Predicting Hydraulically Induced Fractures Using Acoustic Impedance Inversion Volumes: A Barnett Shale Formation Example*

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Abstract

Once considered only as source rocks and seals, shale formations are now also considered as tight-porosity and low-permeability unconventional gas reservoirs. The classification as a reservoir is mainly technology- and economics-driven. Major gas (and minor oil) production from these plays is facilitated by massive hydraulic fracturing treatments that increase permeability and help to reactivate natural fractures. Stimulation ultimately enhances reservoir drainage, yielding economically viable hydrocarbon production. Natural faulting and fracturing are critical factors controlling present day stress distribution, which in turn influences hydraulically induced fracture system development. Most predictive models used to estimate recovery in microseismicity monitoring wells are based on assumptions that lead to oversimplified fracture network geometry. To avoid such assumptions, and better understand the created fracture geometry, borehole-based induced microseismicity monitoring may be used.

Hydraulically induced fracture networks mapped in various formations around the world using borehole-based microseismic monitoring techniques correlate closely to stress states at various scales. Mapped fracture systems generally tend to propagate perpendicularly or nearly perpendicularly to the minimum horizontal stress while influenced by local and regional structural features. However, the heterogeneous and anisotropic mineralogical composition of the shale formation results in variable fracture gradients and fractured zones. To characterize the variations of rock properties within such formations, we generated seismic inversion volumes from a 14-square-mile seismic survey acquired over the Barnett Shale within the Fort Worth Basin using P- and S-impedance and Lamé parameters from density, shear, and compressional velocity logs. We show that the locations of microseismic events correlate to specific values of the inverted surface seismic properties. Fractured zones correlate to low density and low P- and S-impedance values. While impedance characterizes the matrix properties of the Barnett Shale, Lamé parameters shed light on the extent of the fracture system into gas-bearing zones. This initial correlation suggests that

3D surface seismic-derived inversion volumes may serve as a tool to help design hydraulic stimulation programs using a prior knowledge of the most likely fracture propagation trends and failure loci.

References

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American Association of Petroleum Geologists
Annual Convention and Exhibition
Seismic Visualization and Attributes

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Overview

I. Introduction
- Objectives
- Significance of Project

II. Geologic Background
- Geologic History

III. Theoretical Background
- Hydraulic Stimulation and Microseismicity
- Curvature from 3D Seismic Data Volumes
- Seismic Inversion

IV. Application of Theory for Surface Seismic Analysis
- Curvature Attribute
- Seismic Inversion

V. Microseismic Analysis
- Microseismic Interpretation
- Microseisms and Volumetric Curvature
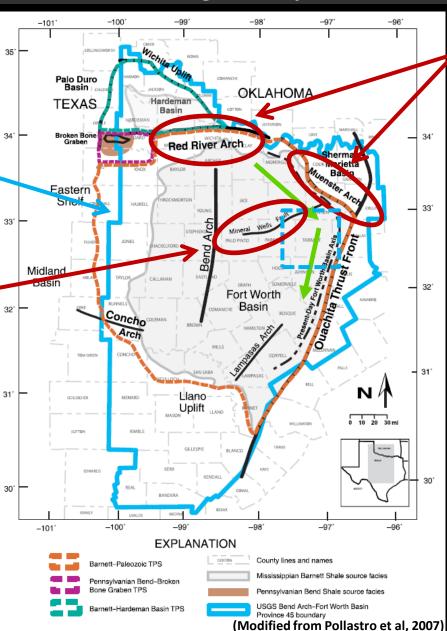- Microseisms and Seismic Inversion Properties

VI. Conclusions

VII. Moving Forward

Overview

Introduction

Objectives

- **Characterize zones of fracture network propagation during hydraulic stimulation using:**

  - Recorded microseisms
  - Volumetric curvature attribute
  - Inversion volumes

- **Define characteristics of fracture-prone zones from mapped microseism clusters for fracture network prediction**

Significance of Project

- TOC 3-13%
- 26 tcf (gas)
- R_o = 1.7-2.0

Hydrocarbon Resources

Hydraulic Fracture

- Increase in reservoir connectivity

Commercial Production

Overview

Geologic History

Basement uplifts formed by reactivated basements faults during Ouachita compression.

