Using Innovative Technology to Enhance Performance in Unconventional Reservoirs – Eagle Ford Study

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Concept and Reality

• Unconventionals is not a single type of opportunity but rather spans a concept. They can include shales (oil and gas), tight sands & carbonates or coals.

• In this discussion we will focus on shales. These are reservoirs of different intrinsic characteristics where the effectiveness of fracing and completion determines the success of the well.

• Completion success:
  − Develop a multidisciplinary & integrated approach (Earth Model)
  − Need for high-resolution understanding of the subsurface
  − Expand the scope of investigation beyond the borehole wall

Key to successful unconventional is completion effectiveness

Comparison of shale characteristics for 5 different types of shale reservoirs (for 8 properties, after Roth, 2010)
Major Unconventional Plays

Five states accounted for about 65% of total U.S. dry natural gas production in 2015:

- Texas (26%)
- Pennsylvania (18%)
- Oklahoma (9%)
- Wyoming (6%)
- Louisiana (6%)

Large-scale natural gas production from shale began around 2000, when shale gas production became a commercial reality in the Barnett Shale located in north-central Texas.

The oil industry invested more than $28 billion in buying up land in the Permian Basin in 2016, three times the amount spent in 2015, according to Reuters. That accounted for about 39 percent of all money spent on land acquisitions in the U.S. oil industry last year. Other shale basins do not even come close to that level of investment. By way of comparison, the Marcellus Shale attracted 10 percent of total land investment in 2016, while the once-hot Bakken only captured 3 percent.
Drillinginfo: While most of the Permian strata have been developed by conventional methods over many decades, vast resources are being explored by unconventional drilling.
Unlocking Unconventional Resources

• Build a comprehensive digital database to organize and upgrade current well data investment
• Resolve near surface corruption of the seismic signal
• Recover previously missed faults and natural fracture swarms with full azimuth seismic diffraction imaging and fracture characterization
• Develop a velocity model for precision depthing, well planning and geosteering
• Integrate geophysical, geological, geomechanical, and petrophysical properties for a comprehensive understanding of reservoir quality and well performance in an accurate Erath model
• Develop probabilistic lithofacies models from rock type analysis, electrofacies analysis, and seismic inversion to better understand well performance
• Evaluate and optimize field parameters (e.g. lateral length, well spacing)
• Perform geomechanical modeling, analysis, and simulation to evaluate well bore stability, fault reactivation potential and value of refracturing operations
• Identify the potential drilling hazards to reduce risk and increase production
Paradigm Shale Technology Investment

**SHALE GEOPHYSICS**
- Full azimuth diffraction imaging
- Full azimuth fracture determination (AVA(Z) and VVA(Z)); HTI and Orthorhombic
- Geologically-constrained anisotropic velocity models
- Grid or model-based tomography for precision depthing
- Pre-stack seismic inversion with stochastic refinement (thin bed)
- Seismic determination of TOC
- Seismic facies classification
- Rock type classification
- Seismic structural attributes

**SHALE FORMATION EVALUATION**
- Zone-based Lithofacies Prediction and Rock Typing
- Multi-mineral analysis with uncertainty
- Full waveform sonic processing with frequency-slowness analysis
- Well bore stability modeling and analysis / Core & Image log analysis
- Well and seismic based pore-pressure prediction
- TOC and shale gas analysis
- 3D Petrophysics and Geosteering

**SHALE MODELING, ANALYSIS, & PERFORMANCE**
- Integrated structural and facies modeling in chrono-stratigraphic space
- Discrete Fracture Modeling
- Time dependent parameter analysis (microseismic, production, tracer data)
- Stimulation Path Modeling from microseismic data (SRV/MRV)
- Well planning and landing in 3D structural/property models
- Geomechanical simulations (SKUA-Abaqus)
Shale Geophysics

Improved subsurface insight with full azimuth imaging and characterization

**Full Azimuth Fracture Determination**
Characterizing tight reservoirs with high precision and reliability

**Full Azimuth Diffraction Imaging**
High Resolution Interpretation

**Precision Depthing**
Precision synthetics and markers tie in anisotropic regimes

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HTI Inversion carried out on full azimuth ES360 gathers Baltic Basin Margin, Onshore Poland

Co-visualization diffraction and thinned fault likelihood attributes, Eagle Ford

Data Courtesy of SEITEL
Wavefield Separation Approach

- High resolution seismic interpretation of small scale discontinuities from diffracted energy to understand compartmentalization of heterogeneous reservoirs

The specular direction carries the most energy.

