Longitudinal Variability within a Delaware Basin, Wolfcamp Horizontal Well: Insights from Integrating Data from Borehole Image, Dipole Sonic, Drill-bit Geomechanics and Mass Spectrometry

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Abstract

As the pace of horizontal drilling in unconventional reservoirs has exploded in recent years, many questions remain unanswered regarding the ability to predict rock characteristics along a lateral wellbore and which tools can be used to reduce uncertainty. This research presents the results of a comparative study aimed at characterizing lateral changes within a Wolfcamp target horizon. We integrate borehole images with dipole sonic, drill-bit geomechanics, mass spec-based organic geochemistry and hydraulic fracturing data to assess changes in rock properties, fractures and hydrocarbon composition and flow. This integrated study reveals a high-degree of longitudinal variability in rock properties that is significant to hydrocarbon recovery and improved drilling economics.

A detailed analysis was completed on 4,000+' of image log data acquired from a horizontal well in the Wolfcamp from the Delaware Basin. Image data includes lithology, rock texture, bedding structural dip and natural and drilling-induced fracture geometry. Three distinct image zones were identified based upon changes in gamma, resistivity, structural dip, fracture type and the distribution of mass-flow and deformed beds. The boundaries between the three image zones match stratigraphic subdivisions within the target horizon that were transected during well steering. These boundaries are also notable in geomechanical and geochemical data.

Drill-bit geomechanical data correlates well with dipole sonic data and highlights the lateral heterogeneity observed from the borehole image and the mass spectrometry data. Fractured intervals correlate with higher ISIP's when evaluating the hydraulic fracture treatment data by stage. Geomechanical variability can be used to design hydraulic stimulation operations, maximize treatment efficiency and mitigate borehole stability issues in future wells.

Mass spectrometry identified 10 unique zones along the lateral, based upon distinct changes in hydrocarbon composition, inorganics, and aromatic soluble species. These data reveal changes in relative GOR, water saturation, porosity, permeability and hydrocarbon composition that correlate with changes in rock characteristics from image log and drill-bit geomechanical data. Changes in hydrocarbon chemistry in different natural fracture types could indicate connection to different sources, possibly revealing degree of compartmentalization. Defining strata by distinctive chemical signatures and linking them to geomechanics and natural and induced fracturing, can help avoid water, improve stimulation and reduce uncertainty in geosteering.

In an increasingly competitive market, low-risk / high-value data as a means of reducing reservoir quality uncertainty is key to economic success. Mass spectrometry, LWD, and seismic are capable of identifying significant lateral changes in rock and fluid properties, which can indicate the need for additional detail provided by image logs and additional open-hole logs. This study shows that these disparate data sets can be integrated to generate a synergistic product that improves the ability to predict reservoir quality.

Mass Spectrometry

Mass spectrometer data identifies the concentration of fluid constituents liberated by drilling. These data are used to chemically define "The Sweet Spot" for oil production and natural porosity and to avoid "The Sour Spot" of elevated water saturation, low natural porosity, and higher bit wear. Mass spectrometer data can assist in geosteering placement to remain within the optimal zone for drilling and completions.

In our example, mass spectrometry reveals variation in fluid chemistry that is linked to changes in position along the lateral, changes in stratigraphic interval, and changes in fracture density and geometry. The geochemistry data suggest subdivision into 10 Mass Spec Zones. These zones are broken out in Mass Spec track to the left of center in the large graphic. Salient features of Mass Spec Zones are described below.

Zone MS 1: A consistent pattern of increasing hydrocarbons (HCs) with depth is seen into a reset mud system after landing. A possible open fracture is indicated by gas and inorganics after a trip.

Zone MS 2: This zone has mechanical damage due to bypassing shakers, resulting in loss of data.

Zone MS 3: This zone shows gradual a increase in C5 and C8 HCs, hydrogen (H) and benzene, toluene and xylenes (BTX). These changes accompany an increase in condensate and oil.