Fort Worth Basin formed during the late Paleozoic Ouachita Orogeny, a major tectonic event of thrust-fold deformation.

The basin deepens towards the north and its axis roughly parallels the Muenster arch, then bends southwards to parallel the Ouachita structural front.

The Mineral Wells fault has a NE-SW trend and has been proposed to be a basement fault periodically reactivated during the late Paleozoic.

(Modified from Pollastro et al, 2007)

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I. Introduction
- Objectives
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II. Geologic Background
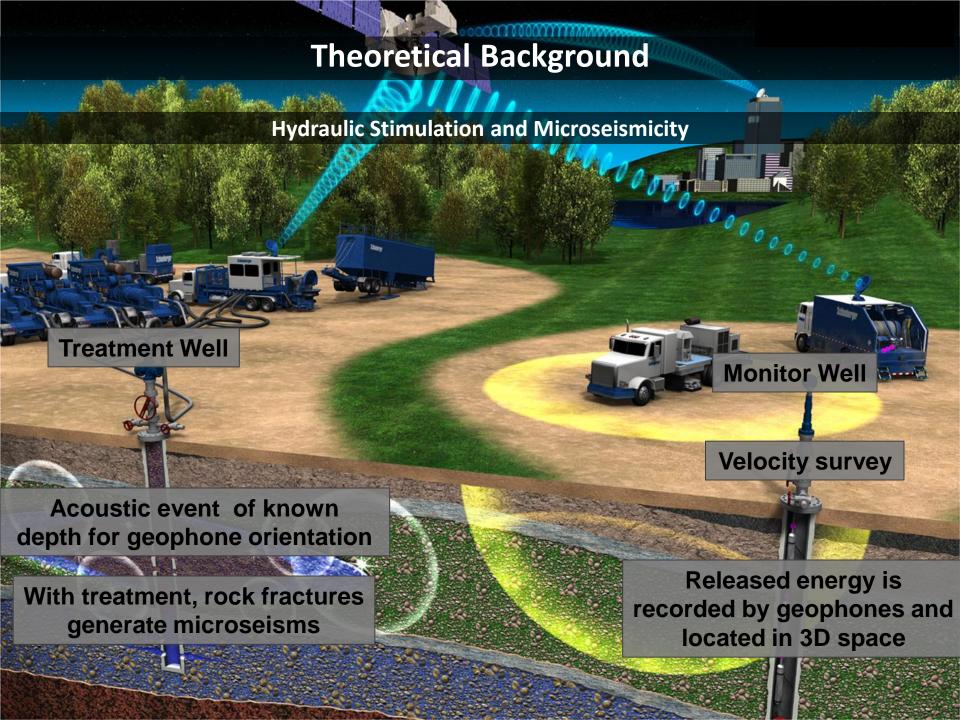- Geologic History

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- Seismic Inversion

IV. Application of Theory for Surface Seismic Analysis
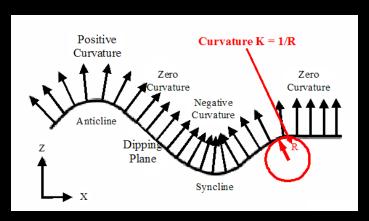- Curvature Attribute
- Seismic Inversion

