Shale Reservoirs: Improved Production from Stimulation of Sweet Spots*

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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

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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

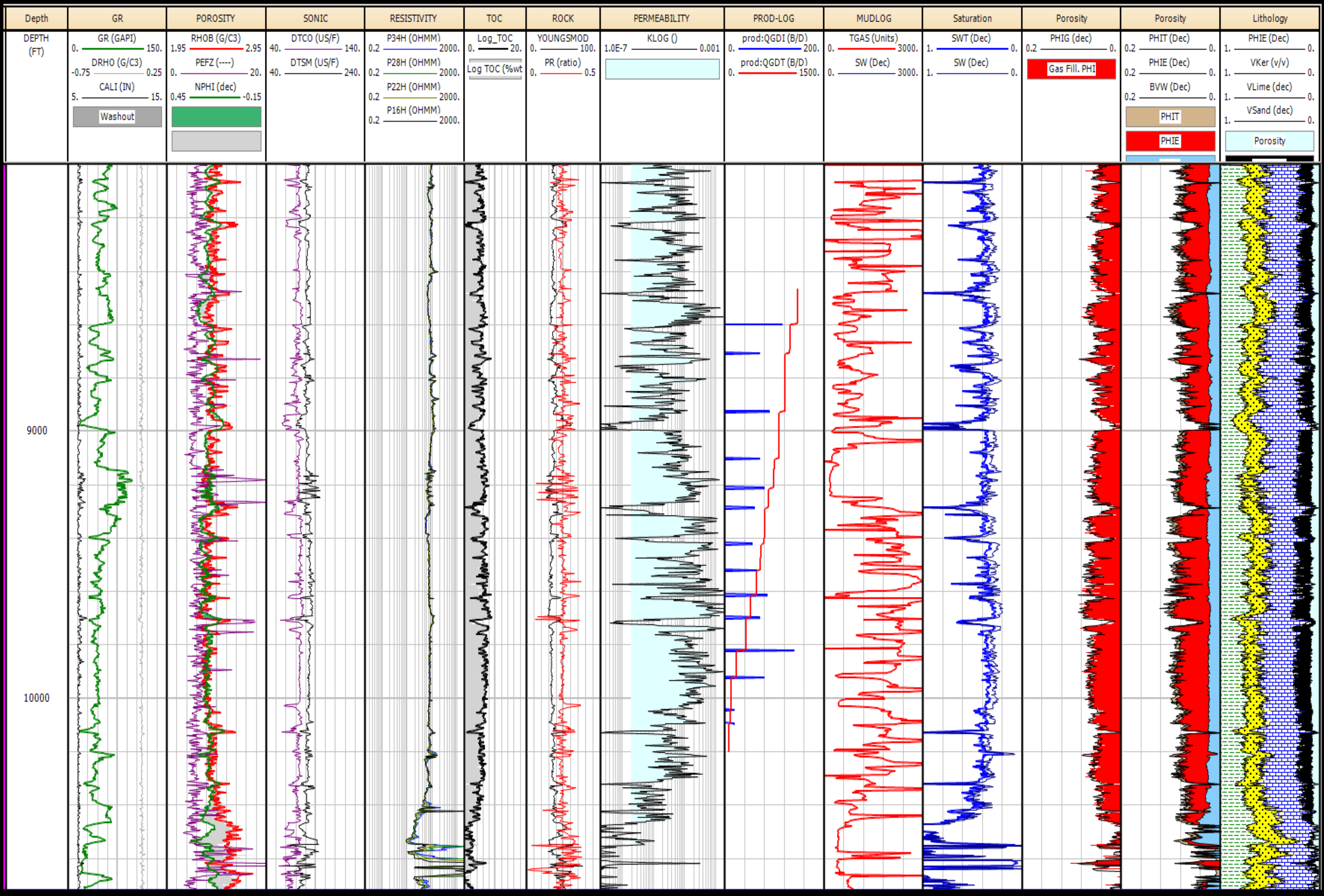
STUDIES HAVE SHOWN THAT:

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

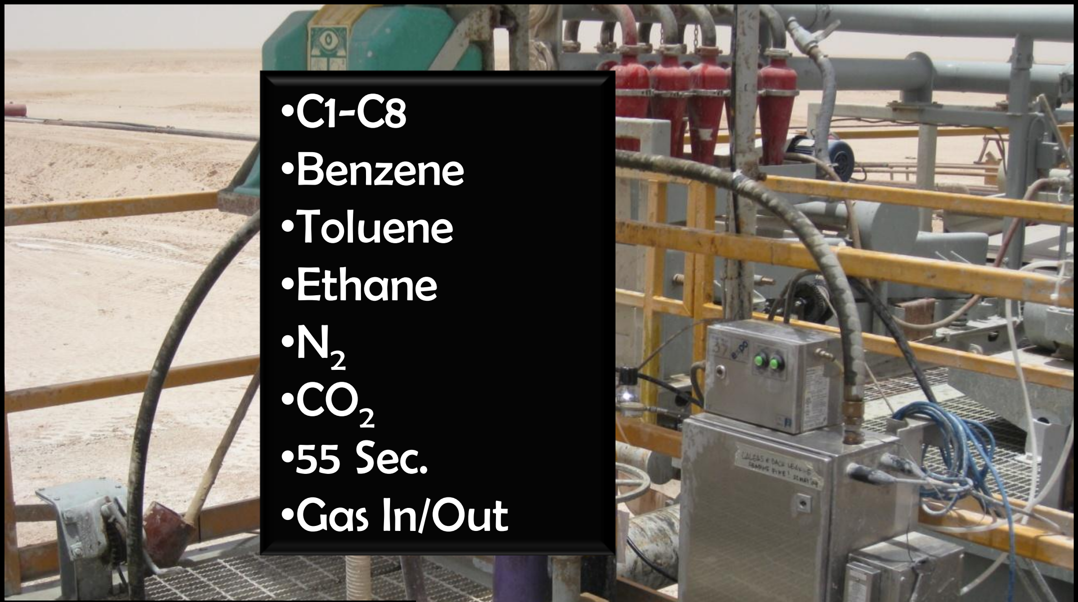
- Measurements on Drilling Fluids and Rock Cuttings offer Approach for Sweet Spot Identification
  - Advanced Mud Gas Extraction/Detection
  - Cuttings Analysis
    - X-Ray Fluorescence, X-Ray Diffraction & Pyrolysis
      1. In Pilot Holes
      2. In Laterals
- Logging While Drilling
- Wireline Logging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

