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Optimized Shale Resource Development using proper placement of Wells and Hydraulic Fracture Stages

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Outline

• Illustration of the Prize
• Present trend in Unconventional Reservoir Modeling and it’s impact on production
• Challenges the industry face to enhance recovery factor while reducing cost per unit of hydrocarbon recovered
• Where should the future engineers focus?
  – What technologies are there and what are needed in the near future to optimally place wells for the enhanced recovery
  – What technologies are there and what the industry needs in the near future to decide the optimum placement of the hydraulic fracture stages
• Illustrative field examples and the recommended way forward
Unconventional Gas Resource: A Global Phenomenon

Over 44,300 TCF
Gas in place resources

Source: Baker Hughes, EIA, SPE 68755,
Kawata & Fujita from Rogner

Pie size to scale

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Unconventional Oil Resources 2-3 Trillion Barrels

**Key Regions and Reserves:****

- **Russia Bazhenov Shale**
  - WSB 1,600 BBO
- **Permian, Mississippian**
  - 9 BBO
- **Utica, Eagle Ford, Barnett, 15 BBO**
- **Bakken 24 BBO, Niobrara 3 BBO**
- **Argentina Neuquén Basin 23 BBO**
- **Canada Cardium**
- **Europe 100 BBO**
- **China**
- **Australia**
- **MENA**
- **South Africa**
- **Basin**

*Sources: Oil Shales of the World: Their Origin, Occurrence and Exploitation by Paul L. Russel and UNITAR Heavy Oil and Oil Sands Database, 2010; Energy Information Administration, World Shale Gas Resources, 2011; and Hart Energy*
Unconventional Development – Learning Curve
Barnett Shale Development

- Horizontal
- Vertical
- Directional

Maximum gas 6 mo. production (MCF)

- Small energized fracs
- Crosslinked massive hyd. fracs
- First horizontal well
- Slickwater
- μ–seismic
- Multistage Completions

Date
Jan-81 Jan-83 Jan-85 Jan-87 Jan-89 Jan-91 Jan-93 Jan-95 Jan-97 Jan-99 Jan-01 Jan-03 Jan-05 Jan-07 Jan-09 Jan-11 Jan-13
Unconventional Development – Learning Curve
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A Closer Look at the “Shale Revolution”

70% of unconventional wells in the U.S. do not reach their production targets*

60% of all fracture stages are ineffective**

73% of operators say they do not know enough about the subsurface*

**Source: Hart’s E&P, 2012

**Efficiency and Effectiveness are key for Proper Placement of Well and Frac Stage in Sweet Spots**
• Identify sweet spots

• Predict performance /EUR

• Where to place wells: Well placement, spacing, drainage area, lateral orientation, and length

• Which Method of completion: Open hole, cased hole,

• Optimal Stimulation design: Stage placement, number of stages, fluid, proppant, volume

• Production management: Flowback, managed rate of production
Low Cost vs Cost Efficient Development: Implications?
Unconventional Workflow: How is it Different?

Seismic data → Structural modeling → Geological model → Lithofacies model → Geomechanical model → Frac model & Microseismic

Regional → Detailed → Scenario’s

Economics

Flow Simulation

Frac optimization model

JewelSuite™
Moving from Conventional To Shales

Conventional
- Porosity
- Saturations
- Permeability
- Resource Base
- Reservoir Pressure

Shales
- Reservoir Pressure
- TOC
- Ro (Vitrinite Reflectance) / TM
- Permeability / NF
- Brittleness

Black Shale
3.5% TOC (avg)
0.83% Ro (avg)
Technology Evolution and Production
Selected Unconventional Gas Basins, Onshore U.S.

**Horizontal Gas Stages Per Well and Average Lateral Length.**

- **Source:** BHI, HPDI, IHS, Company data

**Horizontal Gas Well Average**

- **Source:** HPDI
Three Key Elements To Avoid Sharp Production Decline

Hydraulic Fracture Model
- Single well treatment
- Fracture grid representation
- Geometries and properties

Reservoir Fracture Grids
- Multiple wells and stages
- Fracture refinement
- Various scenarios

Reservoir Flow Model
- Fit-for-purpose flow simulator
- Dec curves
- Drainage Scenarios

STIMULATION PERFORMANCE: REDUCE THE SHARP PRODUCTION DECLINE
Shale Reservoir Analysis

• Conventional reservoir modeling & analyses not effective for shale

• Shale reservoirs require new approaches to Analysis & Forecast

• An integrated “shale engineering” approach is required to plan wells, stimulate & forecast long-term production for economic evaluations

• SWEET SPOTS: Well and Frac Stage Locations
What is a “Sweet Spot”? 