V. Microseismic Analysis
- Microseismic Interpretation
- Microseisms and Volumetric Curvature
- Microseisms and Seismic Inversion Properties
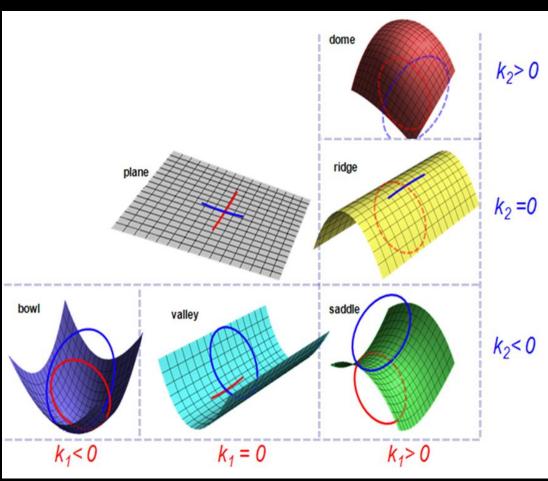
VI. Conclusions

VII. Moving Forward

Theoretical Background

Hydraulic Stimulation and Microseismicity

Treatment Well

Monitor Well

Velocity survey

Acoustic event of known depth for geophone orientation

With treatment, rock fractures generate microseisms

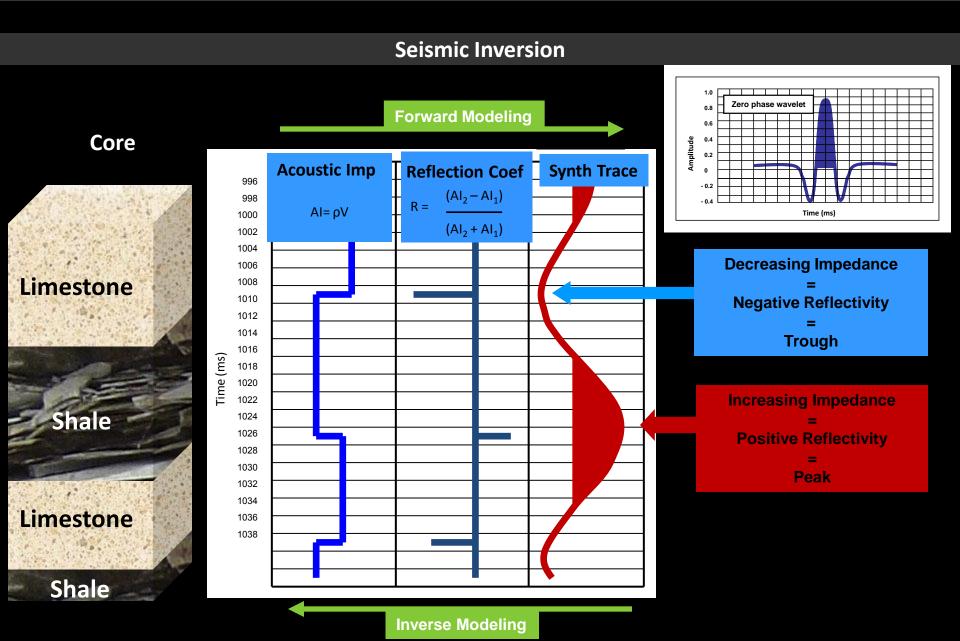**Released energy is recorded by geophones and located in 3D space**

Theoretical Background

Two-dimensional curvature, where by convention, positive curvature is concave downward, and negative curvature is concave upward (from Roberts, 2001).

Three-dimensional quadratic shapes of most-positive and most-negative principal curvatures (k_1 and k_2) (modified from Mai, 2010).

Theoretical Background

Seismic Inversion

Core

Limestone

Shale

Limestone

Shale

Forward Modeling

Inverse Modeling

Acoustic Imp

$AI = \rho V$

Reflection Coef

$R = \dfrac{(AI_2 - AI_1)}{(AI_2 + AI_1)}$

Synth Trace

Decreasing Impedance
=
Negative Reflectivity
=
Trough

Increasing Impedance
=
Positive Reflectivity
=
Peak

Zero phase wavelet

Amplitude

Time (ms)

Time (ms)

