Abstract

Recently introduced azimuthal LWD measurements combined with well-site measurement of parameters on drill cuttings have proven to be a game changer in the quest for improved productivity in laterals drilled in shale reservoirs. While Pyrolysis, XRF, and XRD measurements on drill cuttings at the well site provide mineralogical and organic content information in near real-time, of particular interest are the LWD Azimuthal Spectral Gamma Ray and the LWD Azimuthal Sonic devices, both of which gather data in sixteen azimuthally-fixed bins. The LWD Azimuthal Spectral Gamma Ray furnishes clay types and identifies zones with high TOC based on the response of the uranium measurement.

A unipole configuration with a single, directionally focused transmitter and one array of six directional receivers that are azimuthally aligned with the transmitter is used in the LWD Azimuthal Sonic device. The azimuthally focused sensors can differentiate the slowness of the refracted compressional and shear waves emanating from different azimuthal directions around the borehole. The sonic waveforms received in 16 azimuthally fixed-orientation bins are processed to yield 16 independent, azimuthally oriented compressional and refracted shear slowness curves, which in turn, combined with the LWD density, provide 16 curves of Young’s Modulus, Poisson’s Ratio and rock Brittleness Index, each of which can also be used to generate the corresponding 360° borehole image along the length of the lateral.

The combination of mineralogy, abundance of organic material and accurate brittleness coefficient along the length of the lateral is often sufficient to define the sweet spots that exhibit enhanced reservoir properties and are amenable to stimulation and fracturing. The LWD Azimuthal Sonic in horizontal wells provides compressional and shear slowness in the vertical and horizontal directions, and as is common in anisotropic shale reservoirs, the shear velocity in the horizontal plane is often greater than that in the vertical plane. Combined with the cross-dipole measurements in a vertical well, an accurate orthorhombic velocity model may be generated. This will lead to greater precision in tracing the topography of the shale pay on the seismic section and hence lead to more precise definition of the well trajectory. This will facilitate in confining the well path to the targeted pay zone. Not the least of the benefits of determining the shear anisotropy is that it could be factored into the stimulation design to achieve more effective hydraulic fracturing.
Selected References


Shale Reservoirs: Improved Production from Stimulation of Sweet Spots

Khaled H. Hashmy, Weatherford Petroleum Consulting, Houston, TX
Ashok Bhatnagar, Weatherford Petroleum Consulting, Houston, TX

AAPG/STGS Eagle Ford plus Adjacent Plays & Extensions Workshop
24-26 February 2014 | San Antonio, Texas
Completion Methods

1. Frac Stages are often placed at arbitrary spacings along the Lateral WITHOUT considering the variations in rock and reservoir properties.
2. Safety, cost and time considerations sometimes impel operators to minimize studies in laterals
SELECTING THE STIMULATION INTERVALS IS THE KEY

STUDIES HAVE SHOWN THAT:

1. UPTO 21% OF PERFORATION CLUSTERS ARE NOT CONTRIBUTING
2. 30% TO 43% OF THE PERFORATION CLUSTERS CONTRIBUTE LESS THAN 1% OF TOTAL PRODUCTION
3. ONE OF THE PROBABLE CAUSES COULD BE PLACEMENT OF PERFORATION CLUSTERS IN ZONES WITH POOR RESERVOIR QUALITIES
Sweet Spot: Identification Methods

- Measurements on Drilling Fluids and Rock Cuttings offer Approach for Sweet Spot Identification
  - **Advanced Mud Gas Extraction/Detection**
  - **Cuttings Analysis**
    - X-Ray Fluorescence, X-Ray Diffraction & Pyrolysis
      1. In Pilot Holes
      2. In Laterals

- Logging While Drilling
- Wireline Logging
- Seismic
Quad-Combo for Sweet Spots

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>GR (GAPI)</th>
<th>FORCITY</th>
<th>SONIC</th>
<th>RESISTIVITY</th>
<th>TOC</th>
<th>ROCK</th>
<th>PERMEABILITY</th>
<th>PROD-LOG</th>
<th>MUDLOG</th>
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</table>
GC TRACER FOR SWEET SPOTS
Advanced Mud Gas Measurement

- Critical fluid properties can be predicted directly from mud gas sample
- Need good calibration data set and good mathematical models

Delineates top and bottom of the reservoir
Identifies changes in fluid type
Can optimize downhole fluid sampling

Tonner et al., AAPG ICE 2012
GC Tracer to Detect and Identify Hydrocarbon Zones

Track 4: Increased Total Hydrocarbon

Track 5: Separation C1 and Balance Ratio

Track 6: Increased Gas to Liquids Ratio

Track 7: Crossover HC and ARO/ALK
Total Hydrocarbon Content (THC%) identifies the Zones of Interest which results in increased efficiency during completions planning.