Quad-Combo for Sweet Spots

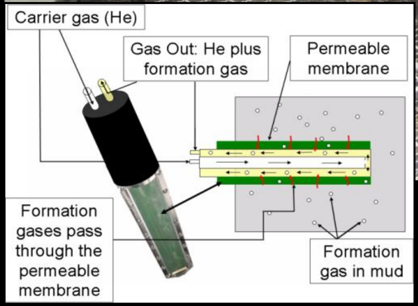


GC TRACER FOR SWEET SPOTS

Advanced Mud Gas Measurement



- C1-C8
- Benzene
- Toluene
- Ethane
- N_2
- CO_2
- 55 Sec.
- Gas In/Out



Delineates top and bottom of the reservoir

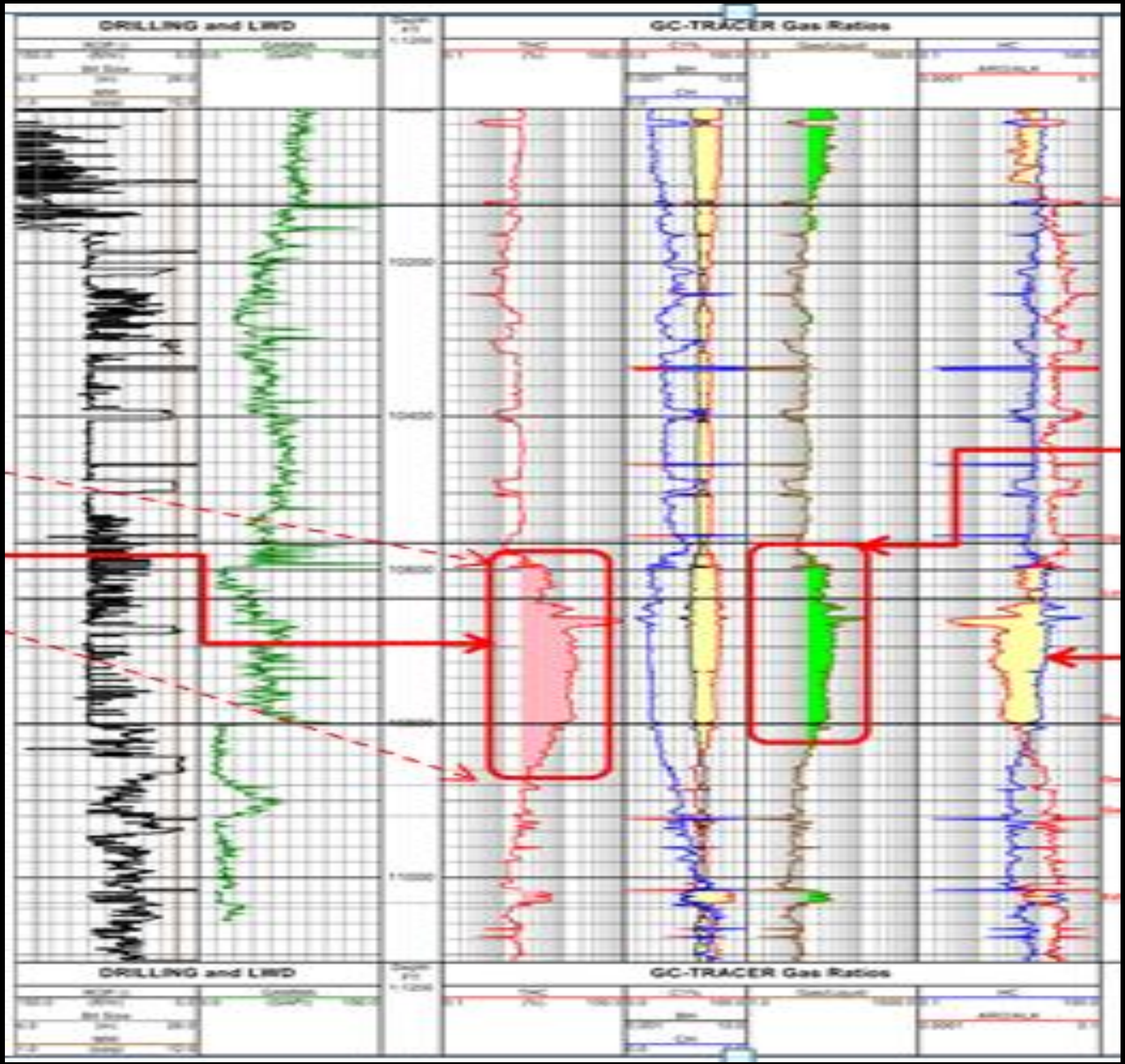
Identifies changes in fluid type

Can optimize downhole fluid sampling

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

Tonner *et al.,* AAPG ICE 2012

GC Tracer to Detect and Identify Hydrocarbon Zones



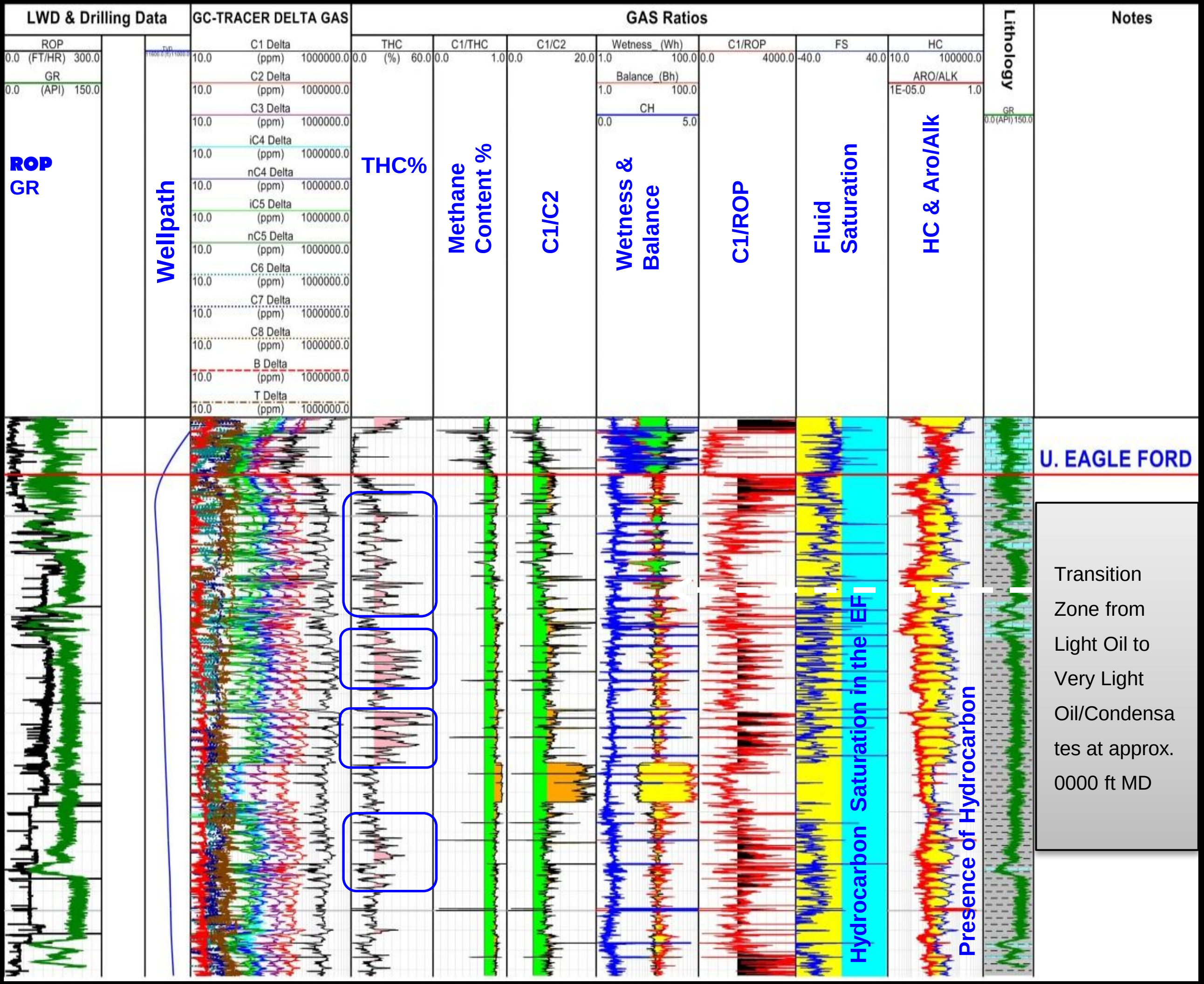
Track 4: Increased Total Hydrocarbon

Track 5: Separation C1 and Balance Ratio

Track 6: Increased Gas to Liquids Ratio

Track 7: Crossover HC and ARO/ALK

GC-TRACER™ Data Highlighting the Primary Zones of Interest in a Horizontal Section



