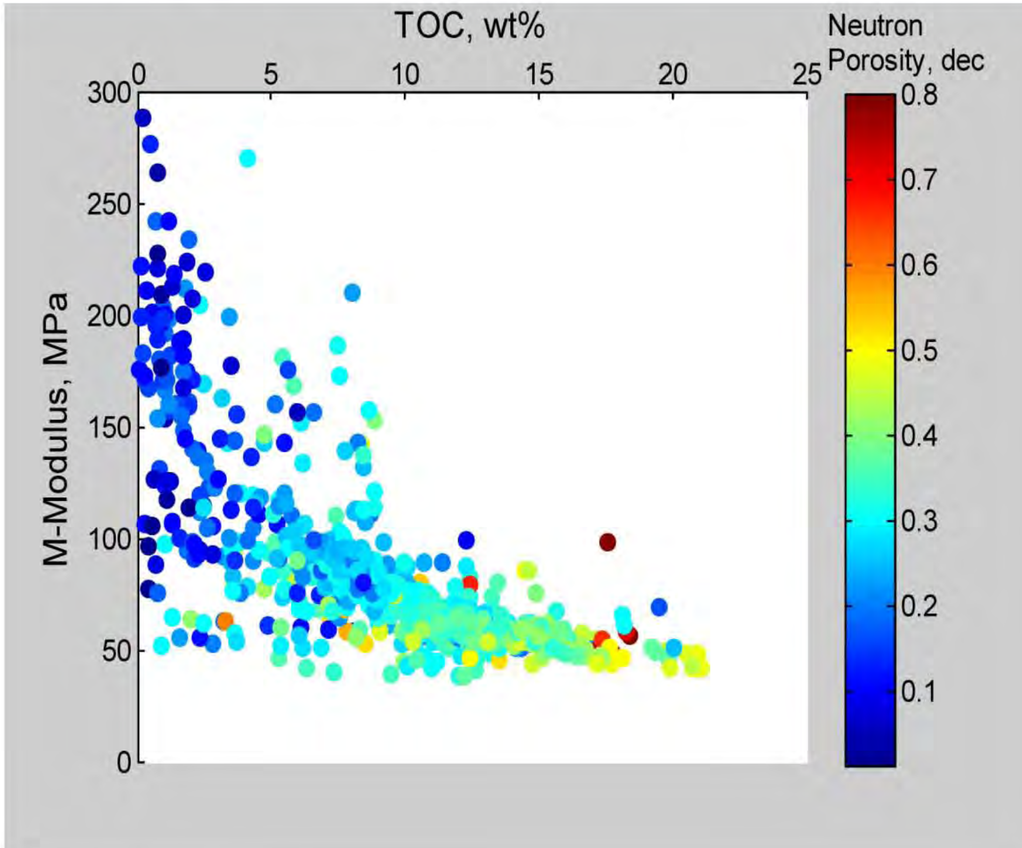
CENTER FOR ROCK ABUSE – Squeezing Rocks since 1994

Notes by Presenter: Conventional maturity detection methods limited in application to regional and sub-regional delineation of maturity. In the figure TR from core pyrolysis at several well locations was contoured to show increasing maturity towards the basin center. Point out that map is only as good as well density and location of pyrolyzed core. Not really sufficient for individual field maturity estimation. Explain that the enclosed polygon defined by low S2 value was also interpreted as being in high paleogeothermal gradient area of the Bakken.

RESULTS

- **LOG CROSS-PLOTS**
- **QEMSCAN MINERALOGY IMAGING AND ANALYSIS**
- **NANO-INDENTATION**

M-MODULUS vs TOC



- M-Modulus = Vp^2 x Density
- M-Modulus shows fairly good non-linear relationship with TOC (Schmoker)