Overview

Application of Theory for Surface Seismic Analysis

Curvature Attribute

Most Positive Principal Curvature k1

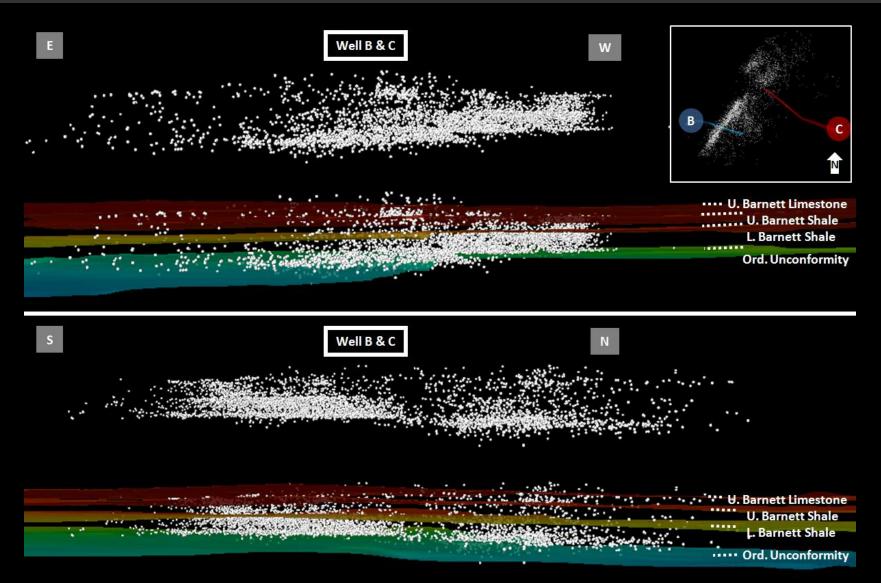**Most Negative Principal Curvature k2**