Fluid indicators (C1%, C1/C2, HC & ARO/ALK & Wetness/Balance) help in characterizing the Hydrocarbon fluid type.

Gas components & ratios also provides an insight into the petrophysical properties (Porosity & Permeability).

Fluid saturation differentiates between a Hydrocarbon saturated & Water Saturated.
WELLSITE ANALYSIS OF DRILL CUTTINGS

XRD, XRF AND PYROLYSIS MEASUREMENTS ON DRILL CUTTINGS IN NEAR REAL TIME
1. Commence with XRD/XRF and Pyrolysis on Pilot vertical holes and laterals.
2. Establish proxies for TOC with Trace Elements.
3. Resolve Mineralogy from the elemental data set.
4. As uncertainty is reduced move to XRF only.
XRF Elemental Composition at Wellsite

Benchtop when compared to hand held device provided greater range of elements and superior accuracy and precision

- XRF measures 10-12 Major Elements (oxide wt.%)
  - SiO₂ TiO₂ Al₂O₃ Fe₂O₃ MnO MgO CaO Na₂O
  - K₂O P₂O₅ (plus S and Cl for most lithologies)

- XRF measures 18 Trace Elements (ppm)
  - V Cr Co Ni Zn Ga As Br Rb Sr Y Zr Nb
  - Mo Ba Hf Th U

- Many minerals show considerable variability in their elemental composition, particularly with regard to trace elements.

Tonner et al., AAPG ICE 2012
XRF On Cuttings Compared To Elemental Capture Tool on Wireline

![Diagram showing elemental analysis data across various units and packages]
Pilot well: XRF COMBINED with Enhanced Gas Measurements
Identify the “Sweet Spot”

<table>
<thead>
<tr>
<th>XRF Chemostratigraphy / Mineralogy / Brittleness</th>
<th>GC-TRACER™ Gas Data</th>
</tr>
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<tbody>
<tr>
<td>Depth (m)</td>
<td>Elemental Units</td>
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<tr>
<td>1200-1500</td>
<td>Unit 2</td>
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<td>Unit 3</td>
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<td>1200-2500</td>
<td>Unit 4</td>
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Proxy for TOC
Total HC
Heavy Oil
Light Oil Condensate
Dry Gas

- Excellent agreement between elemental-derived TOC and gas-derived total hydrocarbons

Hashmy et al., 2012
Wellbore maintained +/- 10 feet above target in dipping beds
XRF Defines Target Zone

150 Foot Refined Target Interval
Customized Frac Treatments for Specific Rock Types

Cocktail A
- 600’ of Lateral
- 17% of The Lateral

Cocktail B
- 2000’ of Lateral
- 57% of The Lateral
- 1000 feet

Cocktail C
- 900’ of Lateral
- 26% of The Lateral

Abou-Sayed et al., 2011
LWD FOR SWEET SPOTS
Unipole configuration used with a single, directionally focused, transmitter and one array of six directional receivers which are azimuthally aligned with the transmitter.

X-Y Magnetometers track the azimuthal orientation as the drill string rotates. Differentiates P & S from different azimuthal directions.

Mickael, M.: (SPE 162175, 2012)
As the tool rotates, X- and Y-axis magnetometers track the orientation of the transducers.

Over a 30 second acquisition cycle, 210 azimuthally-oriented waveform sets are acquired and sorted into 16 azimuthal bins to facilitate analysis of shear wave anisotropy.