COLORADOSCHOOLOFMINES
EARTH ▲ ENERGY ▲ ENVIRONMENT

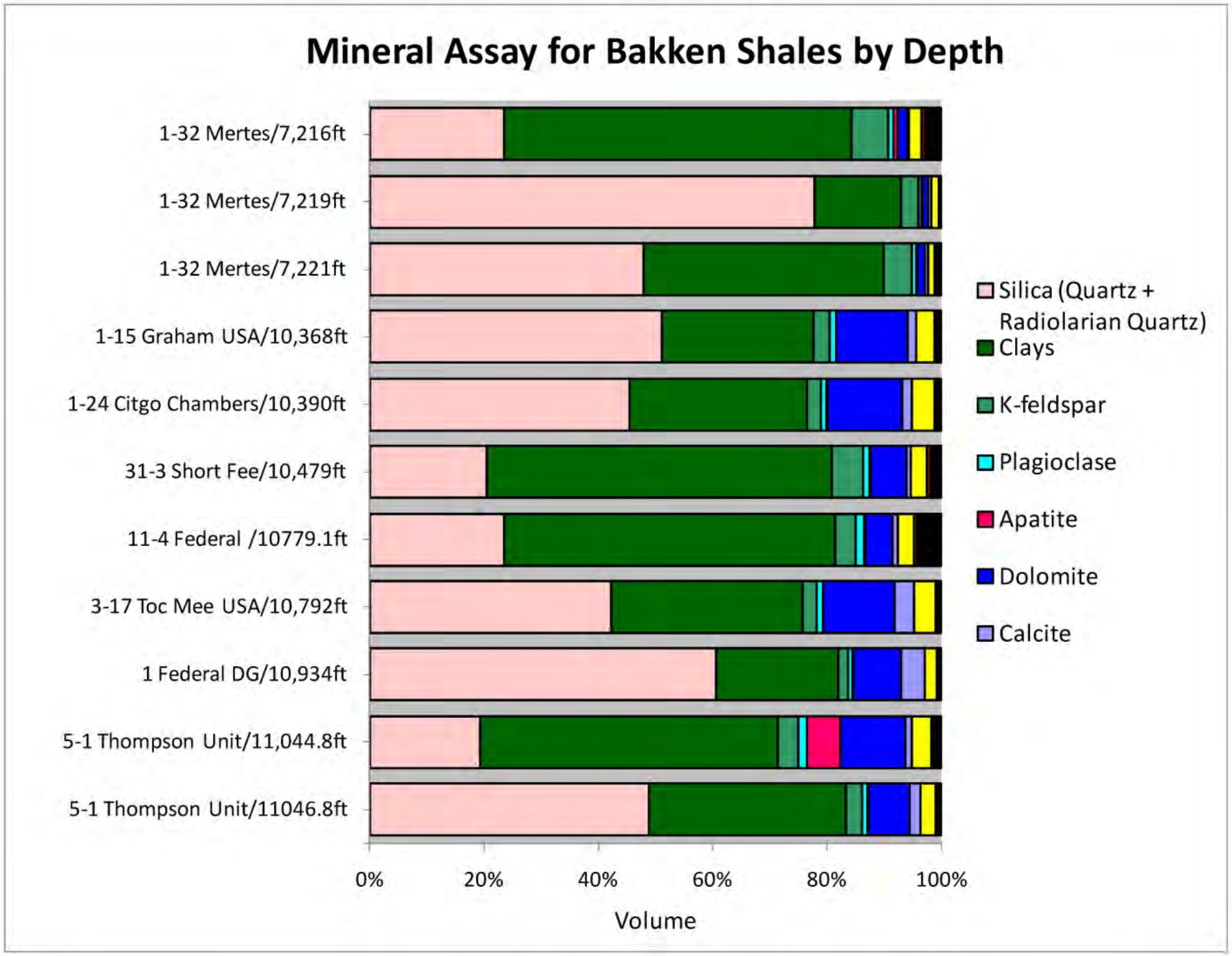
CENTER FOR ROCK ABUSE
Squeezing Rocks since 1994

Notes by Presenter: TOC was calculated from log density using Schmoker's empirical relationship derived for the Bakken shales. Plot shows that a predictable relationship exists between rock elasticity and organic matter content.

RESULTS

- LOG CROSS-PLOTS
- **QEMSCAN MINERALOGY IMAGING AND ANALYSIS**
- NANO-INDENTATION

QUANTITATIVE MINERALOGY – QEMSCAN RESULTS



COLORADO SCHOOL OF MINES
EARTH ▲ ENERGY ▲ ENVIRONMENT

CENTER FOR ROCK ABUSE
Squeezing Rocks since 1994

Notes by Presenter: Shales have high silica content, but some samples dominated by clay. Dolomite also present in some samples. No particular trend as far as increase or decrease of mineral types with depth. It is important to note the presence of clays as their content and manner of occurrence in the rock matrix affect the elastic properties of the rock.