- 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

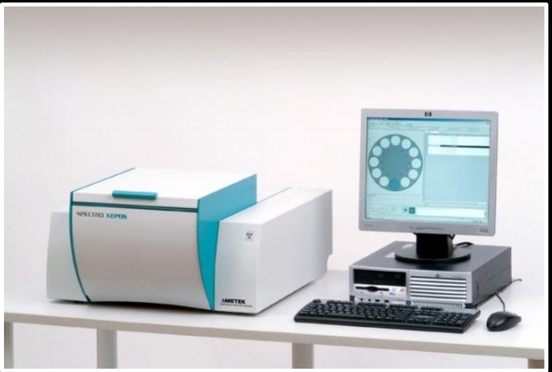
Wellsite Cutting Analysis Work Flow

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

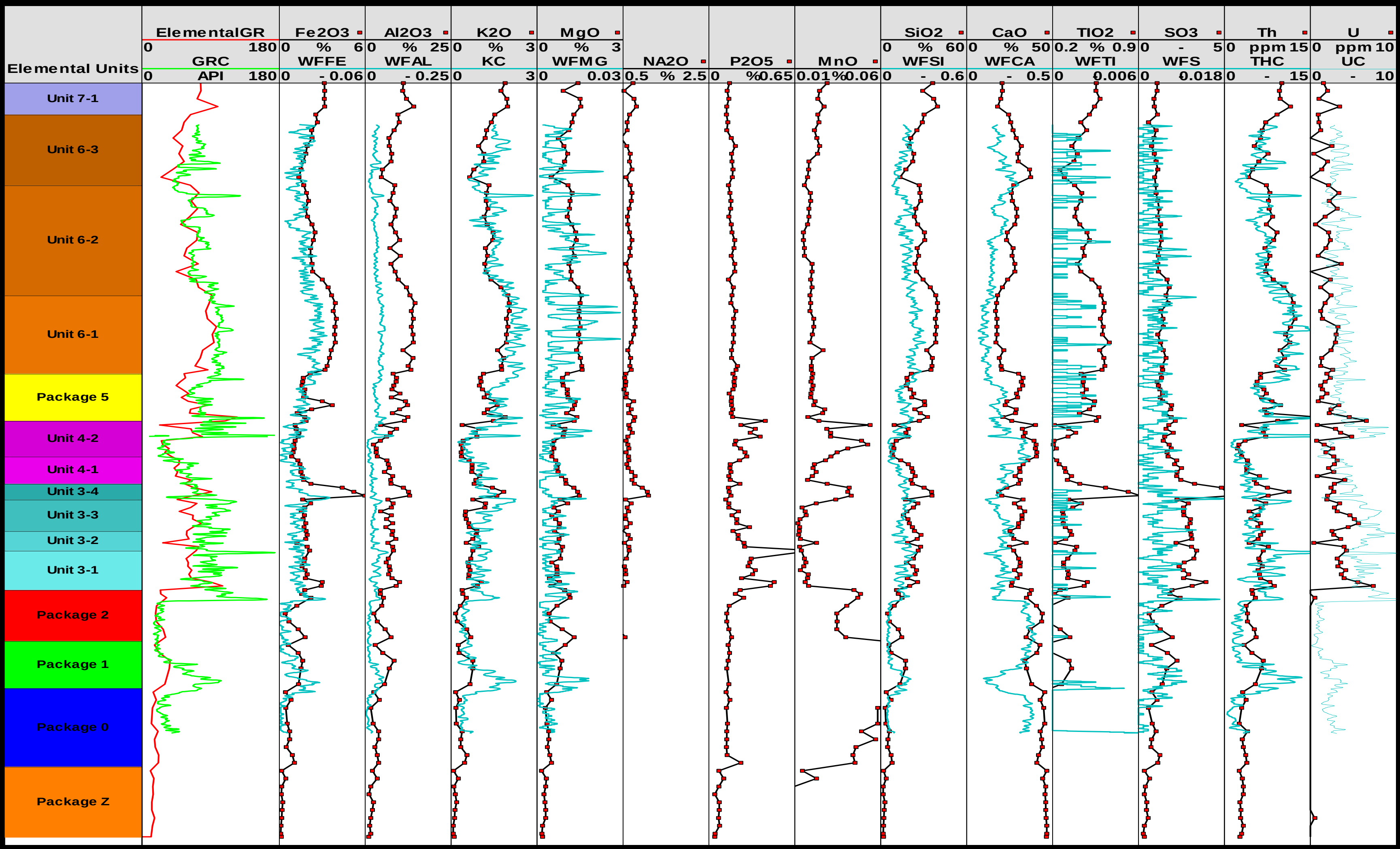
- XRF measures 10-12 Major Elements (oxide wt.%)
  SiO_2 TiO_2 Al_2O_3 Fe_2O_3 MnO MgO CaO Na_2O
  K_2O P_2O_5 (plus S and Cl for most lithologies)



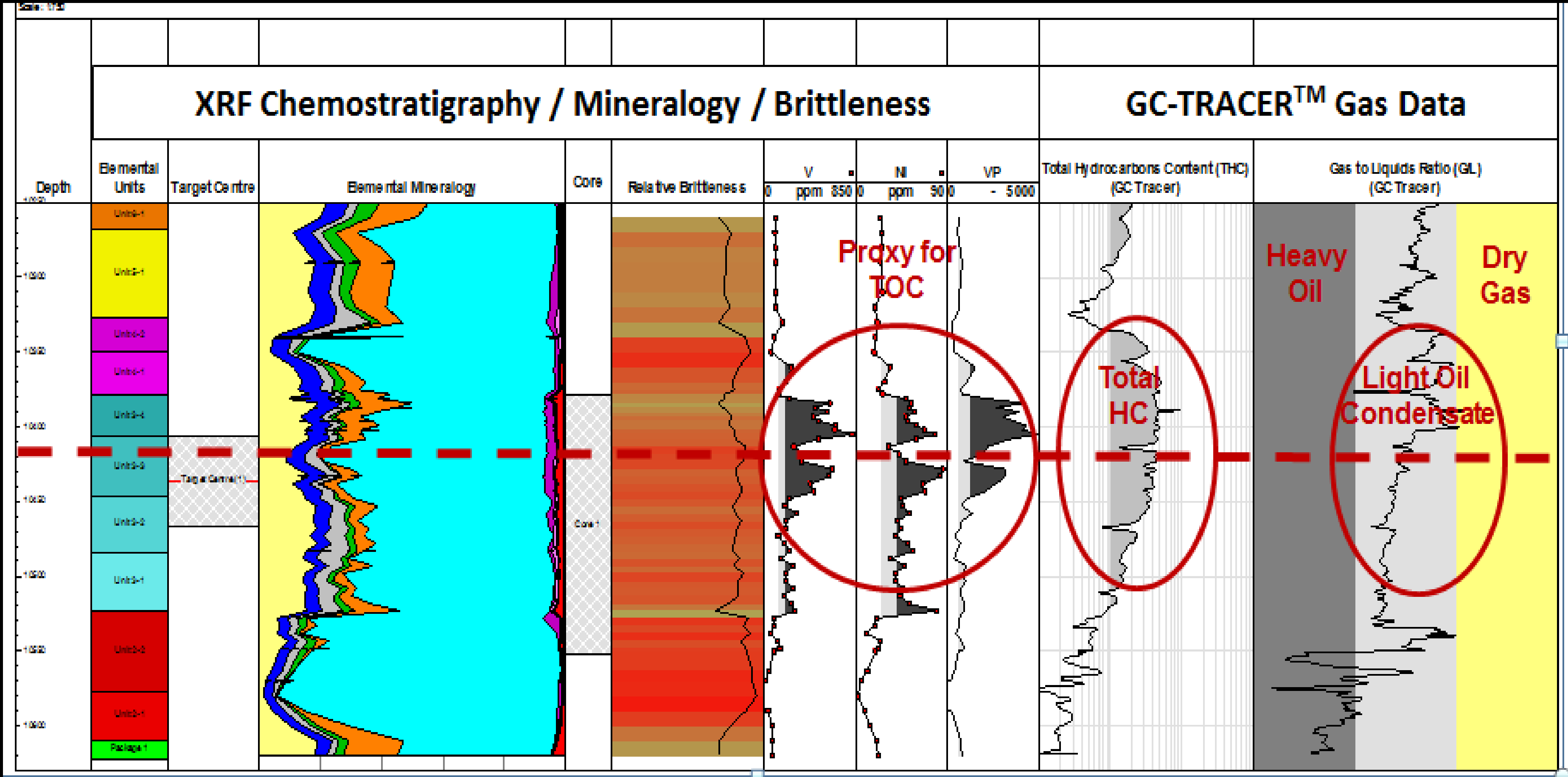
- XRF measures 18 Trace Elements (ppm)
  V Cr Co Ni Zn Ga As Br Rb Sr Y Zr Nb
  Mo Ba Hf Th U
- Many minerals show considerable variability in their elemental composition, particularly with regard to trace elements.