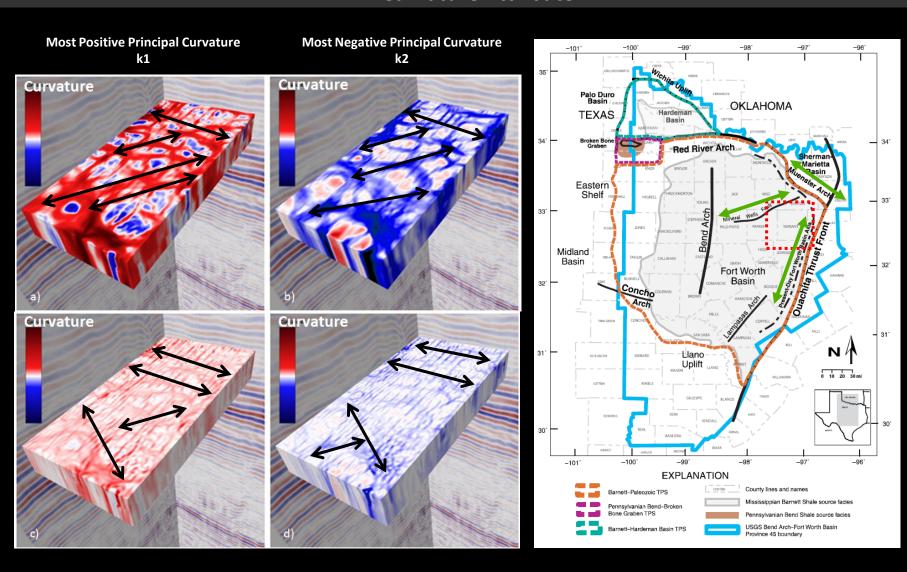
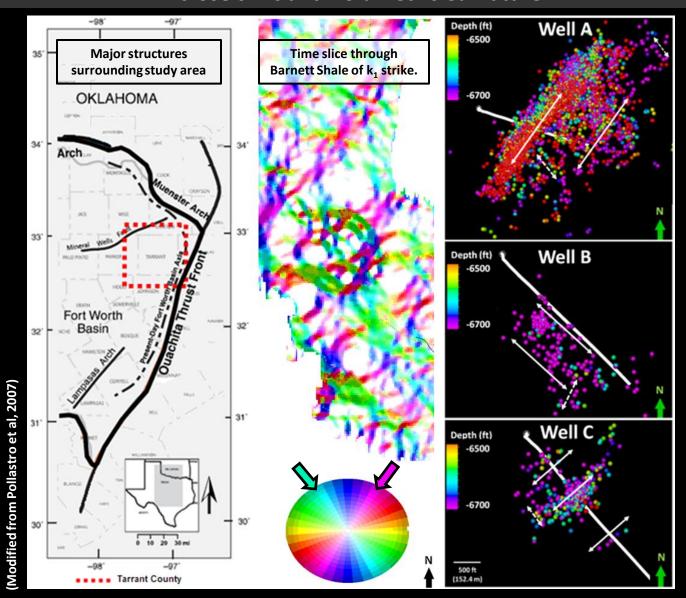# Application of Theory for Surface Seismic Analysis
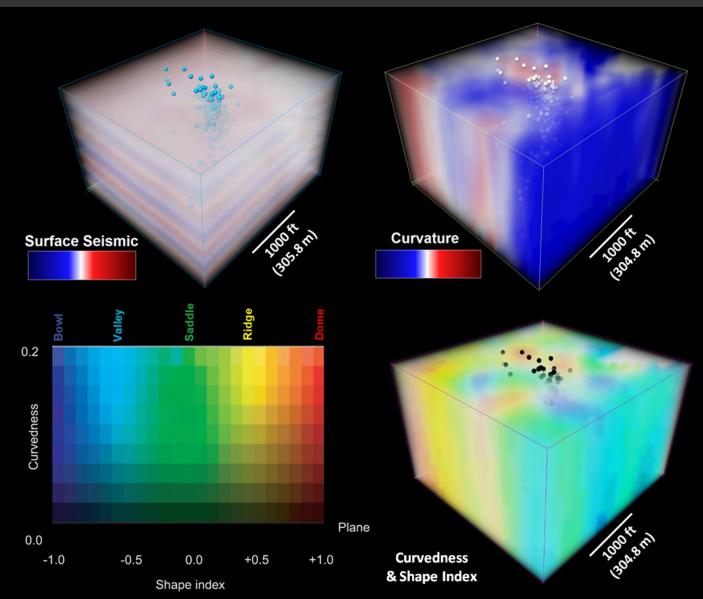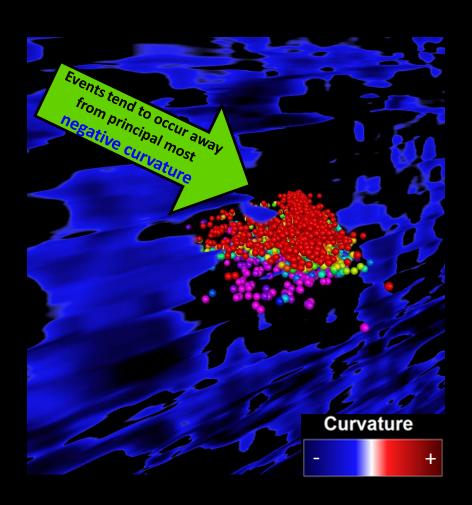
Seismic Inversion