COMPARISON OF UPPER AND LOWER SHALES

Mineral	Upper Shale Ave, %	Lower Shale Ave, %	Total Ave, %
Quartz	34	51	42
Clays	44	34	40
K-feldspar	3	4	4
Plagioclase	1	1	1
Apatite	1	0	1
Pyrite	3	2	3
Calcite	2	1	2
Dolomite	9	5	7
Others	2	1	2
Biotite/Phlogopite	0	0	0

A

	Lab Measurements		
	TOC, wt%	QEMSCAN Porosity, %	Vp, m/s
Upper Shale	9.58	8.2	4727
Lower Shale	13.37	11.7	4646

B

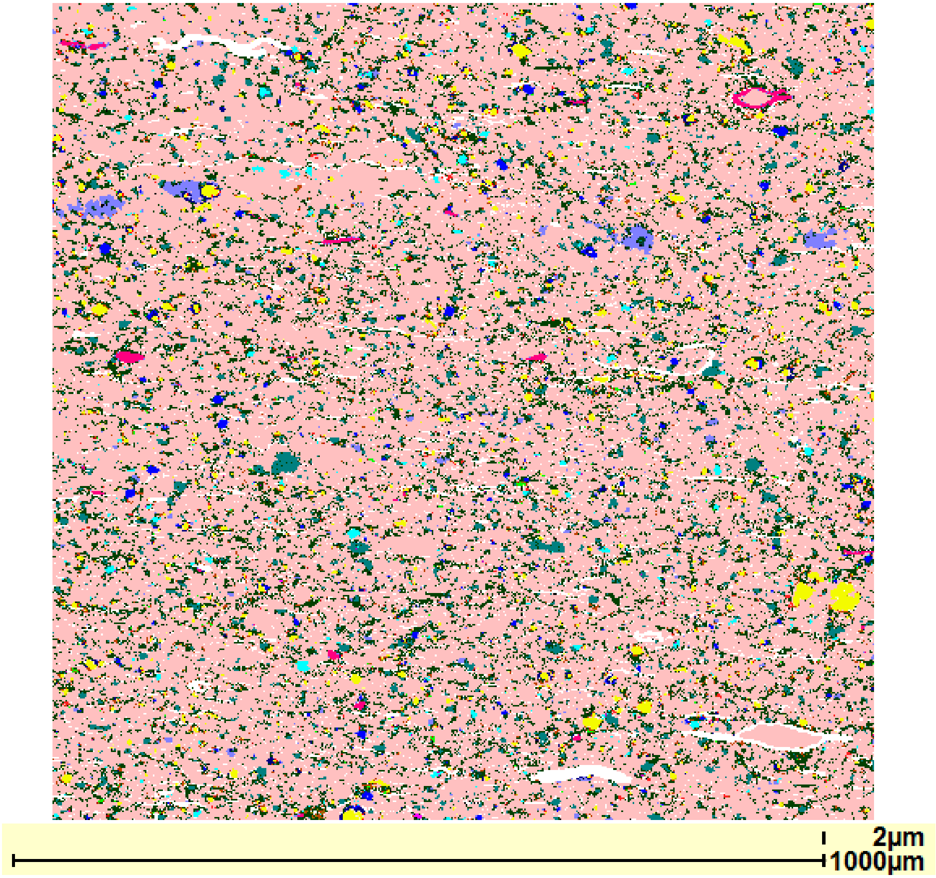
	Well Log-Derived Measurements			
	TOC, wt%	NPHI, %	Density, g/cc	Vp, m/s
Upper Shale	9.386	29.6	3.33	3247
Lower Shale	9.759	31.5	3.32	3197