Tonner *et al.*, AAPG ICE 2012

XRF On Cuttings Compared To Elemental Capture Tool on Wireline



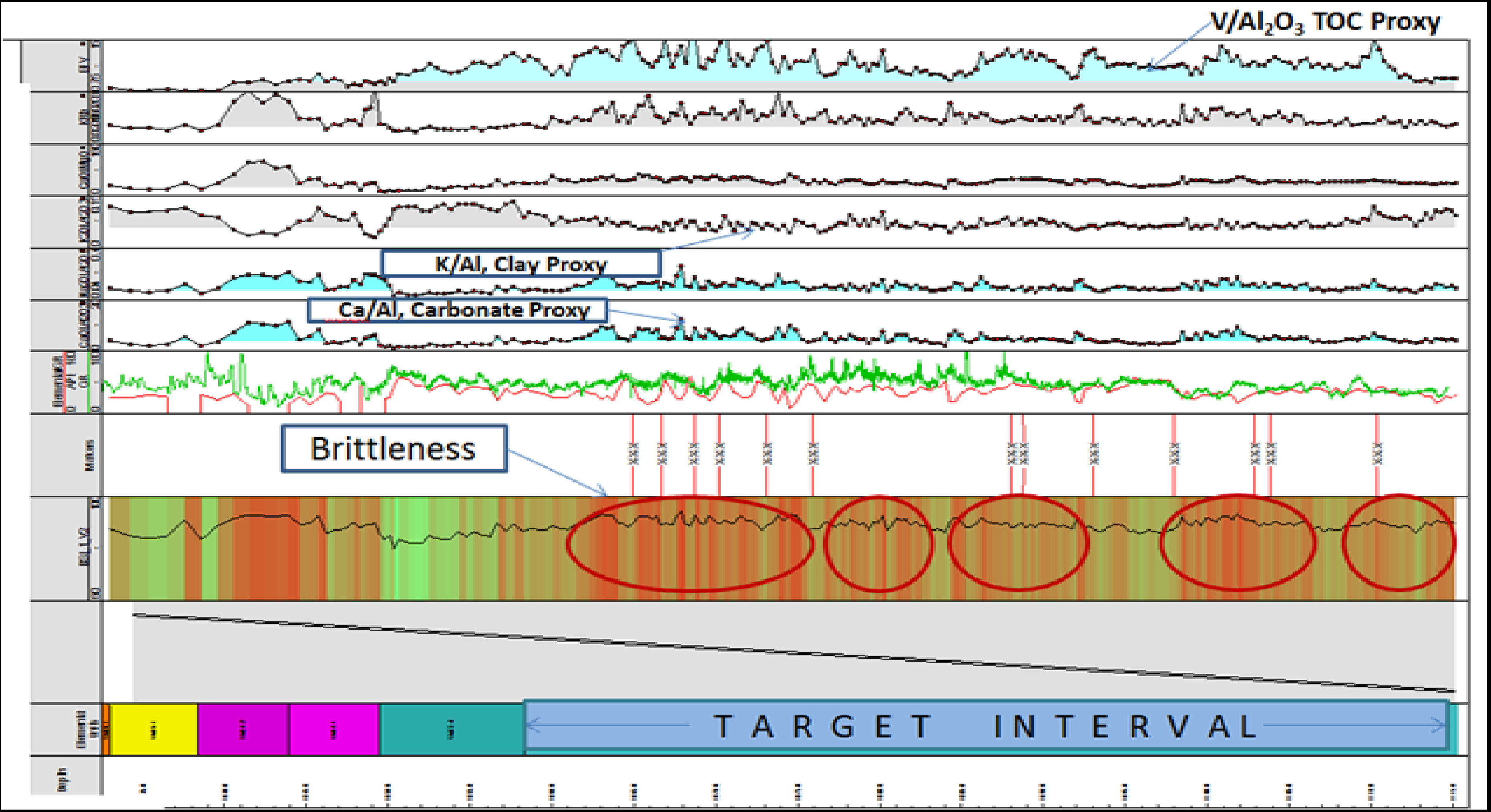
Pilot well: XRF COMBINED with Enhanced Gas Measurements Identify the "Sweet Spot"