Zone MS 4: Zone 4 displays a rapid increase in H, C2 and benzene and a decrease in C5, C8, normalized C4 and C7 (nC4 and nC7), normalized carbon dioxide (nCO_2), toluene and xylenes. Water saturation (S_w) increases.

Zone MS 5: MS 5 shows an abrupt Increase in H associated with a decrease in C1, C2, C5, C8, nC1, nC4, and nC7. This indicates low porosity and permeability rock. Helium (He) decreases abruptly with a rapid increase in S_w. Changes across Zone MS 5 correspond with changes in rock properties identified in the image log.

Zone MS 6: The upper contact is the image zone boundary that crosses from Wolfcamp A Thin Bed to Wolfcamp A. Both gamma and resistivity become less erratic and accompany an abrupt decrease in H and a significant increase in all HCs (except Naphthalene, Naph) and He (porosity). S_w remains elevated, but decreases with depth.

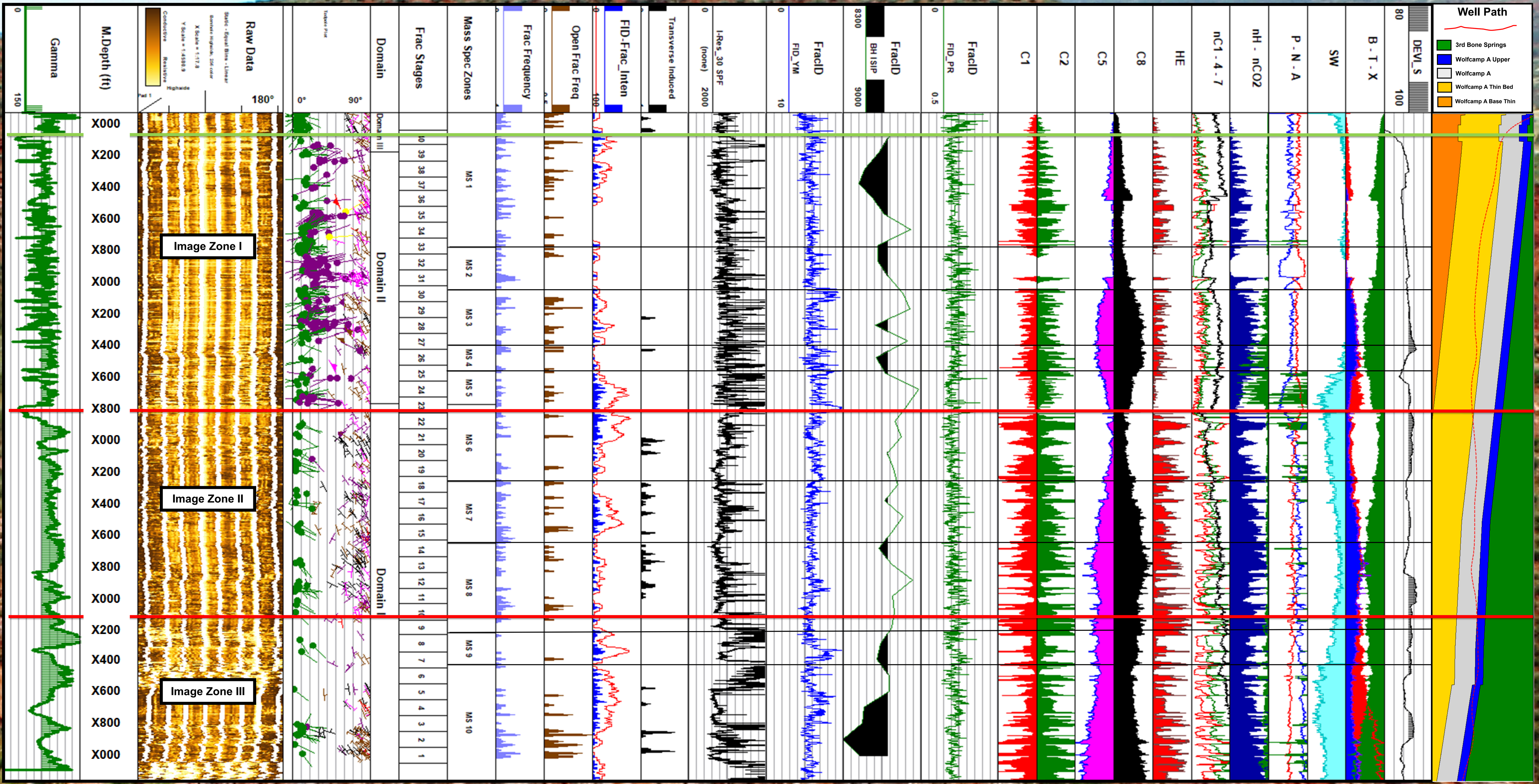
Zone MS 7: This zone displays an increase in all HCs (except naph) and nCO_2. Gradually increasing oil signal goes with continued gradational decrease in S_w with depth.