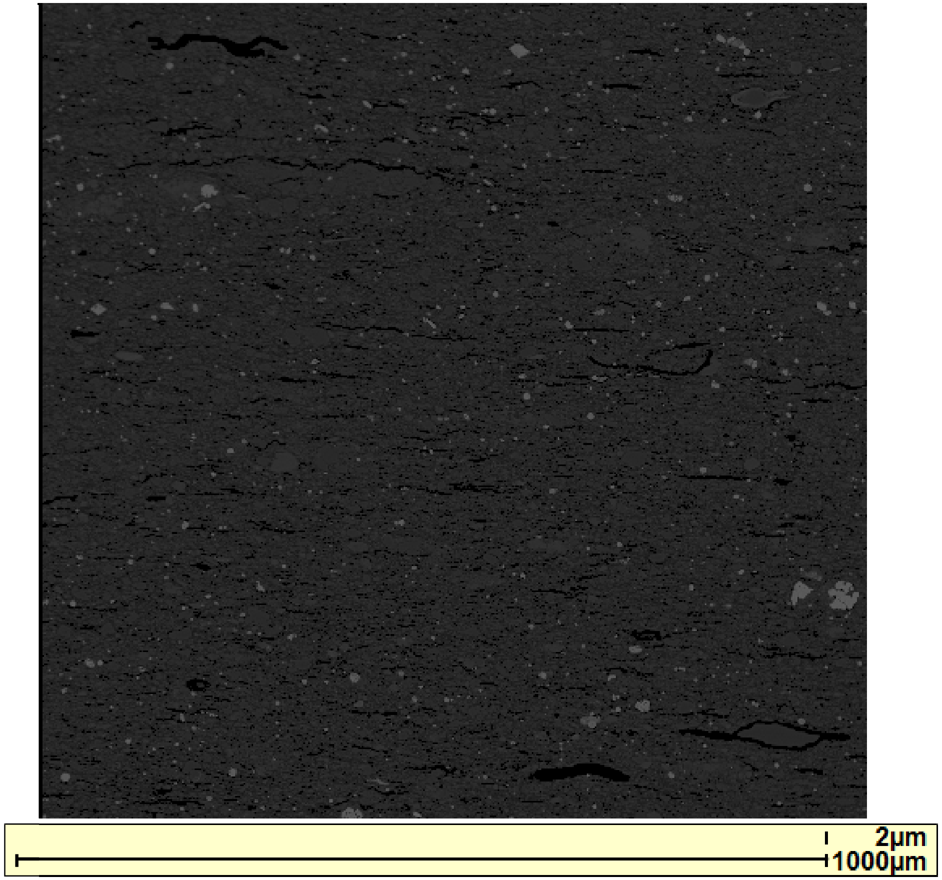
COLORADOSCHOOLOFMINES
EARTH • ENERGY • ENVIRONMENT

CENTER FOR ROCK ABUSE
Squeezing Rocks since 1994

Notes by Presenter: Comparison of the Upper and Lower shale mineral compositions show differences: Higher clay, but lower quartz content in the Upper shale than the Lower shale samples.This mineralogic composition would cause the Upper shale to be higher density than the Lower shale, due to the higher density of silica as compared to clays. In view of this, it would be expected that the Upper shales would have higher velocity than the Lower shale. This is not the case as seen table A (bottom left). from the same core data to check the effect of sampling bias, log data from database of 59 wells was used to get averages for TOC (Schmoker), NPHI, density and velocity. These showed similar differences between the Upper and Lower shales as far as velocity is concerned.TOC and Porosity for the Lower shales in the core sample are higher than that of the Upper shales. This shows that the organic matter and porosity compensate for the higher silica in Lower shales, enough to make the Upper shales higher velocity. The implication of this is that despite differences in mineralogic content in the shales, they may not be distinguishable using velocity alone due to the compensation caused by porosity and organic matter content.

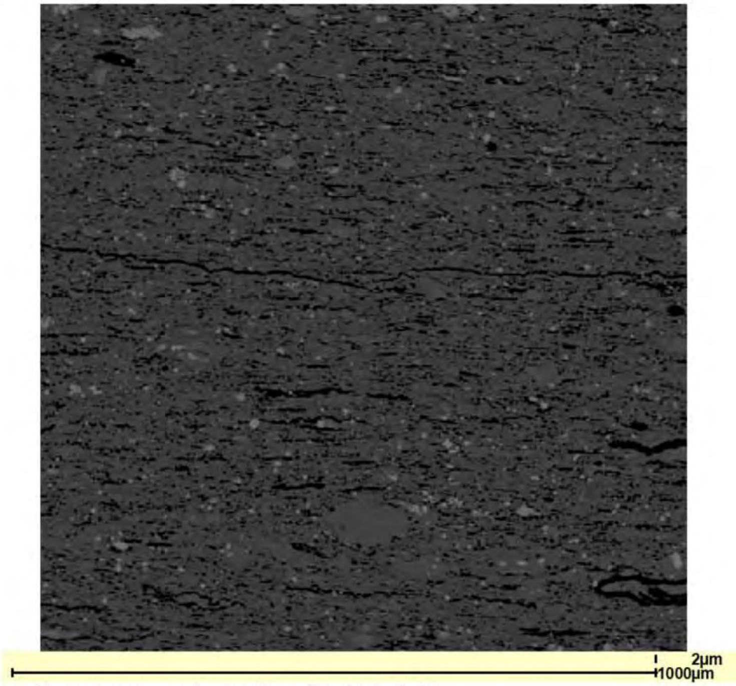
QEMSCAN IMAGES: MINERALOGY AND PORE SPACE/CLAY





- Intermediate maturity sample (HI = 217) showing pore space occurrence.
- Same sample imaged in for mineralogy (left), and porosity (right).

CLAY ANISOTROPY OR KEROGEN ANISTROPY?