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

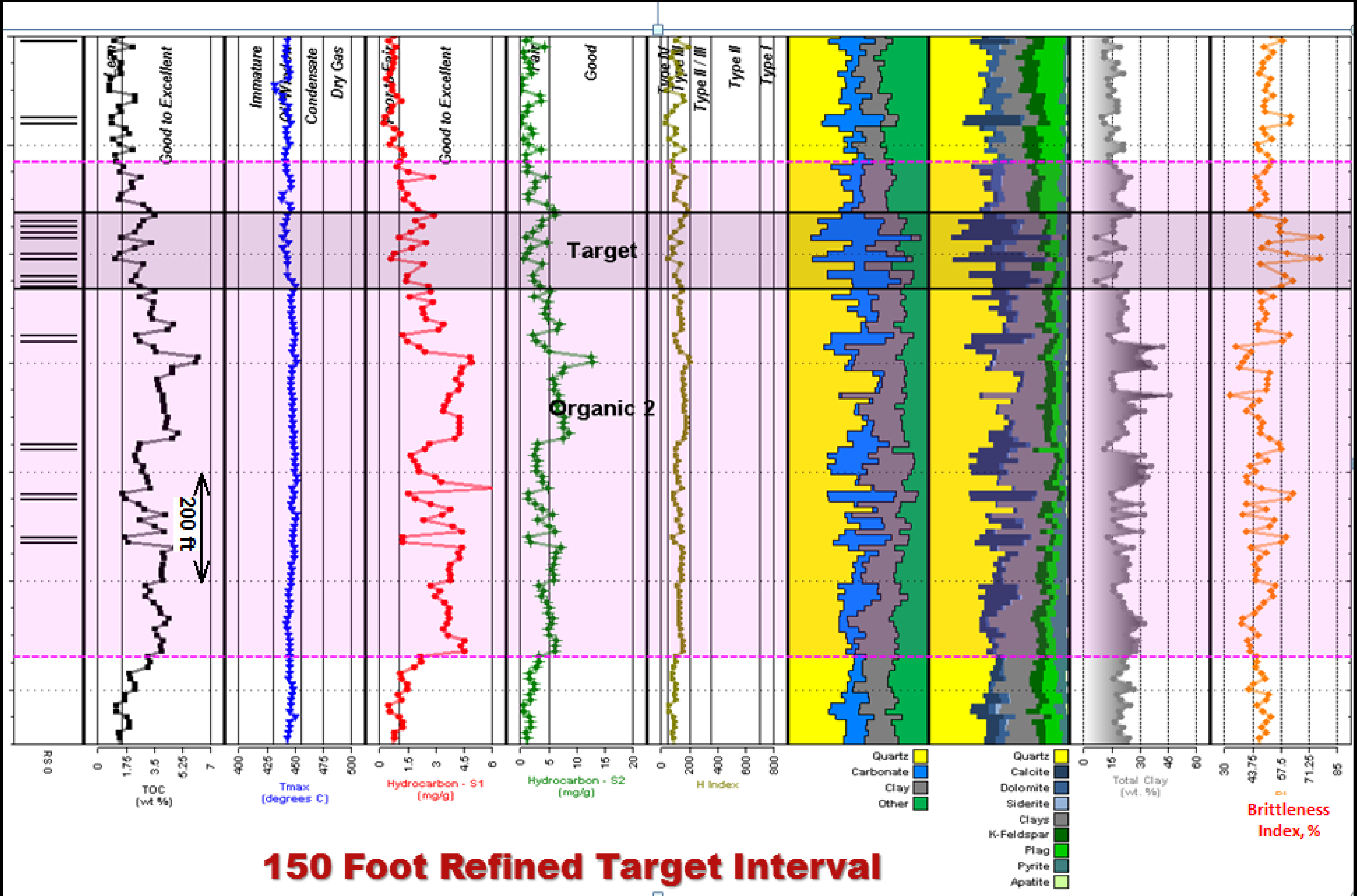
Hashmy *et al.*, 2012

Eagle Ford Lateral: Elemental Geosteering & Formation Evaluation



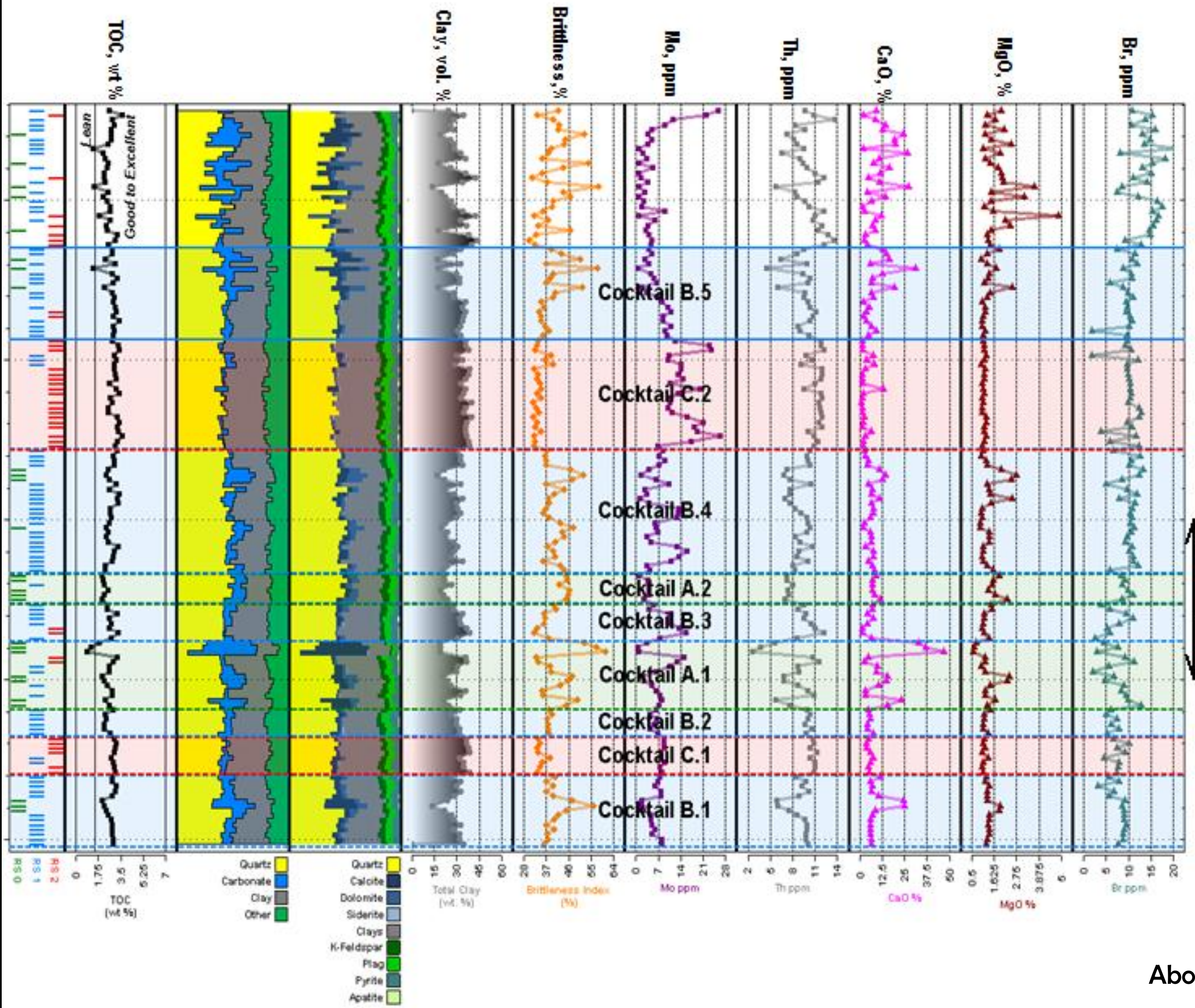
Wellbore maintained +/- 10 feet above target in dipping beds

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

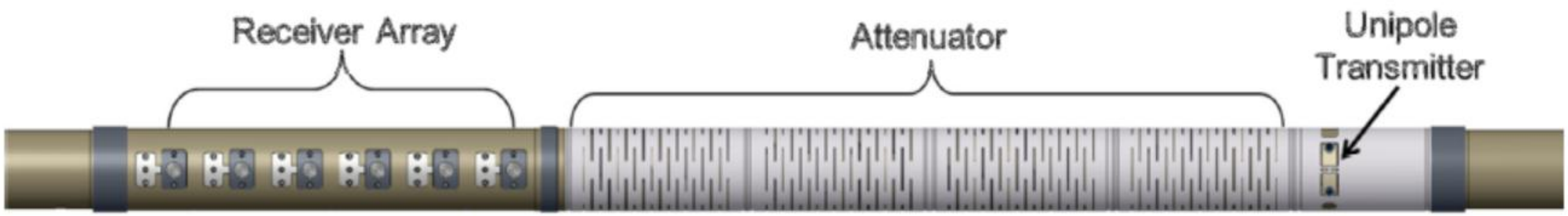
Cocktail C

- 900' of Lateral
- 26% of The Lateral

Abou-Sayed *et al.*, 2011

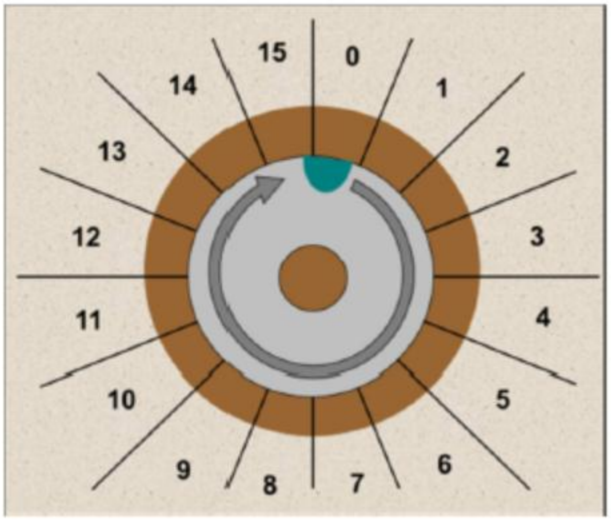
LWD FOR SWEET SPOTS

AZIMUTHALLY FOCUSSED UNIPOLE LWD SONIC



Configuration of the azimuthally focused LWD unipole sensor.

Unipole configuration used with a single, directionally focused, transmitter and one array of six directional receivers which are azimuthally aligned with the transmitter



Orientation of the 16 azimuthal bins.

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

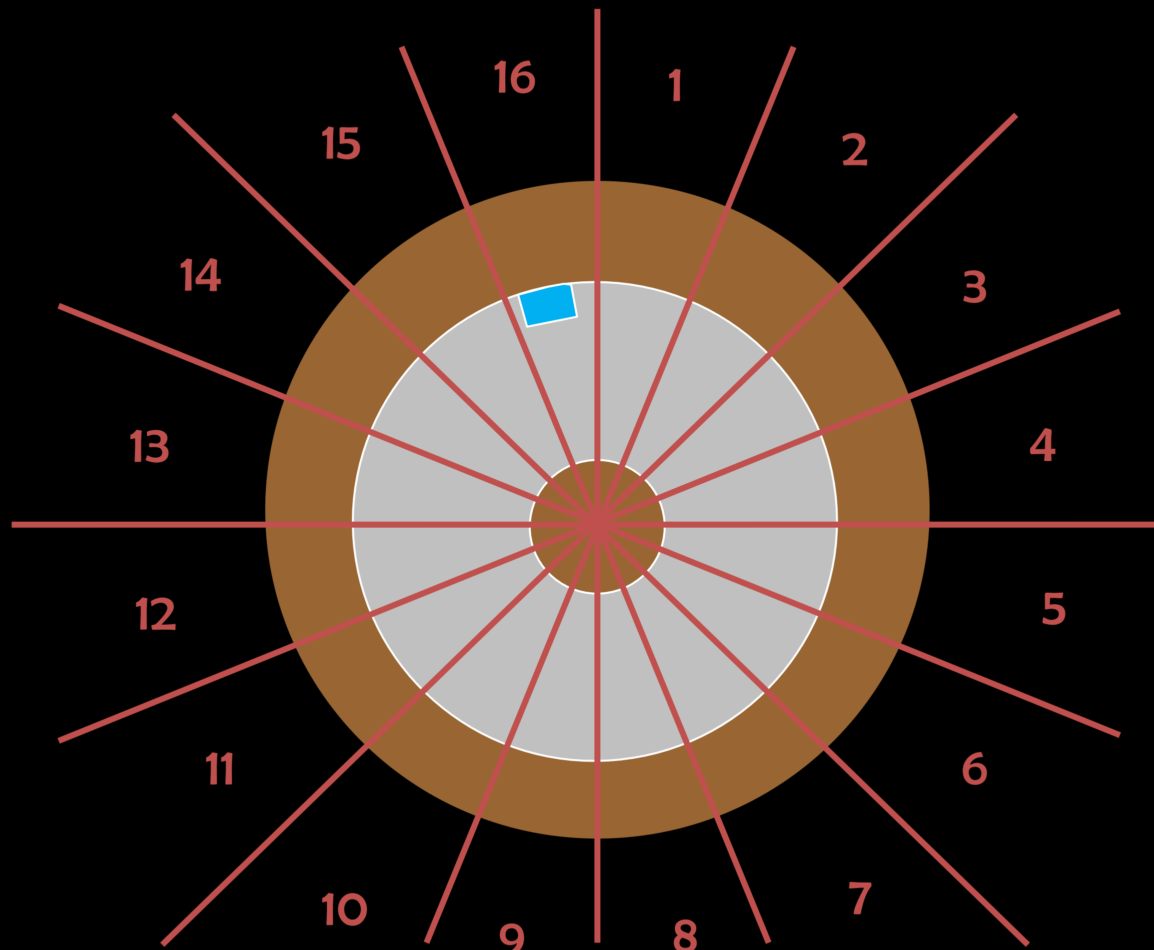
Mickael, M.: (SPE 162175, 2012)

CrossWave Azimuthal Sonic Data Acquisition

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.)