Depth Slice on diffraction volume @ 15000ft. Tectonic induced Faults & fractures
Wavefield Separation Approach

- High resolution seismic interpretation of small scale discontinuities from diffracted energy to understand compartmentalization of heterogeneous reservoirs

Diffraction image superimposed with coherency

The major faults are salt related normal faults, dipping NW-SE

Main bounding Faults

transfer zone

relax zone

The specular direction carries the most energy.

(Half Opening Angle, Opening Azimuth)

\[ \frac{\nu_1, \nu_2}{\gamma_1, \gamma_2} \]

(Opening angle)

\[ 0 \leq \gamma_1, \gamma_2 \leq 360^\circ \]

Local Angle Domain Table

v1 Dip & Azimuth

v1 Dip & Azimuth

Mute

Full Azimuth Directional Angle Gather

Wavefield Energy or Structural (Dip/Azimuth) Separation

Wavefield Separation Approach

High Resolution Seismic Interpretation

High resolution delineation of diffraction generators

Advanced Structural Analysis

Data Courtesy of SEITEL
High Resolution Structural Interpretation

• Objective: Improve fault interpretation for accurate structural framework

Volumetric curvature and diffraction weighted stack co-visualization
Scale = 2 miles

Fault network and diffraction energy stack
Model-Based Tomography

- Generate Initial Interval Velocity (ISO/VTI/TTI/HTI)
- Scale interpretation to depth
- Calculate mistie maps for target horizons
- Create Pencil Database Perturbations
- Build and solve matrix
- Update structural interpretation
- QC new mistie values

Final Velocity Model

- YES
- NO

Initial velocity blended with specular weighted image- Tops are not aligned to structure

Mistie map and pencils with mistie values draped as attribute

Final velocity blended with updated specular weighted image- Tops are aligned to structure
Shale Formation Evaluation

Improved reservoir description at wellbore

Shale Analysis
Shale gas models for TOC, total gas & gas in place, Shale gas cumulative

Facies determination
High Resolution clustering for rock type classification & log prediction

Image log analysis
Fracture detection at wellbore
Electrofacies Workflow

1. In this example, the Prediction (aka Associated) log controls sampling in the training dataset. If a log/core values goes missing (eg KA_CR below) then the sample is automatically culled from the training dataset.

2. In this example, if core data goes missing in Application wells then prediction of permeability will use existing/available wireline log values.
# Shale Reservoir Geophysics

Improved reservoir description with seismic-derived shale characteristics, stochastic refinement and rock type classification

<table>
<thead>
<tr>
<th>Seismic Determination of TOC</th>
<th>Stochastic Refinement</th>
<th>“Rock Type” Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characterizing TOC from seismic in tight reservoirs with reliability</td>
<td>High Resolution Reservoir Properties Distribution</td>
<td>Predict calibrated facies distribution from seismic attributes</td>
</tr>
</tbody>
</table>

Colin Sayers, 2013

Data Courtesy of SEITEL
Rock Type Prediction

- A probabilistic workflow-based approach
- Innovative methodology to infer rock type at wells from seismic information (prestack or poststack)
- Use a Democratic Neural Network Association (DNNA) approach to establish a non-linear relation between well facies and seismic data
- Propagate a probabilistic model for uncertainty analysis

**Rock Type Prediction**
- Facies cube
- Probability cube for facies related to higher fracability

**Input data**
- Pre-stack

**Reconstruction rates (%)**
- 70
- 75
- 85
- 92
- 93

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Shale Modeling, Analysis & Performance

Build an accurate earth model that integrates seismic, lithological, stratigraphic, petrophysical and mechanical properties

- Constrained structural and stratigraphic model
- Integrated structural and facies modeling in chrono-stratigraphic space