Sample depth: 7,216ft

Higher clay, lower quartz content

Anisotropy: Image = 2.6; Vs = 15.2

Heterogeneity: 47%

Sample depth: 7,219ft

Lower clay, higher quartz content

Anisotropy: Image = 1.8; Vs = 6.7

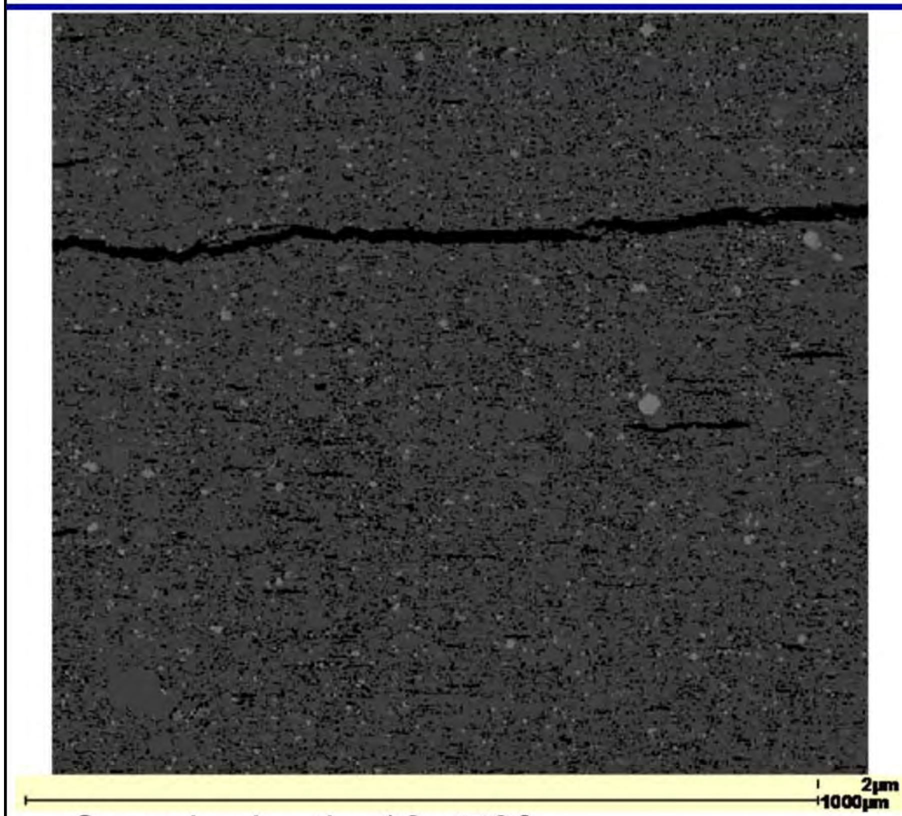
Heterogeneity: 38%

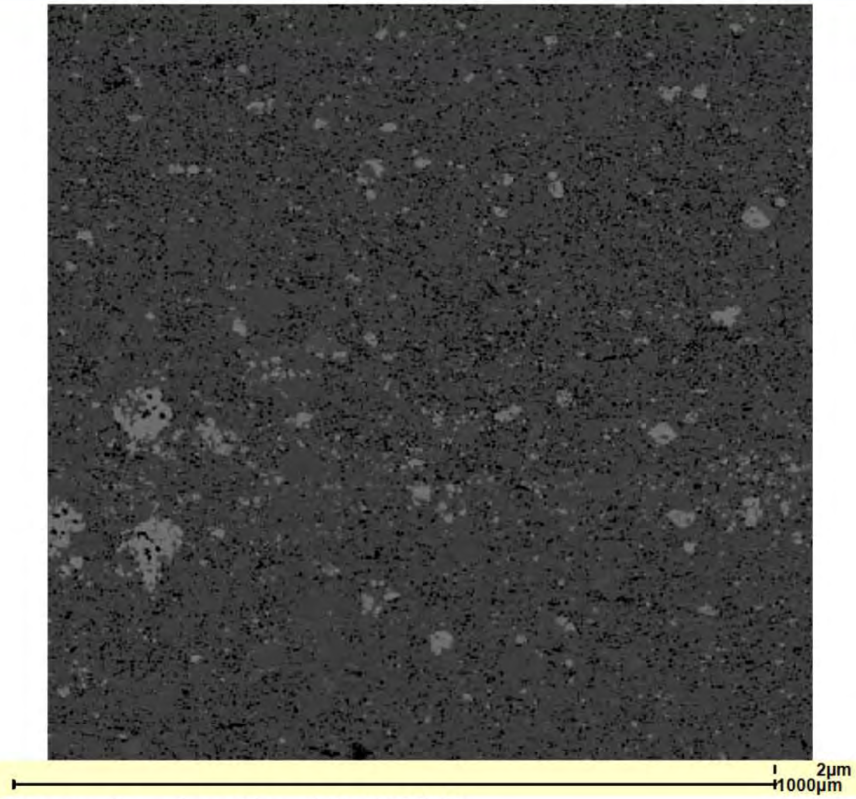
COLORADOSCHOOLOFMINES
EARTH ▲ ENERGY ▲ ENVIRONMENT

CENTER FOR ROCK ABUSE
Squeezing Rocks since 1994

Notes by Presenter: Two samples at about 7200ft showing clay/organic matter occurring as thin lenses, in partings, and in dissolution spaces around minerals. Left image shows increased presence of these softer components in a preferred horizontal orientation. This sample has higher clay content and lower silica content than image on right. Comparison of anisotropy shows that sample on left is higher anisotropy and heterogeneity than that on right.