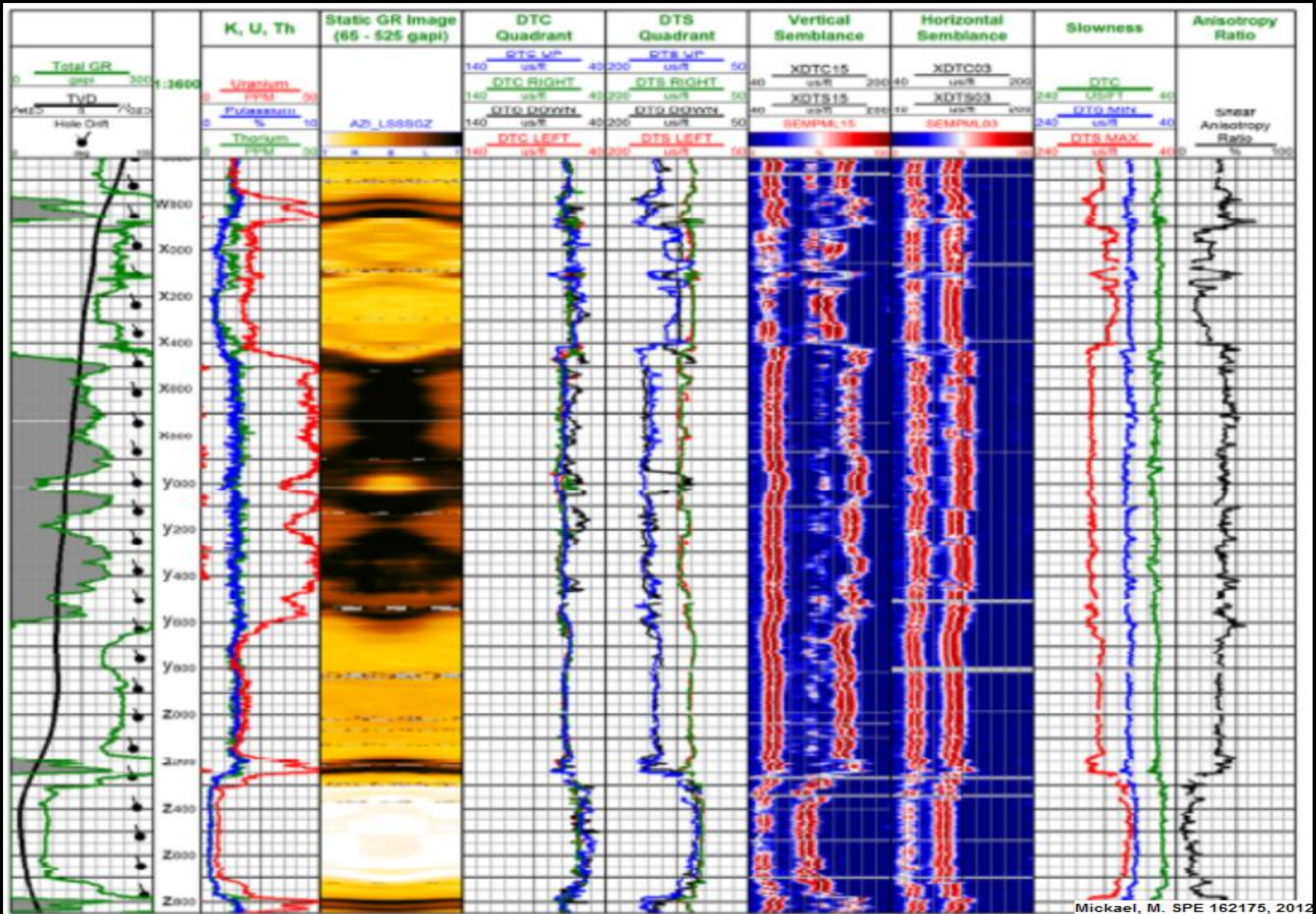
AZIMUTHAL LWD SONIC vs. WIRELINE COROSSED DIPOLE

- AZIMUTHAL SHEAR NOT SIGNIFICANTLY DSIPERSSIVE:
  - 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 THR BOREHOLE FLUID
- HIGH TRANSMITTER FREQUENCY RESULTS IN FAIRLY SHALLOW DEPTH OF INVESTIGATION

