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

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Search and Discovery Article #10946 (2017)**
Posted May 29, 2017

*Adapted from poster presentation given at 2017 AAPG Annual Convention & Exhibition, Houston, Texas, April 2-5, 2017
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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

**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.

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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!

**WFMP Cross plot:**

P impedance –vs- Vol SS%

P impedance –vs- Vol LS%

Total Porosity in Color

Total porosity < 5% grayed out

**Multi-disciplinary Data Integration:**

- Seismic Stratigraphic Interpretation
- Petrophysics + Geology
- Structural Interpretation
- Lithofacies Volume
- Closure Pressure Volume
- Brittleness Volume

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

• 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-off-slope with nearby carbonate margin rimming basin
- Laminated mudrocks interbedded with carbonate debrites
- Siliceous and carbonate mudrock (reservoir) composition varies cyclically
- Toe-off-slope, low-gradient depositional setting
- Laminated mudrocks interbedded with turbidite/fan lobe siltstones
- More siliceous mudrock (reservoir) composition; siltstones also reservoirs

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

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

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.
**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

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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

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

Problem:
Cannot differentiate lithology based upon P impedance alone – which is output of post-stack inversion!
Seismic Inversion Integration With Petrophysics—Predicting Lithofacies

**CROSS-PLOTT 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
  - $\lambda_p$, $\mu_p$
  - $\lambda = $ incompressibility
  - $\mu = $ rigidity

- How do we compute $\lambda_p$ and $\mu_p$ from $I_p$ and $I_s$?
  - $\lambda_p = (I_p^2 - 2I_s^2)$
  - $\mu_p = I_s^2$

- Where have we seen $\lambda$ and $\mu$ before?
  - $\lambda = (\frac{1}{3})\sum_{i=1}^{n} (\sum_{j=1}^{n} x_{ij}^3 - 3\sum_{j=1}^{n} x_{ij})$
  - $\mu = \frac{6}{5} \sum_{i=1}^{n} (\sum_{j=1}^{n} x_{ij}^2)

**FACIES**

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

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

- Wolfcamp LMR Facies
  - “Best” LMR-defined reservoir facies with most fracable fabric: Laminated quartz-rich mudrock with thin interbeds of siliceous or calcareous siltstones.

- Spraberry LMR Facies
  - “Best” LMR-defined reservoir facies with most fracable fabric: Laminated mudrock with thin interbeds of quartz-rich siltstones.

**Facies Zones** defined in crossplots used as templates to create classified volumes of “LMR Facies” in Wolfcamp and Spraberry.

- Use these templates to calculate and output facies classification 3D volumes
- Map facies proportions along borehole trajectories

- Facies classifications (Wolfcamp and Spraberry) from petrophysical LMR cross plots
Inversion Results and Analysis—Integration with Lithofacies, Basin Architecture and Geomechanics

LMR FACIES DISTRIBUTION WITHIN STRATIGRAPHIC GEOMETRY

- LMR Facies proportions correspond to stratal geometries
- Wolfcamp: LMR Facies A—widespread oil-prone facies interbedded with carbonate debris; advance of carbonate mudrocks into area towards top of WFMP A
- LMR Facies B—higher proportion of tight, wet carbonate debris; oil-prone facies (siliceous mudrock) dominates in SE
- LMR Facies C—high proportion of oil-prone facies; significant debris proportion interbedded in north

LMR FACIES DISTRIBUTION WITHIN BASIN ARCHITECTURE

- Lower Spraberry: Stratal Slice Through LSBY Facies volume (shallower)
- Stratal Slice Through LSBY Facies volume (deeper)

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

DECRYPTABLE 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.
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)

- Fracable (what’s it take to break it?)
- Frac container (vertically & horizontally)

\[
s_{hv} = \frac{V}{1-V} \left( p_x - p_y + \frac{E}{1-v^2} \right)
\]

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 & Milnren, 2015; UTReC 2172545)

Reformulated to accommodate LR and MR

**HORIZONALS DRILLED IN THE WOLFCAMP AND LOWER SPRABERRY WITHIN THE 3D AREA**

- **WFMP**
  - AVF 16BPD
  - AVF 768 BWPD (71% water cut)
  - AVF 360 BOPD
  - AVF 1089 BWPD (75% water cut)

- **LSBY**
  - AVF 286 BOPD
  - AVF 768 BWPD (75% water cut)
  - AVF 306 BOPD
  - AVF 1089 BWPD (75% water cut)

- **CUM PRODUCTION**
  - 92,000 BO
  - 230,000 BW
  - 59 MCFG
  - 148 MCFG

**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
- 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.