Zone MS 8: MS 8 witnesses larger surges in hydrocarbon volatility in intervals displaying paired high resistivity and low gamma. S_w decreases and begins to show a minor increase at the end of this zone.

Zone MS 9: In Zone 9, the upper contact is the image zone boundary that crosses from Wolfcamp A to Wolfcamp A Upper. This zone reveals decreased hydrocarbon volatility with a gradual decrease in oil. An increase in benzene over toluene and xylenes indicates an increase in S_w.

Zone MS 10: In Zone 10, an abrupt increase in HCs with oil influx coincides with much stronger volatility, likely indicating increased porosity. S_w shows a rapid increase, possibly indicating open porosity near an interpreted fault. Benzene increases significantly indicating liquid phase solubility. A separation of PNA concentrations suggests a change in compartmentalization. This zone may contact the base of the 3rd Bone Springs.

The Mass Spec geochemical changes along the lateral correspond with changes observed in borehole image logs and drill-bit geomechanics. Mass Spec data can be used in (virtual) real-time to establish vertical location in the stratigraphic section, permitting geosteering to access the best reservoir properties seen in image logs.



Drill-Bit Geomechanical

Mechanical rock properties are measured by analyzing the intensity of vibrations that emanate from the bit while drilling. Standard data outputs are Young's Modulus (YM), Poisson's Ratio (PR), Bedding (intrinsic) anisotropy and fracture intensity (see plot at right). Minimum horizontal stress is calculated from PR and is shown as well.

These high resolution drill-bit geomechanical data correlate well with dipole sonic data and highlight the lateral heterogeneity that has been observed from borehole image and the mass spectrometry data.

The three zones identified from borehole image log data are marked here and correspond with stratigraphic boundaries shown on the geosteering interpretation cross-section (top track). From Fracture ID data, YM and PR display distinct character by zone. Zone 1 (Wolfcamp A Thin Bed, yellow) is generally higher stress with minimal fracturing. Zone 2 (gray) is more fractured, and has a more consistently high bedding anisotropy. Zone 3 (blue) is also fractured, but has lower bedding anisotropy and higher dynamic range in YM and PR than Zone 2.

A good correlation exists between Instantaneous Shut-In Pressure (ISIP) and stress by stage (see histogram chart below curves). The exception is in highly fractured zones where stress underestimates ISIP. Fractured stages will likely accept stimulation differently and have different hydraulic fracture geometry than unfractured stages.

Geomechanical variability can be used to design hydraulic stimulation operations, to maximize treatment efficiency and to mitigate borehole stability issues in future wells.