ANISOTROPY FROM LWD AZIMUTHAL SONIC



Mickael, M. SPE 162175, 2012

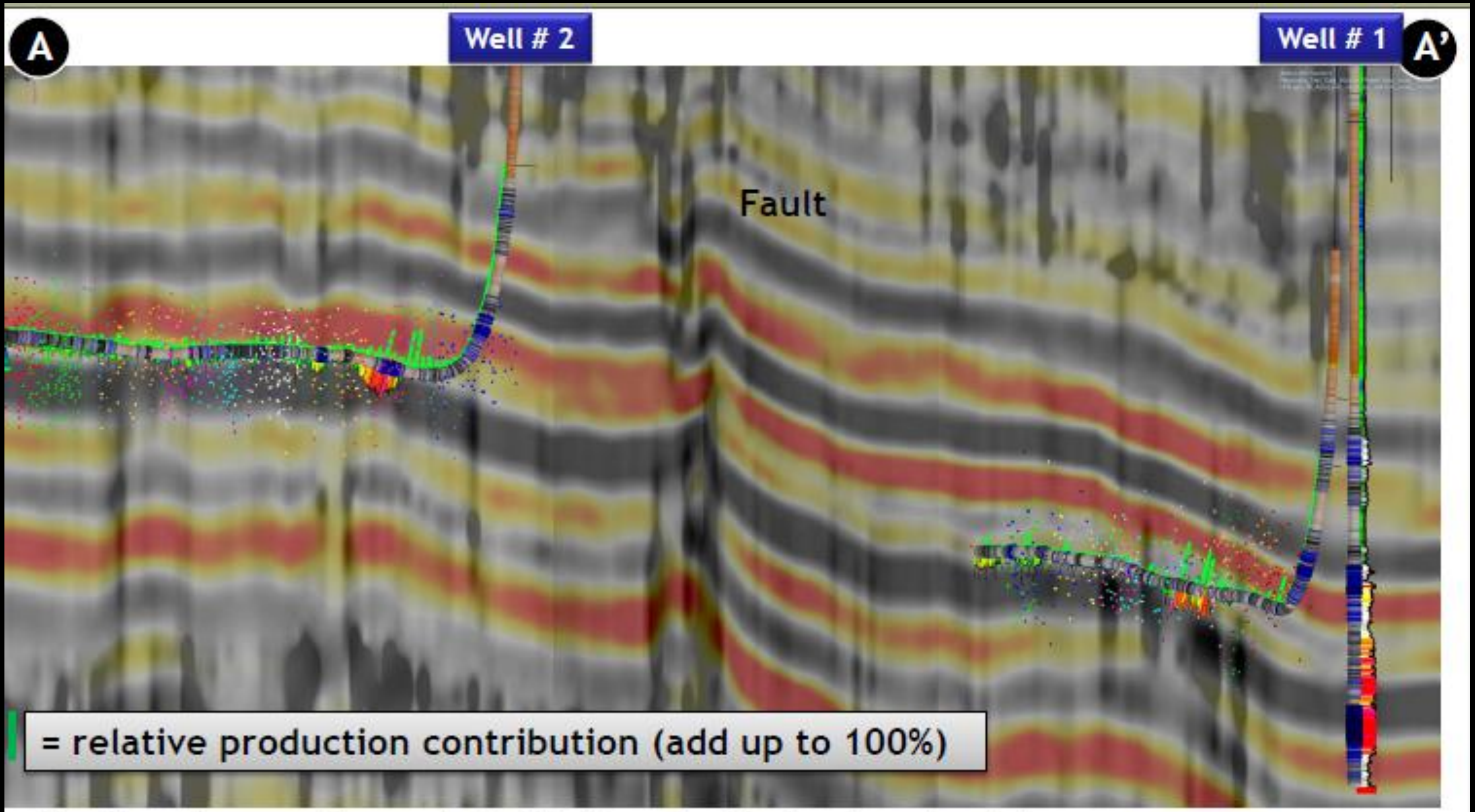
AZIMUTHAL LWD SONIC , SPECTRAL GAMMA AND BULK DENSITY

- 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

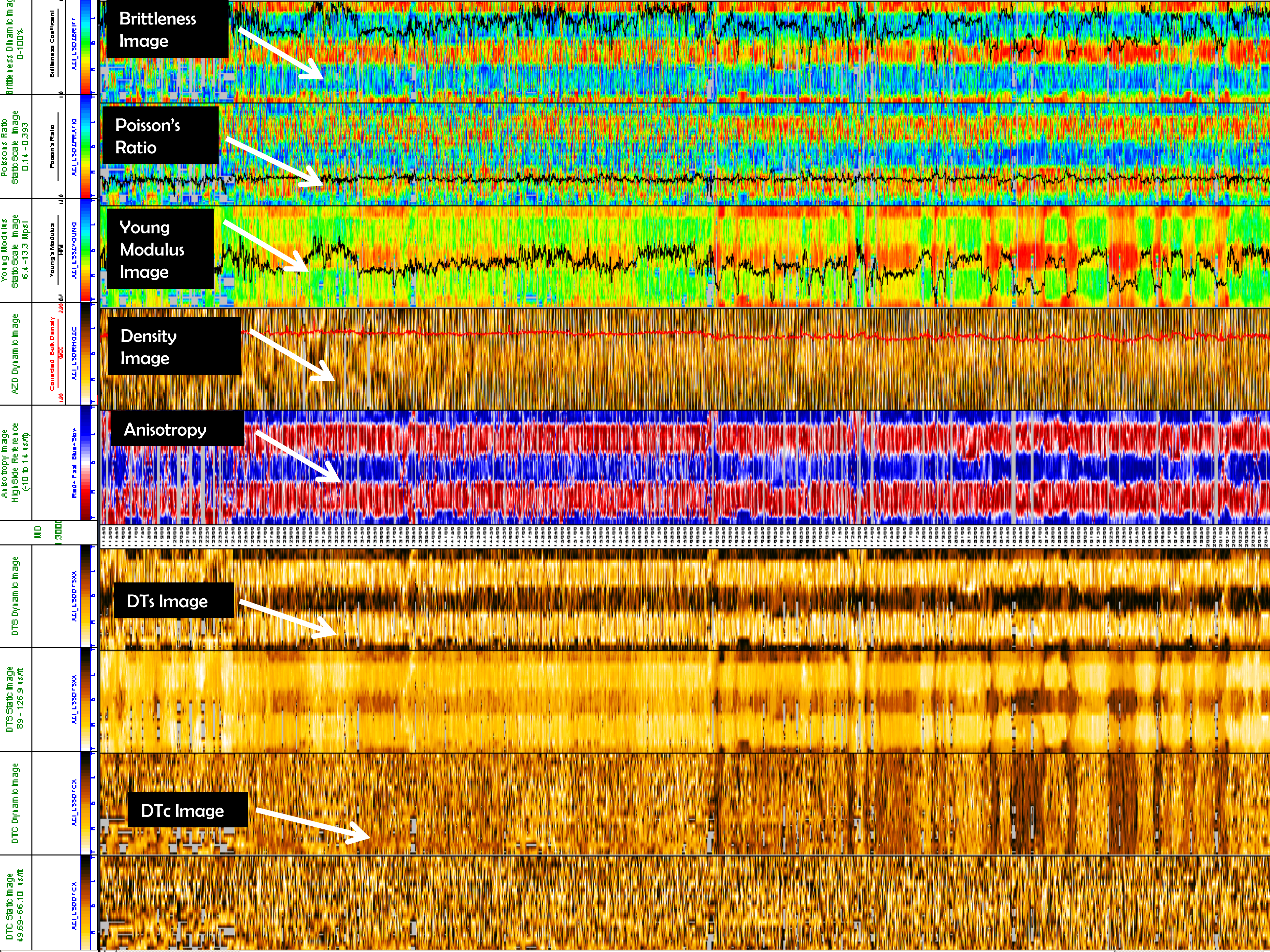


Max Tgas from mudlogs and initial oil production is related mainly to presence of faults and associated fractures (high-order geometries); high-resolution coherency is detecting mainly high-angle faults.

Eagle Ford Reservoir Characterization from Multisource Data Integration*N. Basu1, G. Barzola1, H. Bello1, P. Clarke1 and O. Viloria1 Search and Discovery Article #80234 (2012)

BENEFITS OF 16 AZIMUTHALLY FOCUSSED MEASUREMENTS

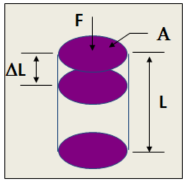
a) 16 Radially spaced P & S Measurements and corresponding Images along the lateral
b) 16 Radially spaced E and μ computations and corresponding Images along the lateral
c) 16 Radially spaced computations of Brittleness and corresponding image along the lateral


Brittleness Image
Poisson's Ratio
Young Modulus Image
Density Image
Anisotropy
DTs Image
DTc Image

360º Rock Properties Imaging

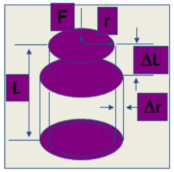
Young's Modulus

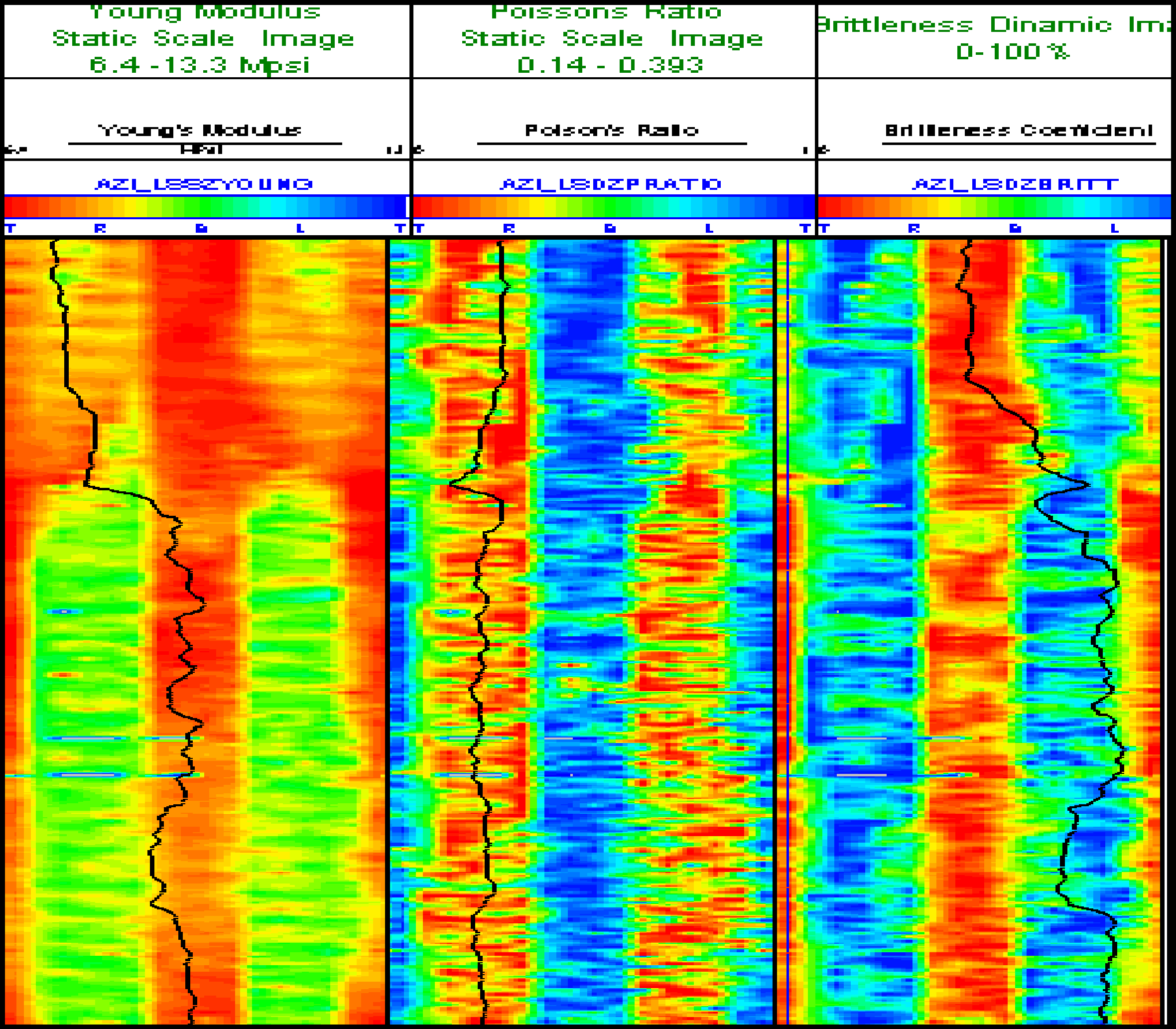
- Modulus of Elasticity
- Stress / Strain

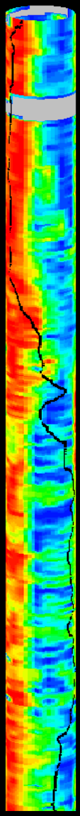


Poisson's Ratio

- Lateral / Longitudinal Strain
- "Squish/Squash"





