IMPEDEANCE MICROSTRUCTURE OF KEROGEN SHALES

Manika Prasad
Rock Abuse Laboratory
Colorado School of Mines

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OUTLINE

• Motivation
• Working Principles
• Quantitative Studies
• Ultrasonic Impedance Analyses
• Impedance Microstructure
• Conclusions
MOTIVATION

- Microstructural investigations based on impedance changes
- Quantitative impedance mapping
- Mapping with 1 - 100 μm resolution
  - quantify textures as impedance values
  - quantify textural changes with maturation
- Non-destructive evaluation
• High porosity kerogen shales resemble sandstones
• Low porosity kerogen shales require different approach

Data from Vernik and Liu, 1997

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MATURATION - VELOCITY RELATION

Vp increases with maturity in low porosity kerogen shales.

Vp (km/s)

7
6
5
4
3
2

Maturity stage

Stage II  III - IVa  IV  V - VI

high porosity

Vp increases with maturity in low porosity kerogen shales.
Gray scale calibration with materials of known impedance. Gray color in image of unknown sample gives its AI values.

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MATURITY GRADE: II

Elongated grains
Very low acoustic impedance

Bakken Formation

62.5 μm  100 μm  1000 μm

8.2  7.4

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MATURITY GRADE: II

Woodford Formation
Elongated grains
Very low acoustic impedance

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MATURITY GRADE: III

Bazhenov Formation

Fine grained, elongated grains
Low acoustic impedance

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MATURITY GRADE: III

Bakken Formation

Elongated grains, connected textures
Low acoustic impedance
MATURITY GRADE: IVa

Bazhenov Formation
Coarser grained
Higher acoustic impedance

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MATURITY GRADE: IVb

Bakken Formation
Coarser grained, elongated texture
Higher acoustic impedance

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MATURITY GRADE: V

Woodford Formation
Coarser grained, elongated texture
Higher acoustic impedance
Transition from kerogen load-bearing (immature) to grain supported (mature) Bakken Shales
HYDROGEN INDEX - ACOUSTIC TEXTURE

Transition from kerogen load-bearing (immature) to grain supported (mature)

Bakken Shales
HYDROGEN INDEX - Vp RELATION

Vp increases with increasing shale maturity.

Bakken Shales
HYDROGEN INDEX - IMPEDANCE

- Impedance increases with increasing shale maturity.
- Ultrasonic values match well with AM values

Micro-Impedance

Bulk Impedance

Bakken Shales
MICRO- AND MACRO IMPEDANCE

- Bulk impedance increases with maturation
- Microstructural changes
- Micro-impedance increases with maturation

Remote detection of kerogen maturity
Statistical tools for texture analysis

Heterogeneity – Coeff. of variation (CV)

\[ CV = \frac{\text{std. dev}\{I(x,y)\}}{\text{mean}\{I(x,y)\}} \]

Autocovariance function (ACF)

\[ R(m,n) = E\left\{ \left[ I(x, y) - m_I \right] \left[ I(x + m, y + n) - m_I \right] \right\} \]

Fourier transform

\[ \hat{I}(k_x, k_y) = \iint I(x, y) \exp\{-i(xk_x + yk_y)\} \, dx \, dy \]

Power spectrum

\[ S(k_x, k_y) = \hat{I} \cdot \hat{I}^* \]

\[ S \Leftrightarrow R \]
Autocovariance Function & Textures

From Mukerji and Prasad, 2005
Textural anisotropy ratio (AR)

\[ a_r = \frac{a_{\text{max}}}{a_{\text{min}}} \]

From Mukerji and Prasad, 2005
Texture analysis

Textural Heterogeneity – Coeff. of variation CV
Larger contrast of heterogeneity leads to high values of CV

Textural Anisotropy – Anisotropy Ratio AR
Textural anisotropy leads to a directional dependence of the ACF

Textural Scale – Mean correlation length
Larger sized heterogeneities lead to larger correlation lengths

From Mukerji and Prasad, 2005
Textural anisotropy & scales

- Textural anisotropy (AR) increases with increasing correlation length.
- With depth (= maturity), textural anisotropy increase is lower while the mean correlation length increase is larger → Deeper samples have lower anisotropy but larger heterogeneities.

From Mukerji and Prasad, 2005
Textural heterogeneity and scales - depth dependence

- Mean correlation length decreases as textural heterogeneity (CV) increases → deeper samples have larger heterogeneities with higher contrast

From Mukerji and Prasad, 2005
Textural heterogeneity & shale maturity

From Mukerji and Prasad, 2005
Textural anisotropy and maturity
-depth & scale dependence

From Mukerji and Prasad, 2005
Results from SAM Image Analysis

- The coefficient of variation (CV) (a measure of impedance heterogeneity) ranges from 7% to about 12%.
- The mean correlation length tends to increase with increasing heterogeneity.
- Textural heterogeneity, elastic impedance, velocity, and density increase with increasing shale maturity.
- The textural spatial correlation length varies with direction.
- The textural anisotropy (AR) ranges from 10% to about 70% and tends to decrease with increasing depth & maturity.

Quantifiable and consistent patterns linking
  - Texture,
  - Shale maturity, and
  - Wave propagation properties
CONCLUSIONS

- Acoustic impedance in kerogen shales increases with shale maturity.
- Bulk impedance matches well with impedance measured on a micrometer scale.
- With increasing maturity, there is a transition from kerogen supported to grain supported framework.
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