- Geomechanical simulations
- Link to geomechanical simulator for complex faulted stratigraphic grids and solid models

- Integrate time dependent information
- Microseismic, production, tracer data to optimize well spacing and completion
Integrate Time-dependent Data

Microseismicity

- From an integrated perspective:
  - Seismic attributes
  - Seismic Interpretations
  - Microseismicity data and tracers
  - Petrophysical data
  - Geological data
  - Cultural Data, ...
- Assess effectiveness of treatment
- Stimulated rock volume
- Optimize well spacing
- Control Forecast Production

Microseismic Stimulated Volume with fracture paths derived from microseismic data.
Paradigm Shale Technology Investment

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Global Experience In Shale Plays

Understanding asset analogs

<table>
<thead>
<tr>
<th>Global Exposure</th>
<th>Project Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eagle Ford, US</td>
<td>Full azimuth diffraction imaging for missing faults</td>
</tr>
<tr>
<td>Barnett Shale, US</td>
<td>Full azimuth fracture characterization</td>
</tr>
<tr>
<td>Permian Basin, US</td>
<td>Structural Imaging and Framework</td>
</tr>
<tr>
<td>Haynesville Shale, US</td>
<td>Sweet spot identification</td>
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<tr>
<td>Marcellus and Utica, US</td>
<td>Facies Classification and Lithofacies Prediction</td>
</tr>
<tr>
<td>Bakken Shale, US</td>
<td>Precision Depthing for well planning and Geosteering</td>
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<tr>
<td>Montney Shale, Canada</td>
<td>Production decline analysis</td>
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<tr>
<td>Vaca Muerta, Argentina</td>
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<tr>
<td>Baltic Basin, Poland</td>
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<tr>
<td>Northwest China</td>
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<td>NW Kuwait Shale</td>
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<th>Operator</th>
<th>Shale Play</th>
<th>Technology</th>
<th>Outcome</th>
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<tr>
<td>US Small Independent</td>
<td>Eagle Ford</td>
<td>Full azimuth imaging and characterization</td>
<td>Fracture Density attribute found to be highly correlated to gas production</td>
</tr>
<tr>
<td>US Large Independent</td>
<td>Eagle Ford</td>
<td>Geologic Modeling with Full azimuth imaging</td>
<td>Developed a repeatable workflow for integration of the geophysical and geologic models. Seismic data used for planning and landing of wells.</td>
</tr>
<tr>
<td>NOC</td>
<td>Vaca Muerta</td>
<td>Full azimuth imaging and characterization; Geolog Formation Evaluation</td>
<td>Established a seismic imaging and Formation Evaluation workflow that increased drilling success 40%</td>
</tr>
<tr>
<td>NOC</td>
<td>Middle East Shale</td>
<td>Full azimuth imaging and characterization</td>
<td>Drilling engineers found a direct correlation of fracture intensity and overpressure. Attribute used for mud weight planning.</td>
</tr>
</tbody>
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## Project Impact

### Experience in problem solving

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<tr>
<td>Service Company + NOC</td>
<td>Baltic Basin, Poland</td>
<td>Geolog Deterministic Petrophysics and Image Log Analysis: Full azimuth imaging and characterization</td>
<td>Developed an integrated set of fracture &amp; elastic property deliverables calibrated to borehole image logs and dipole sonics. The attribute was used for sweet spot identification and well geologic targeting</td>
</tr>
<tr>
<td>US Small Independent</td>
<td>Permian Basin</td>
<td>Integrated G/G/P Geolog Geosteer workflow</td>
<td>MWD and 3D seismic model used to properly place laterals in target zone, reducing well cycle time</td>
</tr>
<tr>
<td>US Small Independent</td>
<td>Permian Basin</td>
<td>Reservoir Driven Production Data Optimization workflow – Paradigm Seismic Data Analysis; Geolog Well Data Analysis, SKUA Reservoir Modeling</td>
<td>New reservoir model with new reservoir intelligence, recommendations on fault blocks, traps, compartments, fault transmissivity, and water flooding. Model to select infill locations, extract sector models for EOR pilots, and perform waterflood surveillance.</td>
</tr>
</tbody>
</table>
Thank You