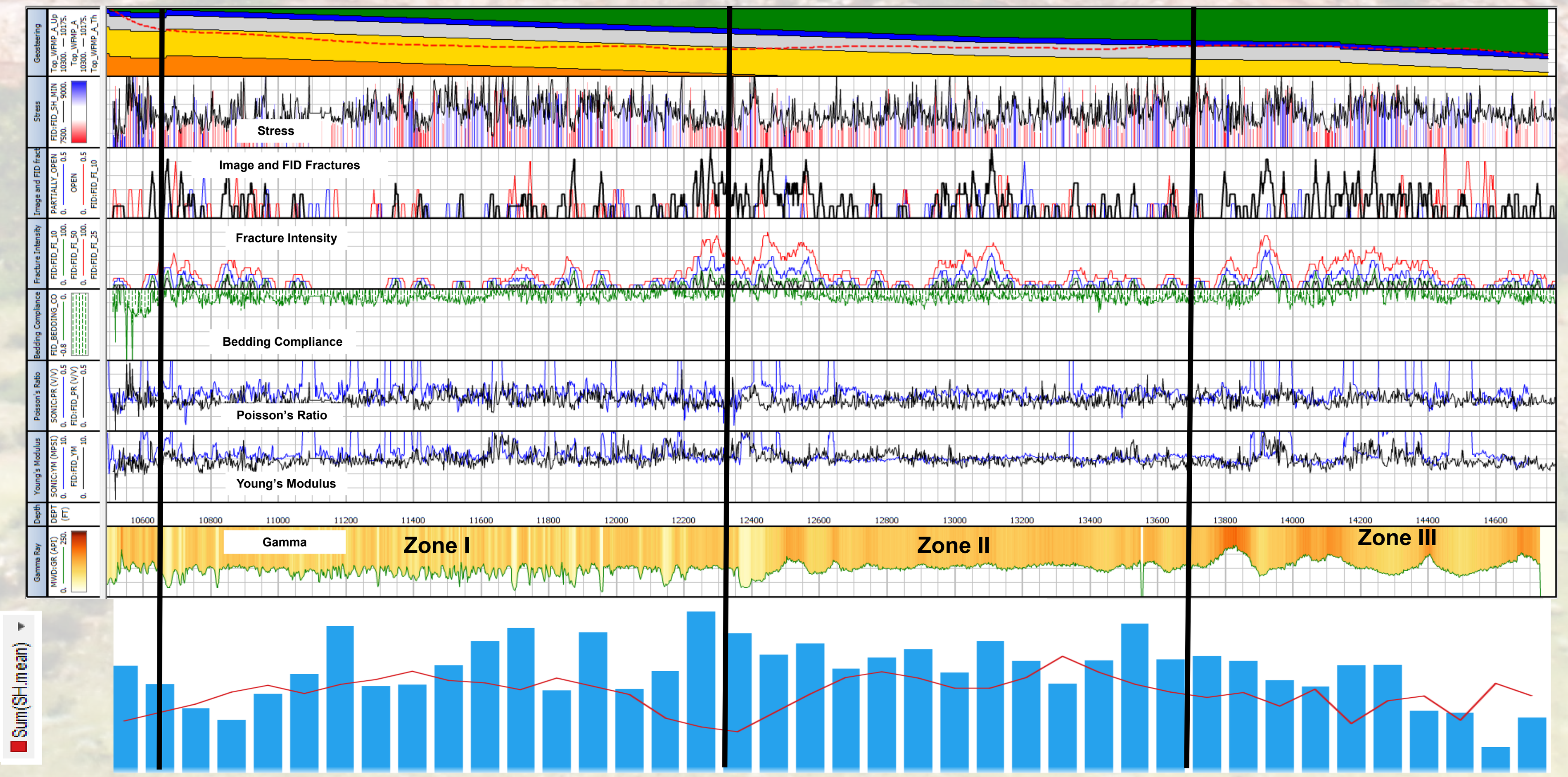
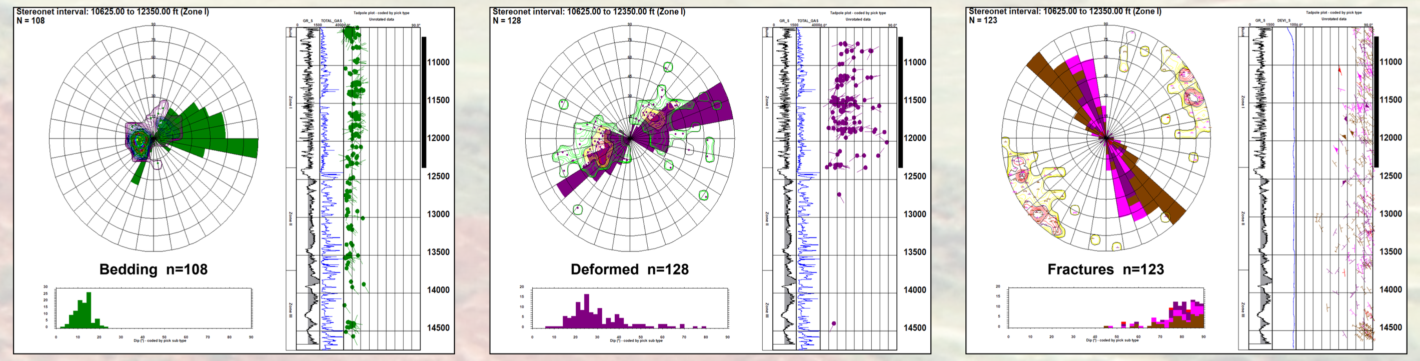