HOW ABOUT ANISOTROPY AT GREATER DEPTH?





Sample depth: 10,479ft

Higher clay, lower quartz content

Anisotropy: Image = 1.6; Vs = 18.6

Heterogeneity: 44%

Sample depth: 10,390ft

Lower clay, higher quartz content

Anisotropy: Image = 1.5; Vs = 15.1

Heterogeneity: 40%

COLORADO SCHOOL OF MINES
EARTH ▲ ENERGY ▲ ENVIRONMENT

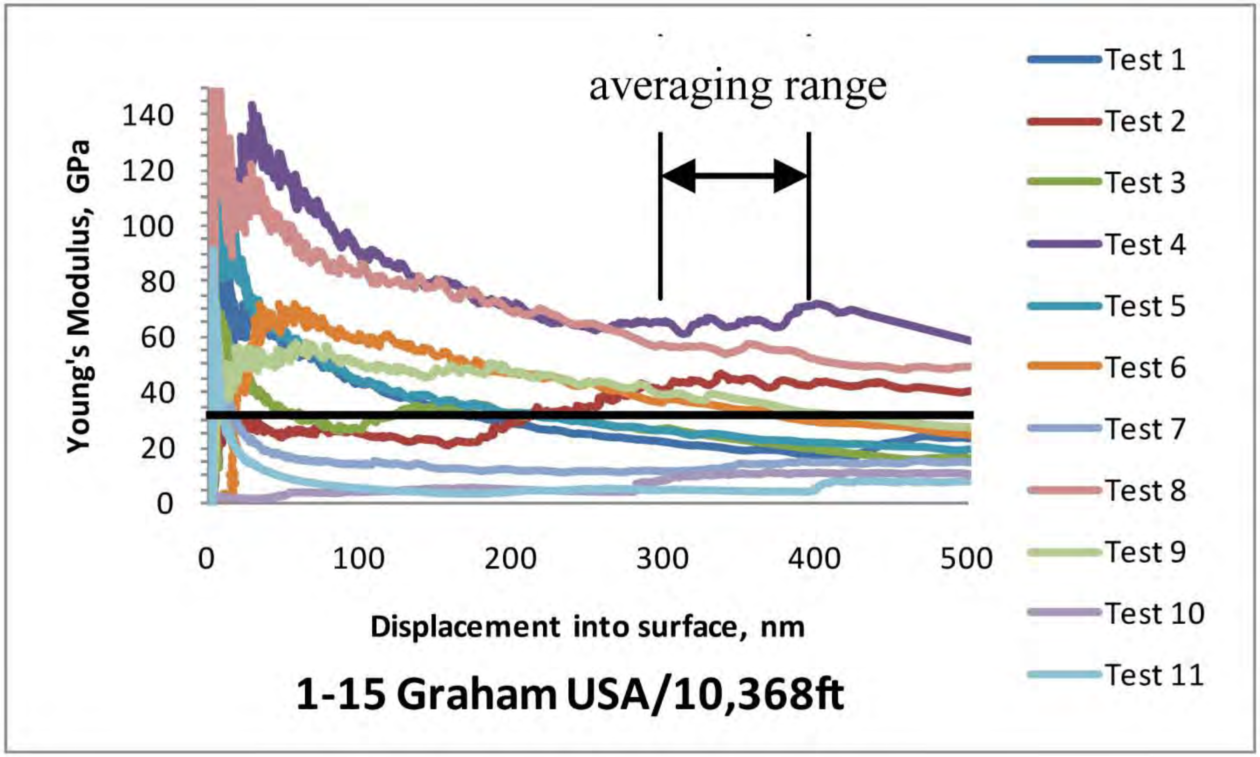
CENTER FOR ROCK ABUSE
Squeezing Rocks since 1994

Notes by Presenter: At greater depth, differences are more subtle, but clay content still contributes to more parting with preferrential orientation.