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- Geologic History

III. Theoretical Background
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- Curvature from 3D Seismic Data Volumes
- Seismic Inversion

IV. Application of Theory for Surface Seismic Analysis
- Curvature Attribute
- Seismic Inversion

V. Microseismic Analysis
- Microseismic Interpretation
- Microseisms and Volumetric Curvature
- Microseisms and Seismic Inversion Properties
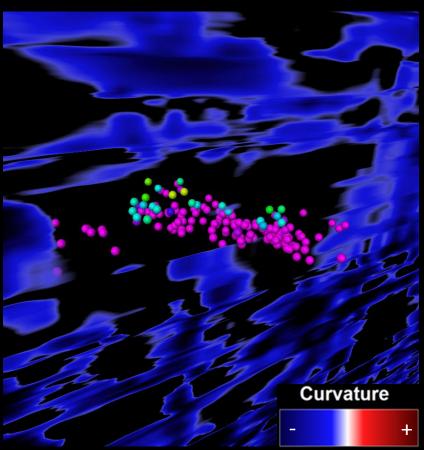
VI. Conclusions

VII. Moving Forward

Microseismic Analysis

Microseismic Interpretation
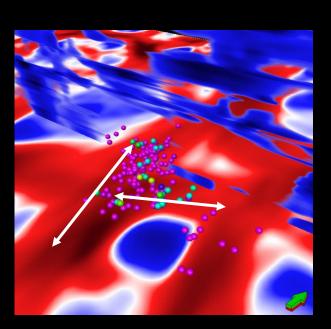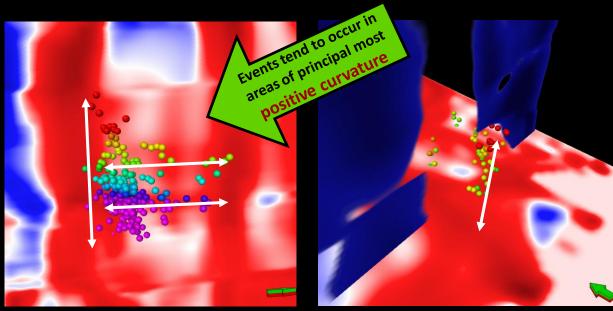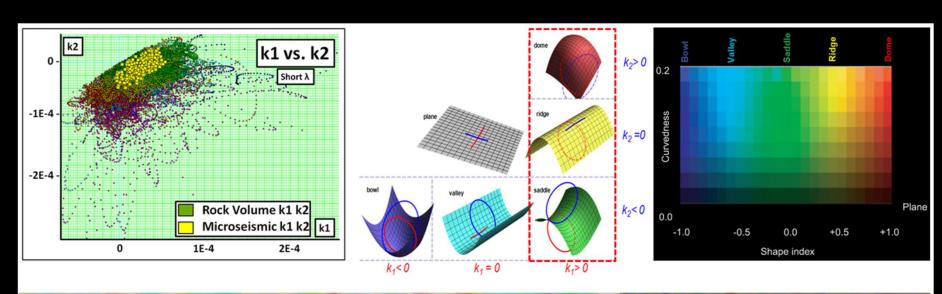
Microseismic and Volumetric Curvature

(Modified from Pollastro et al, 2007)

Microseismic and Volumetric Curvature

Surface Seismic
1000 ft (305.8 m)

Curvature
1000 ft (304.8 m)

Bowl · Valley · Saddle · Ridge · Dome
Curvedness
0.2
0.0
Shape index: -1.0 -0.5 0.0 +0.5 +1.0
Plane

Curvedness & Shape Index
1000 ft (304.8 m)

Microseismic Analysis

Microseismic and Volumetric Curvature

Events tend to occur away from principal most **negative curvature**

Curvature

− +

Curvature

− +

Microseismic Analysis

Microseismic and Volumetric Curvature

Events tend to occur in areas of principal most positive curvature
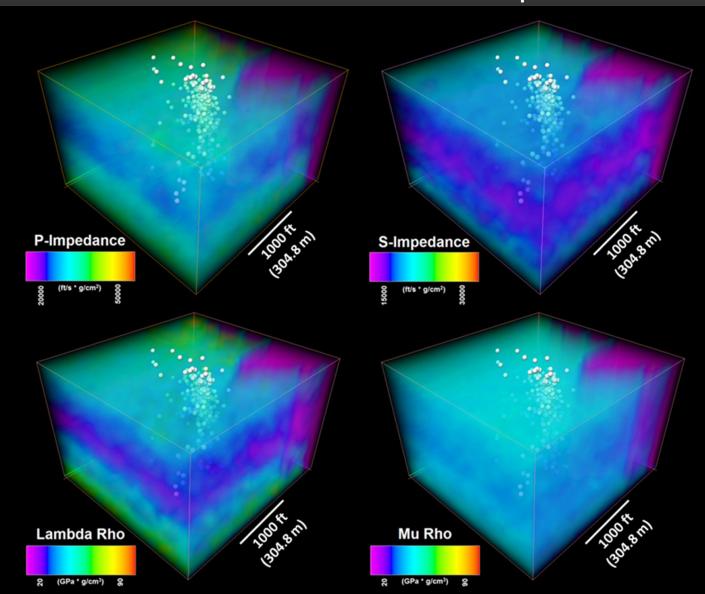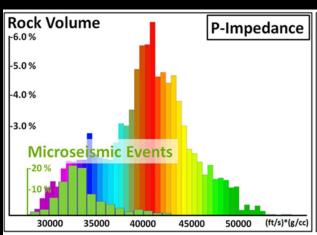
Curvature

