Calibration of surface seismic attributes to natural fractures using horizontal image logs - Mississippian Lime, Osage County, Oklahoma

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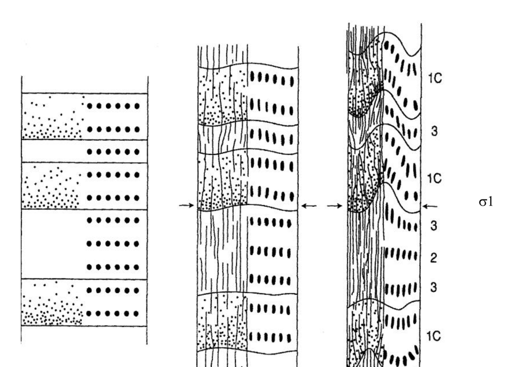
Abstract

The Mississippi Lime, located in parts of Oklahoma, Kansas, Arkansas and Missouri is one of the most recent unconventional plays, and is characterized by tight limestone, fractured chert, and high porosity tripolitic chert sweet spots. Exploited since the early 1920s, this formation has been rejuvenated by the advent of horizontal drilling, hydraulic fracturing, and efficient water disposal into the deeper karsted Arbuckle Formation. In the absence of wide azimuth seismic data, the present-day orientation of maximum horizontal stress can be determined from image logs. Fracture density is controlled by three factors: strain, lithology, and bed thickness. Only a limited number of publications have been reported on the use of image logs measured in horizontal wells. We characterize the fractures seen in these horizontal wells by whether they are layer bound or through-going, open or closed, and by their orientation. These measurements are then correlated to the surface seismic attributes k1/k2 principal curvature, k1/k2 strike, and azimuthal intensity generated by the AASPI consortium to estimate fracture density, orientation, and lithology at the Mississippian Lime objective throughout the survey. Core measurements of the tight and tripolitic chert are used in our lithology estimation. Correlating production from horizontal wells to surface seismic attributes and impedance is problematic and requires a hypothesis that completion is constant along the length of the well. As this play develops into a true resource play, we anticipate the correlation of production data to seismic attributes.

Introduction

More so now than ever before, it is essential to have a three-fold multidisciplinary understanding of geology, geophysics, and engineering in order to be competitive, not only as a company, but as an individual as well. Resource plays, horizontal drilling, and advances in 3D seismic resolution and attribute expression have redefined the oil and gas industry in the 21st century. The presence of natural conductive fractures significantly increases the porosity and permeability of a reservoir and in a tight conventional or resource play will often mean the difference between a commercially productive well and an expensive hole in the ground. Unfortunately for exploration geologists and geophysicists, detection of fractures by direct means falls below traditional seismic resolution (Al-Dossary and Marfurt, 2006). However, structural curvature analysis of the target horizons can provide an indirect means of fracture density estimation and orientation (Chopra and Marfurt 2010). Mathematically, curvature is the measure of a quadratic surface's deviation from being planar. Geologically, we observe that as a planar layer deforms positively (increasing positive curvature value) or negatively (increasing negative curvature value) forming anticlines or synclines, that tensile fractures develop in the areas of highest strain perpendicular to the direction of maximum stress or $\sigma 1$. AASPI's development of a suite of curvature attributes designed to target areas of higher fracture density and subsurface lineament orientation is presently being calibrated by a number of methods including laboratory clay modeling (Staples, 2011), analog outcrop studies (Hennings, 2000), and borehole image log analysis (Staples, 2011). As AASPI's delineation of the correlation between seismic attributes and fracture density and orientation strengthens, we hope to incorporate production data into our study to enhance our understanding of how these seismic attributes can serve as guidelines in predicting reservoir quality in an area and helping to focus the location of future hydrocarbon exploration efforts.



Relationship of fracture density and strain to increasing stress and curvature in a layered sandstone and shale sequence. Sandstone beds are stippled and indicated by a C. Modified after Van der Plujim and Marshak (2004).

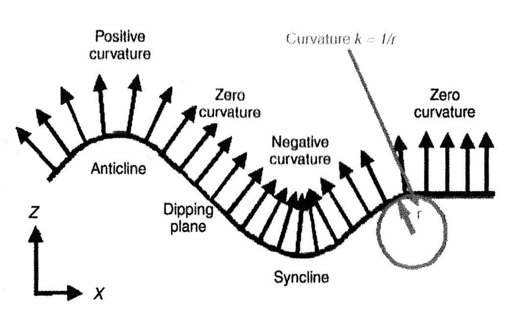


Illustration of 2D curvature. Anticlines display positive curvature. Synclines display negative curvature. Planar surfaces display zero curvature. Maximum curvature is defined by the curve tangent to the smallest circle. After Roberts (2001).