RESULTS

- LOG CROSS-PLOTS
- QEMSCAN MINERALOGY IMAGING AND ANALYSIS
- **NANO-INDENTATION**

YOUNG'S MODULUS FROM NANO-INDENTATION

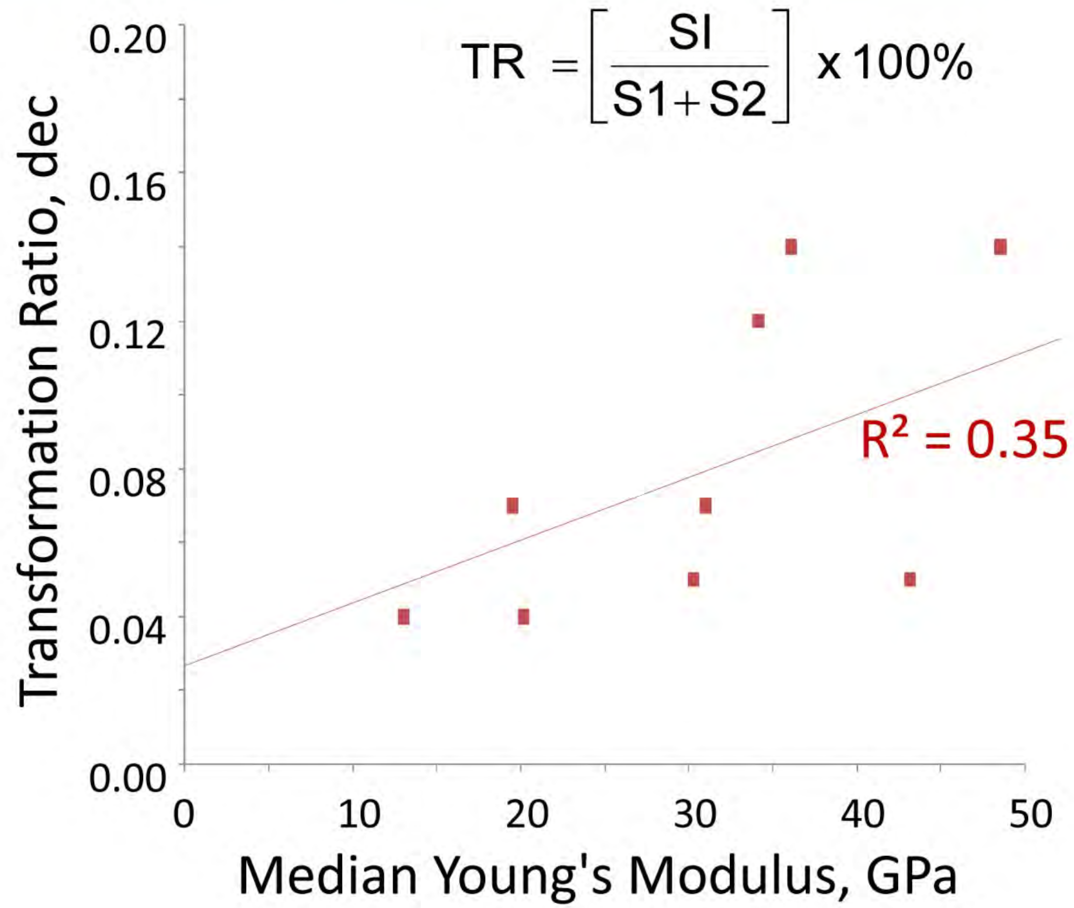


COLORADOSCHOOLOFMINES
EARTH ▲ ENERGY ▲ ENVIRONMENT

CENTER FOR ROCK ABUSE
Squeezing Rocks since 1994

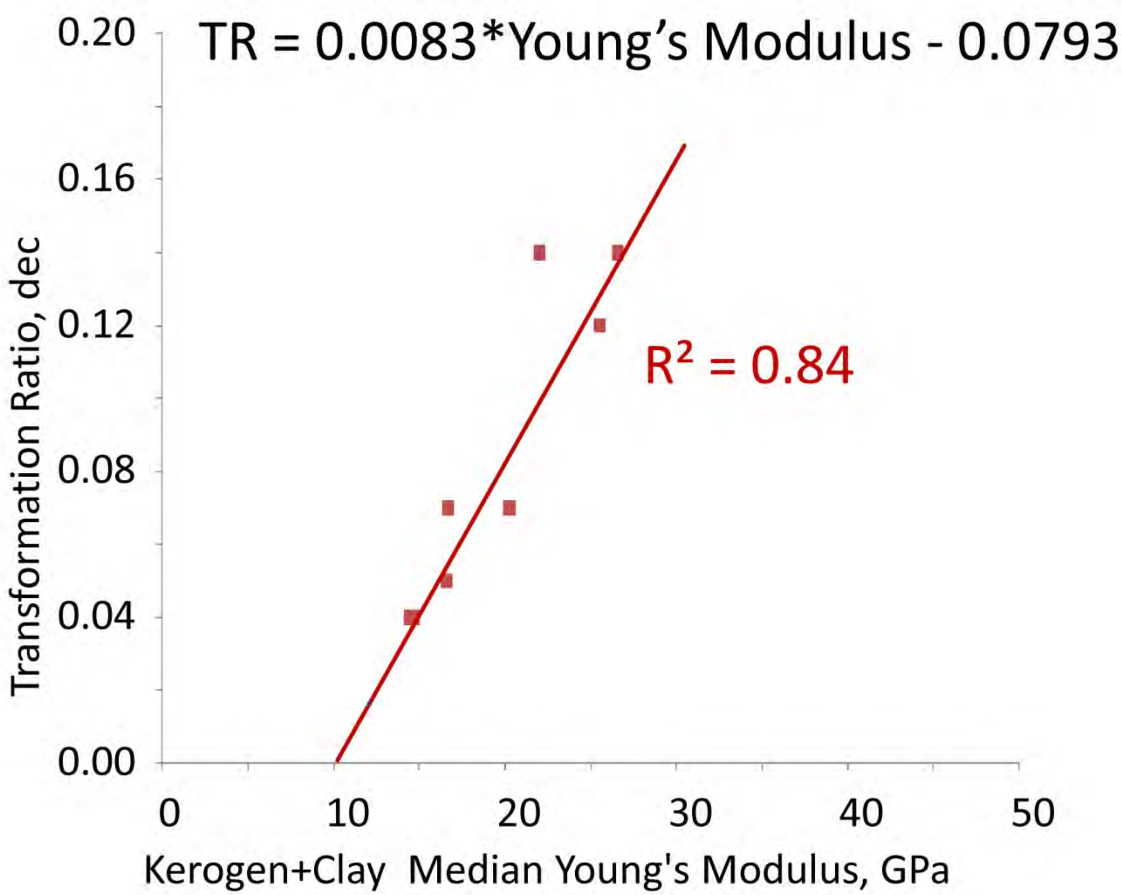
Notes by Presenter: Typical plot from Nano-indentation. Averaging done between 300-400nm where indenter most stable.

POOR CORRELATION BETWEEN MODULUS AND TR



Notes by Presenter: Plot of Young’s modulus against all maturity indices (TOC, TR, HI and Tmax) show poor correlation when the average for entire sample is used.

IMPROVED RELATIONSHIP WITH SOFT COMPONENTS



COLORADOSCHOOLOFMINES
EARTH ▲ ENERGY ▲ ENVIRONMENT

CENTER FOR ROCK ABUSE
Squeezing Rocks since 1994

Notes by Presenter: Plot of Young's modulus against all maturity indices (TOC, TR, HI and Tmax) show better correlation when the average for only softer components is used.

CONCLUSIONS

- **High silica + carbonate content results in high impedance shales.** No simple relationship between velocity, kerogen content, and maturity.
- **Horizontal lamination of clay and organic matter causes anisotropy.** This reduces with depth as shale 'hardens', and hydrocarbons are expelled.