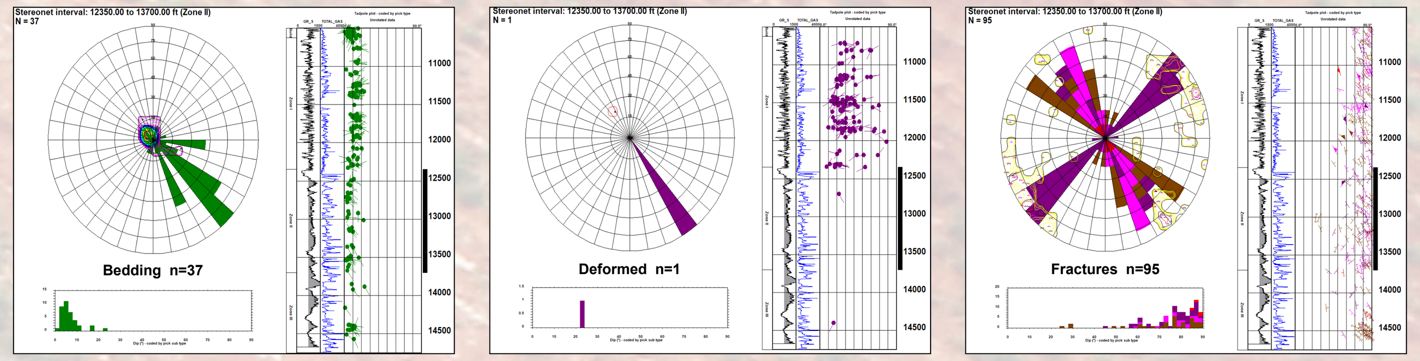
Image Fractures and Structure

Image log analysis established the spatial geometry of deformed and undeformed bedding structure and characterized the components of the fracture system. On the basis of this analysis, 3 distinct image zones were identified along the lateral. The 3 zone boundaries coincide with stratigraphic contacts traversed by the drill bit (see Well Path Track to right of large diagram). Features unique to these 3 zones are described below. (Note that the build interval (10,500' to 10,625') is omitted.