- The “Sweet Spot” is where the maximum power is generated with the least amount of effort and vibration.
- The Sweet Spot is important in these sports because we don’t all have perfect swings.
- What does this have to do with unconventional resources?
Unconventional Resources Sweet Spot Characteristics

A “Sweet Spot” or “Core” represents the concurrence of several favorable parameters such as:

- TOC
- Kerogen Type
- Fluid
- Thermal Maturity
- Depositional Environment (Litho-facies)
- Depth
- Thickness
- Lithology/Mineralogy
- Porosity
- Pressure
- (Continued Producibility)

- Anisotropy
- Stress Regime
- Fractures
- Faulting
- Brittleness (Fracturability)

Sweet Spots are not Contiguous
Can we Identify Optimal Areas For Reservoir Stimulation Before Drilling and Frac’ing?
Attribute Analysis + Lithofacies = Sweet Spot Identification

Location of LPLD events are correlative with amplitude anomalies
Multi-Attribute Prediction of TOC (WPCTOC)

Hampson & Russell
Haynesville Case Study

MAXIMUM VALUE IN HSVL

Courtesy of CGG and BHI Alliance
Locating Areas of High TOC in Seismic Volume

Volumetric View of TOC with well penetrations

Multiple uneconomic wells

Several TOC rich areas yet to be exploited

Courtesy of CGG and BHI Alliance
TOC (Total Organic Content) Vs. Acoustic Impedance

Lower Acoustic Impedance = Higher TOC and Natural Fractures

Pictured here (from top), near stack seismic section, Acoustic Impedance section and TOC section through the northern calibration well. The red arrows point at the top of the Spekk Formation and the black arrows point at the base. In the middle Acoustic Impedance section, the acoustic impedance is lower within the Spekk Formation than in adjacent strata, apart from in the shallowest part where the low impedances are due to the shallow depth and not due to organic content. A trend from very low acoustic impedances in the upper part (blue colors) to higher acoustic impedances further down (red and pink colors) is clearly seen within the Spekk Formation. TCC content greater than 6 percent TOC is highlighted in bright colors in the lower figure.

Graphics courtesy of Statoil Research Center

Source: AAPG Explorer. Dec 2009
Vertical Pilot Well: The start

TOC, Vitrinite Reflectance Ro, Thermal Maturity, Porosity, K, P, Natural fractures, faults, karsts, hazards
Moving from Pilot wells to development wells

Reservoir Navigation Services - RNS
(Azimuthal Resistivity & Gamma Images)
Armstrong Co., Pennsylvania – Marcellus Case History

Target for Lateral
High TOC = only 15ft Thick

Well Trajectory Planned
- Seismic
- Shale Analysis
- Offset Well Data

Monitored LWD GR
- Up and Down
- To determine if well approaching formation top or bottom / correct

Follow the high TOC, Ro, BI and Pp path
Evaluating the Resource and Production Potential

<table>
<thead>
<tr>
<th>Resistivity / Density / Neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Formation Lithology</strong></td>
</tr>
<tr>
<td>Spectroscopy</td>
</tr>
<tr>
<td>Micro-seismic</td>
</tr>
<tr>
<td>Imaging</td>
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<tr>
<td>Large Diameter Coring</td>
</tr>
<tr>
<td>Deep Reading Shear Acoustic</td>
</tr>
<tr>
<td>Nuclear Magnetic Resonance</td>
</tr>
</tbody>
</table>

- Geochemistry
- Lithology
- Mineralogy
- Total organic carbon

- Lithology
- Mineralogy
- Th/U for Carbon classification
- Image correlation with lithology and facies
- Fracture detection
- Core analyses
- Geomechanical properties from Wellbore and away from wellbore