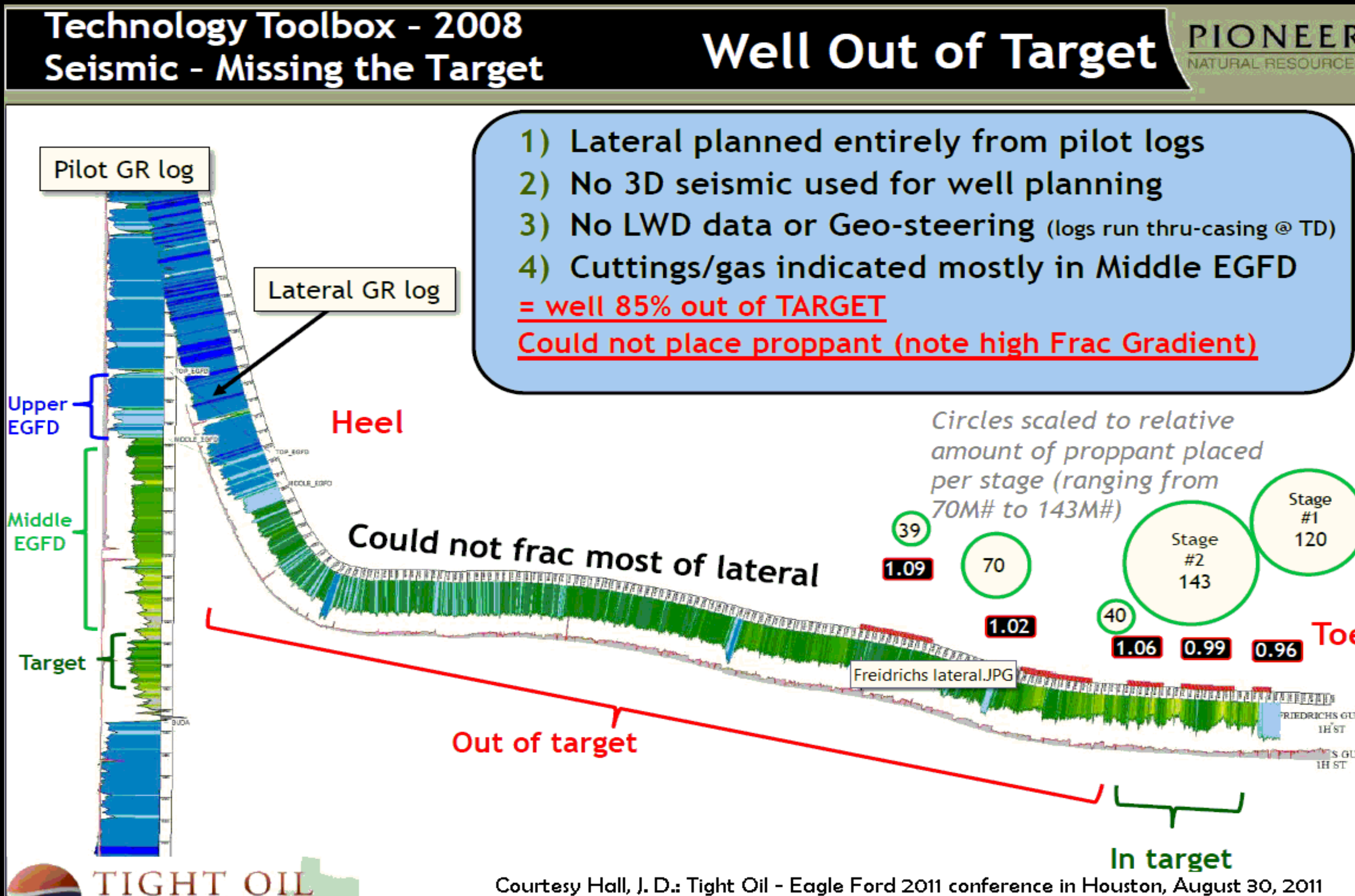


LWD AZIMUTHTAL UNIPOLE ACOUSTIC SUMMARY

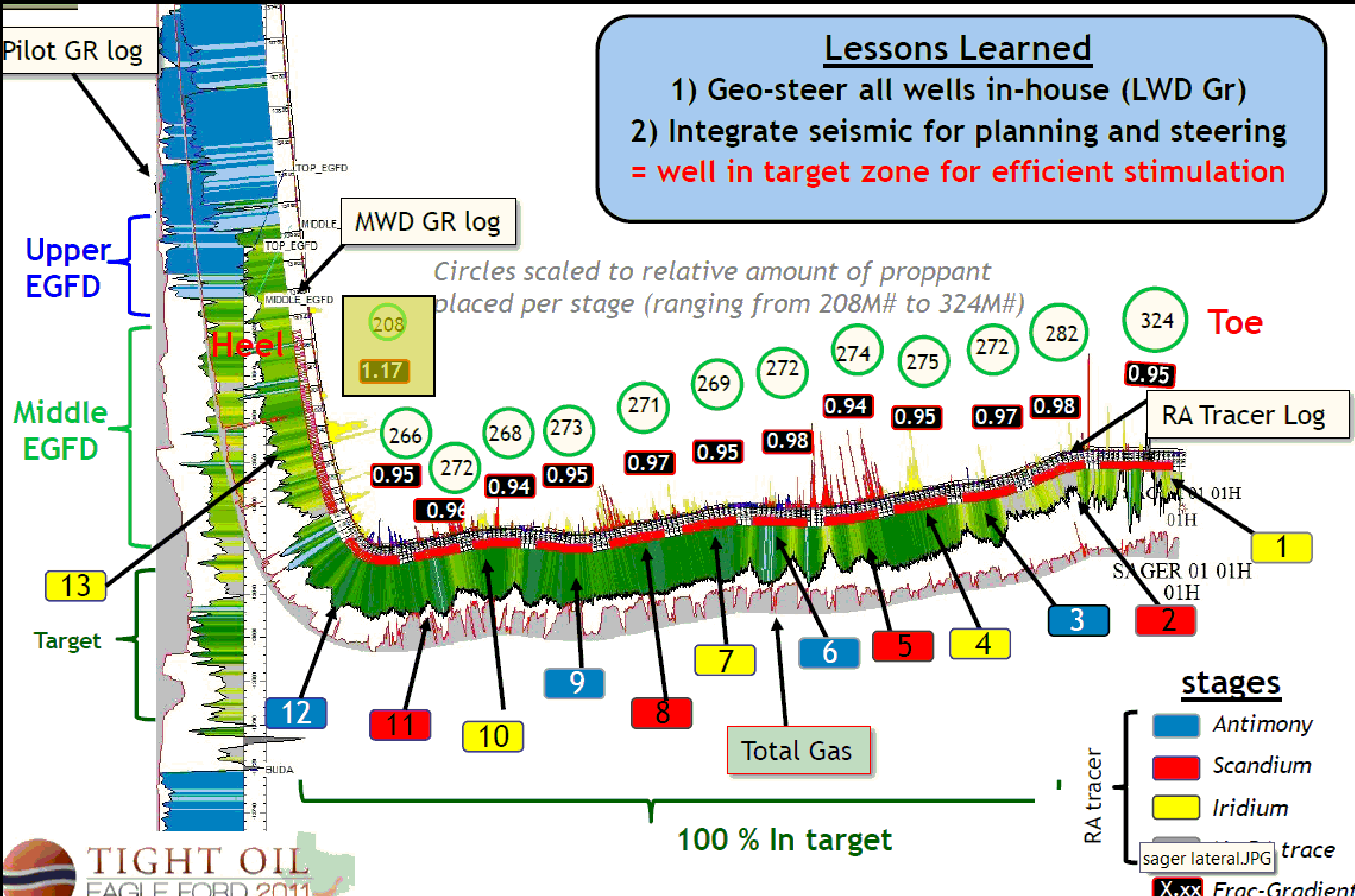
- GEOMECHANICAL DATA ALONG LATERAL LEADS TO COST SAVINGS THROUGH SELECTIVE STIMULATION

- 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
PIONEER
NATURAL RESOURCES
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)
Pilot GR log
Lateral GR log
Upper EGFD
Middle EGFD
Target
Heel
Could not frac most of lateral
Circles scaled to relative amount of proppant placed per stage (ranging from 70M# to 143M#)
39
1.09
70
1.02
40
1.06
Stage #2 143
0.99
Stage #1 120
0.96
Toe
Freidrichs lateral.JPG
Out of target
In target
TIGHT OIL
Courtesy Hall, J. D.: Tight Oil - Eagle Ford 2011 conference in Houston, August 30, 2011

Improved Well Placement and Completion



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

Conclusions

- 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