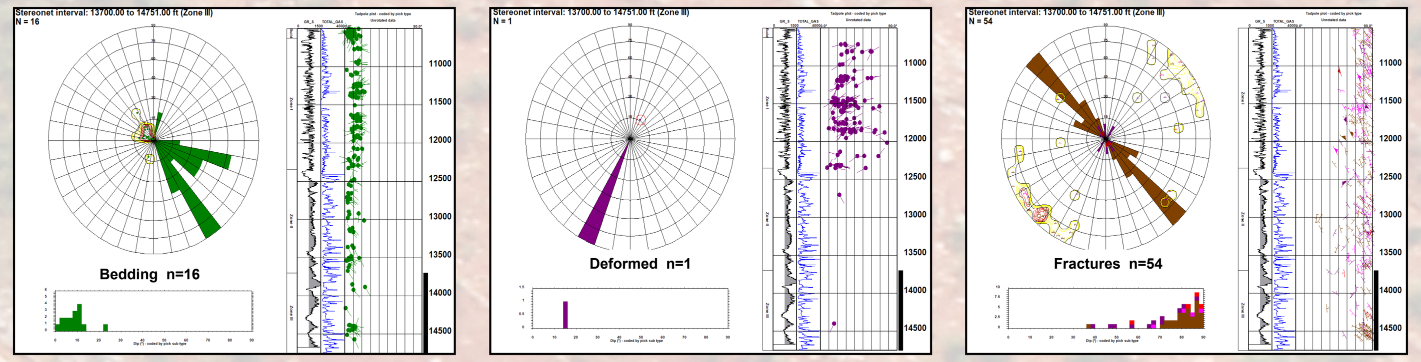
Zone I: (10,625'-12,350'): Zone I traverses the Wolfcamp A Thin Bed unit (yellow) and has very active gamma ray, resistivity (I-Res_30 SPF), and Youngs Modulus (FID_YM) curves. Bedding dips strongly to the E and deformed bedding is abundant (unlike the other zones). Fractures consist of high-angle open (brown) and cemented types that strike NW-SE. This zone contains the largest number of picks in all categories: bedding (67%); deformed beds (99%) and fractures (45%).



Zone II (12,350'- 13,700'): Zone II, which lies entirely within the Wolfcamp A (gray), displays curve responses that are more muted. Gamma is more stable and both I-Res_30 SPF and YM decrease. Bedding points to the SE and only one deformed bed is present. Fractures are high-angle open, cemented and partially-open features that strike both NW-SE and NE-SW. Transverse-induced fractures increase dramatically (signifying an increase in stress anisotropy). Instantaneous Shut-In Pressure (ISIP) values are elevated. This zone has fewer picks that Zone I, and more than zone III: bedding (23%); deformed beds (0.5%) and fractures (35%).



Zone III (13,700'-14,751'): Zone III traverses the Wolfcamp A Thin Bed (blue) stratum. This zone maintains muted gamma. Resistivity (I-Res_30 SPF) is high with high GR and low with low GR, the opposite of expectation. YM values are highest in the lower GR intervals. Bedding is to the SE, only one deformed bed is seen and fractures are high-angle, strike NW-SE and are mostly open aperture types. This interval contains the fewest feature picks of the 3 zones: bedding (10%); deformed beds (0.5%) and fractures (20%).



The borehole image data reveal distinct changes along the borehole that are tied to different stratigraphic subdivisions of the Wolfcamp A. These unique strata also display different geochemical and geomechanical characteristics. Mass spec data in (almost) real time can be tied to specific reservoir properties to fine-tune geosteering.

Conclusions and Implications for Completions

All 3 data sets (image logs, mass spectrometry and drill-bit geomechanics) were able to identify changes in the rock and fluids as the wellbore transected 3 distinct stratigraphic intervals.

Image logs can be used to ground truth changes in seen in mass spec data and wellbore geomechanics. Image logs are able to discriminate changes in the bedding structural style, the abundance of deformed bedding and the frequency and geometry of fractures. The strong correlation between mass spectrometry and image log data indicates that mass spec measurements can be used to more accurately geosteer new wells drilled in this area.

Establishing the link between MS geochemistry, drill-bit geomechanics and borehole image features (structure, deformed beds and fractures) can assist in geosteering placement to remain within the optimal zone for drilling and completion.

Rock changes identified with these tools can also be used to optimize existing hydraulic stimulation designs, to maximize treatment efficiency, to avoid high water cuts and high GOR and to mitigate borehole stability issues.

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