- The combined **elastic modulus of kerogen + clay increases with increasing maturity.** Transformation ratio can be calculated from the Young's modulus as: TR = 0.0083*Young's Modulus - 0.0793
- **Increasing impedance with maturity** as hydrocarbons expelled, porosity reduced, and clay compacts. It may be possible to use impedance as a proxy for maturity.

ACKNOWLEDGEMENTS

- Lev Vernik, Rick Sarg, Steve Sonnenberg for contributing discussions.
- Sarah Appleby and Jane Stammer for QEMSCAN analyses, John Stokes for sample preparation, Hui Jin for pyrolysis, and Masood Hashemi for nano-indentation assistance.
- This work was supported by:

  (1) Grants from NETL (Award#:DE-NT0005672, Bakken Petroleum System Characterization Project), and the Norwegian Research Council.

  (2) Center for Rock Physics at the Colorado School of Mines.

  (3) CSM Bakken Consortium.

Colorado School of Mines Bakken Consortium

NETL

Samson

MARATHON

XTO ENERGY

EOG Resources

FIDELITY Exploration & Production Company

TOTAL

THE ENERGY OF enerPLUS

QUESTAR

WHITING Whiting Petroleum Corporation

SAVANT

The Discovery Group Inc

Red Willow Production Company

ANSCHUTZ EXPLORATION CORPORATION

NEWFIELD

Chesapeake ENERGY

Mike Johnson Consulting Geologist

Husky Energy

HENDRICKS and Associates, Inc.

MJ SYSTEMS

IHS

TGS

Statoil