Logging and Core analyses can identify:
- Formation with producible source rock hydrocarbon
- Optimum formations to drill horizontal laterals
  - Optimal placement of frac stages
  - Potential barriers for frac containment
- Mineralogy key component integrated with Geomechanics
Mineralogy Varies in Shale Reservoirs

| Montney | Haynesville | Eagle Ford | Marcellus | Barnett |

| Mineralogy | Lille | Smectite | Kaolinite | Chlorite | Glauconite | Apatite | Zeolite | Anhydrite | Silt | Hematite | Pyrite | Organic C | Siderite | Dolomite | Calcite | K-feldspar | Plagioclase | Quartz |
|-----------|------|---------|----------|---------|-----------|---------|--------|-----------|------|----------|-------|-----------|---------|----------|---------|----------|----------|-----------|--------|
Wellbore Imaging: Fractures, Faults & Geohazards

WBM Imager

Acquire high-resolution resistivity formation images in oil-based mud system.

OBM Imager

Acquire high-resolution microresistivity images in oil-based mud system.
Avoiding fault zone: don’t frac into water below target horizon

Targeting natural fracture swarms maximizes impact of the frac energy

Avoiding fracture swarms from adjacent wells frac job

Targeting natural fracture swarms maximizes impact of the frac energy

Eliminate nonproductive stages

Case Histories Show Production Increases above 20% and above 10% in EUR
Deep Shear Wave Imaging (up to 70m away)

- **Methodology**
  - Filtering direct waves
  - Reflected wave stacking
  - Reflector strike inversion
  - Fullwave data migration

- **Benefits**
  - Illuminate natural fractures up to 70 m away.
  - Identify mechanical strata
  - Placing laterals
The Next 5-10 Years
~100,000 Wells, 1-2 Million Hydrofracs

How Do We Optimize Resource Development?
How Do We Optimize Resource Development?
Production from Nano-Darcy Rocks?

- Shale Resource has typically permeability in the nano-Darcy range
- Gas / hydrocarbon may move in order of few feet in a year!!
- What mechanism is there then to produce hydrocarbon from such low permeability rocks?
- Creation of a stimulated reservoir volume that has both longitudinal and shear fractures
From **Natural** Shale to the **Artificial** Reservoir

**Benefits**

- Enhancing reservoir understanding
- Exploiting modern technology
Shale Engineering Predictive Model
Matched production history and production logging

- Frac stage contribution match
- Proppant placement match
- Well History match

Narrow Uncertainty
NPV Vs. Transverse Fractures

NPV = DWR - CF (10^6$)

Number of Transverse Fractures

NPV = DWR - CF (10^6$)

Number of Transverse Fractures

1 year

2 years

3 years

4 years

5 years

6 years

7 years

8 years

9 years

10 years

15 years

20 years

30 years

40 years

0 10 20 30 40 50 60 70 80 90 100

Number of Transverse Fractures

-2 0 2 4 6 8 10 12 14

NPV = DWR - CF (10^6$)
Ball Activated Sleeve Open / Close Completion System

Varying Ball Sizes

Ball with Frac Sleeve Open

Frac Sleeve in Closed Position

Lighter than AL / Stronger than Steel
Extend and orientation of fractures created

This type of information allows engineers to optimize the fracturing staging and to optimize the placement of additional wells.
Relating stage contributions to production: Impact on Field Development Plan

Rates measured by PLT 5 months later
Fracture Mechanics Based Model

\[ \sigma_h = \sigma_H, \text{ NF 100 EW (90°)} \]

\[ \sigma_h = \sigma_H, \text{ NF 100 NS (45°)} \]

\[ \sigma_h = \sigma_H, \text{ NF 100 NS (0°)} \]
Integrated Display

- Well Logs
- Layers
- Fracture Model
- Events
- Real-Time “SRV”
Concluding Remarks

• Shale resource is not contiguous and no two Shale basins are the same
  – Sweet spot identification is going to be critical (seismic attribute + Lithofacies) for well placement
  – Different shales will require different set of attributes and the associated lithofacies

• Geometric placement of hydraulic fracture stages needs to be replaced by shale productivity based parameters
  – Capitalize on the presence of natural fractures at the well bore as well as away from the wellbore
  – Avoid faults and geohazards
Shale Technology: A Look Ahead

- Nanotechnology: An Enabler for Multiple Oil & Gas Applications

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