Microseismic and Volumetric Curvature

Microseismic Analysis

Microseismic and Seismic Inversion Properties

P-Impedance
20000 — (ft/s * g/cm²) — 50000

1000 ft (304.8 m)

S-Impedance
15000 — (ft/s * g/cm²) — 30000

1000 ft (304.8 m)

Lambda Rho
20 — (GPa * g/cm³) — 90

1000 ft (304.8 m)

Mu Rho
20 — (GPa * g/cm³) — 90

1000 ft (304.8 m)

Microseismic Analysis

Microseisms occur in a narrow range of impedance values
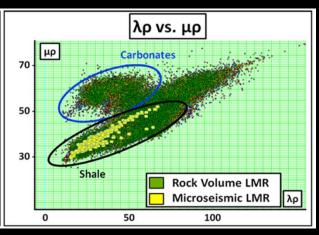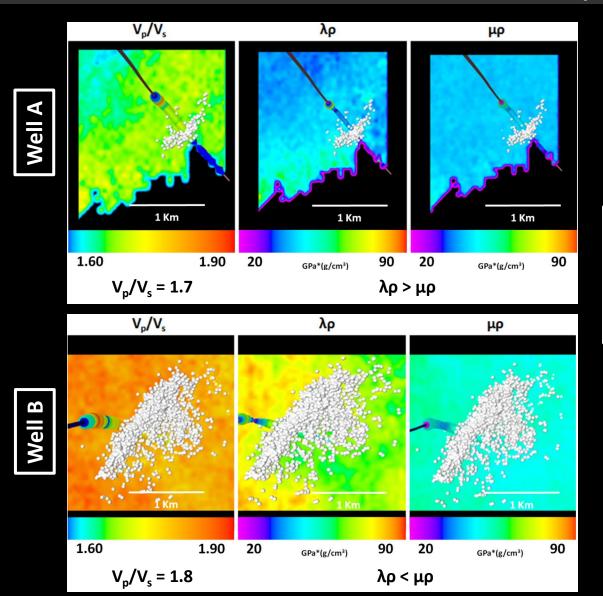
Microseismic Analysis

Microseismic and Seismic Inversion Properties

Low Production

Gas saturated shales:
$V_p/V_s = 1.7 - 3.0$
$\lambda\rho < \mu\rho$
(Goodway et al., 2006; Aibaidula and McMechan, 2009)

High Production

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- Seismic Inversion

IV. Application of Theory for Surface Seismic Analysis
- Curvature Attribute
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- Microseismic Interpretation
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VI. Conclusions

VII. Moving Forward

Conclusions

- Tectonics influence curvature attribute and induced fracture system orientations

- Hydraulic fractures correlate to anticlinal 3D shapes

- Low-density and low-impedance rock is highly fracture-prone

Conclusions

- Lamé parameters delineate the extent of fracture systems into gas-bearing zones and evaluate stimulation effectiveness

- Formation contact zones can act as a relatively impermeable barriers or as weakness planes for propagating fracture systems

- The correlation of microseisms with surface seismic inversion and curvature attributes can be used for improved stimulation plans

Thank You

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Questions?

(Applause)