(Standard real-time DTC and DTS are available every 10 seconds.)
AZIMUTHAL SHEAR NOT SIGNIFICANTLY DISPERSSIVE:

- FREQUENCY DEPENDENT DISPERSSION CORRECTION NOT NEEDED
- BOREHOLE DEPENDENT DISPERSSION CORRECTION NOT NEEDED

CENTERING OF LWD AZIMUTHAL SONIC IN BOREHOLE IS NOT A PROBLEM AS FOR WIRELINE CROSSED DIPOLE DEVICE.
LIMITATIONS

- Shear measurement is only available when formation shear velocity is faster than the compressional velocity in the borehole fluid.
- High transmitter frequency results in fairly shallow depth of investigation.
ANISOTROPY FROM LWD AZIMUTHAL SONIC
AZIMUTHAL LWD SONIC, SPECTRAL GAMMA AND BULK DENSITY

- LWD AZIMUTHAL GR, DENSITY & UNIPOLE SONIC TRANSDUCERS SCAN 360° IN EACH DRILL STRING ROTATION
- MEASUREMENTS STORED IN 16 BINS
- SPECTRAL GR, DENSITY & UNIPOLE SONIC IMAGES GENERATED FOR THE LATERAL
Azimuthally Focused LWD Sonic

- Combined With Wireline Crossed-dipole Data from the Pilot Hole, the Azimuthal LWD Sonic Furnishes an Accurate 3-D Velocity Model for Compressional and Shear Waves
- This is Used to Correct and Upgrade the Seismic Interpretation and Helps in Establishing Seismic Attributes
SWEET SPOTS AND WELL TRAJECTORY ON SEISMIC SECTION

Max Tgas from mudlogs and initial oil production is related mainly to presence of faults and associated fractures (high-order geometries); high-resolution coherency is detecting mainly high-angle faults.
BENEFITS OF 16 AZIMUTHALLY FOCUSED MEASUREMENTS

a) 16 Radially spaced P & S Measurements and corresponding Images along the lateral

b) 16 Radially spaced E and $\mu$ computations and corresponding Images along the lateral

c) 16 Radially spaced computations of Brittleness and corresponding image along the lateral
360° Rock Properties Imaging

Young's Modulus
- Modulus of Elasticity
- Stress/Strain

Poisson's Ratio
- Lateral/Longitudinal Strain
- "Squish/Squash"

<table>
<thead>
<tr>
<th>Young's Modulus</th>
<th>Poissons Ratio</th>
<th>Brittleness Dynamic Image</th>
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<tr>
<td>Static Scale Image</td>
<td>0.14 - 0.393</td>
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Brittleness Dynamic Image

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<tr>
<th>Young's Modulus</th>
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<th>Brittleness Coefficient</th>
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<td>Static Scale Image</td>
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<td>AZL_LSDZBYRIT</td>
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LWD AZIMUTHTAL UNIPOLE ACOUSTIC SUMMARY

- Geomechanical data along lateral leads to cost savings through selective stimulation.

- Provides geological & petrophysical data for understanding factors controlling variation in rates from stage to stage.
Case Study

Technology Toolbox - 2008
Seismic - Missing the Target

Well Out of Target

1) Lateral planned entirely from pilot logs
2) No 3D seismic used for well planning
3) No LWD data or Geo-steering (logs run thru-casing @ TD)
4) Cuttings/gas indicated mostly in Middle EGFD
   = well 85% out of TARGET
Could not place proppant (note high Frac Gradient)

Heel
Could not frac most of lateral

Out of target
In target

Circles scaled to relative amount of proppant placed per stage (ranging from 70M# to 143M#)

Stage #1 120
Stage #2 143
Stage #3 143

Freidrichs lateral.jpg

Courtesy Hall, J. D.: Tight Oil - Eagle Ford 2011 conference in Houston, August 30, 2011
Improved Well Placement and Completion

Lessons Learned
1) Geo-steer all wells in-house (LWD Gr)
2) Integrate seismic for planning and steering
   = well in target zone for efficient stimulation

Circles scaled to relative amount of proppant placed per stage (ranging from 208 M# to 324 M#)

100% In target

TIGHT OIL
EAGLE FORD 2011

Courtesy Hall, J. D., Tight Oil - Eagle Ford 2011 Conference in Houston on August 30, 2011.
Conclusions

- **Hydraulic frac stage placement based on sweet spots will**
  - Eliminate fracking into poor reservoir intervals and concentrate on the Sweet Spots
  - Help in the design of proper frac parameters
  - Optimize frac efficiency and proppant placement.
  - Ultimately all of the above will lead to reduced completion cost
Many approaches for sweet spot identification are available to optimizing fracs.

- GC Tracer, XRF/XRD & Pyrolysis on cuttings offer a rapid, near real time approach for mineralogy and hydrocarbon identification.
- LWD Azimuthal SGR & Sonic provide real time data on TOC and Anisotropy.