Geologic Setting

The Mississippian Lime section represents a single third order (unconformity-bounded), transgressive-regressive eustatic cycle (Manger, 2011).During the Mississippian Period the Osage County region was a broad carbonate shelf environment covered by a shallow sea much like the present day Bahamas Shelf located around 20° south of the equator. The play is developed in carbonates, potentially including oolite, that were transported down-ramp as lobate bodies and grain flows, and deposited below both effective and storm wave base (Manger, 2011)The Lower Mississippian lithologies reflect an impoverished, cratonic, carbonate "factory" dominated by crinozoan detritus and carbonate mud produced at very high rates within effective wave base (Manger, 2011). This interval is known as the St. Joe Formation and is chert free, thin, and condensed, spanning seven conodont zones (Manger, 2011). In the subsurface the chert free zone is dolomitized and exhibits matrix porosity although in outcrop it is mud dominated and tight (Manger, 2011). Above this lies a chert bearing interval called the Boone Formation representing the maximum flooding and highstand/regressive portions of the of the eustatic cycle (Manger, 2011). The chert is formed both penecontemperously under the sediment surface before the point of maximum flooding and later diagenetically formed by groundwater replacement along bedding planes of lithified carbonate following a sea level drop (Manger, 2011). This diagenetic chert is the tripolite that makes up the highest producing hydrocarbon reservoirs in the Mississippian Lime Play.

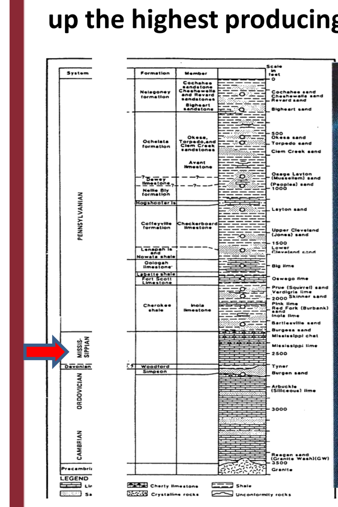


Figure 1

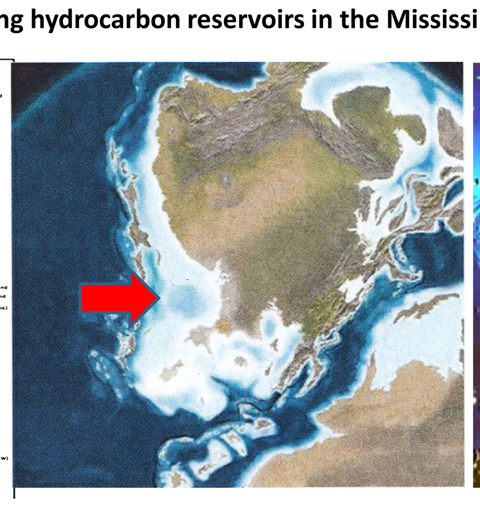


Figure 2

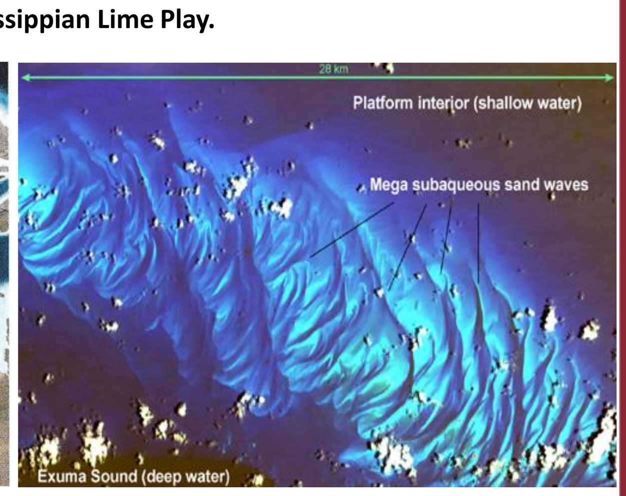
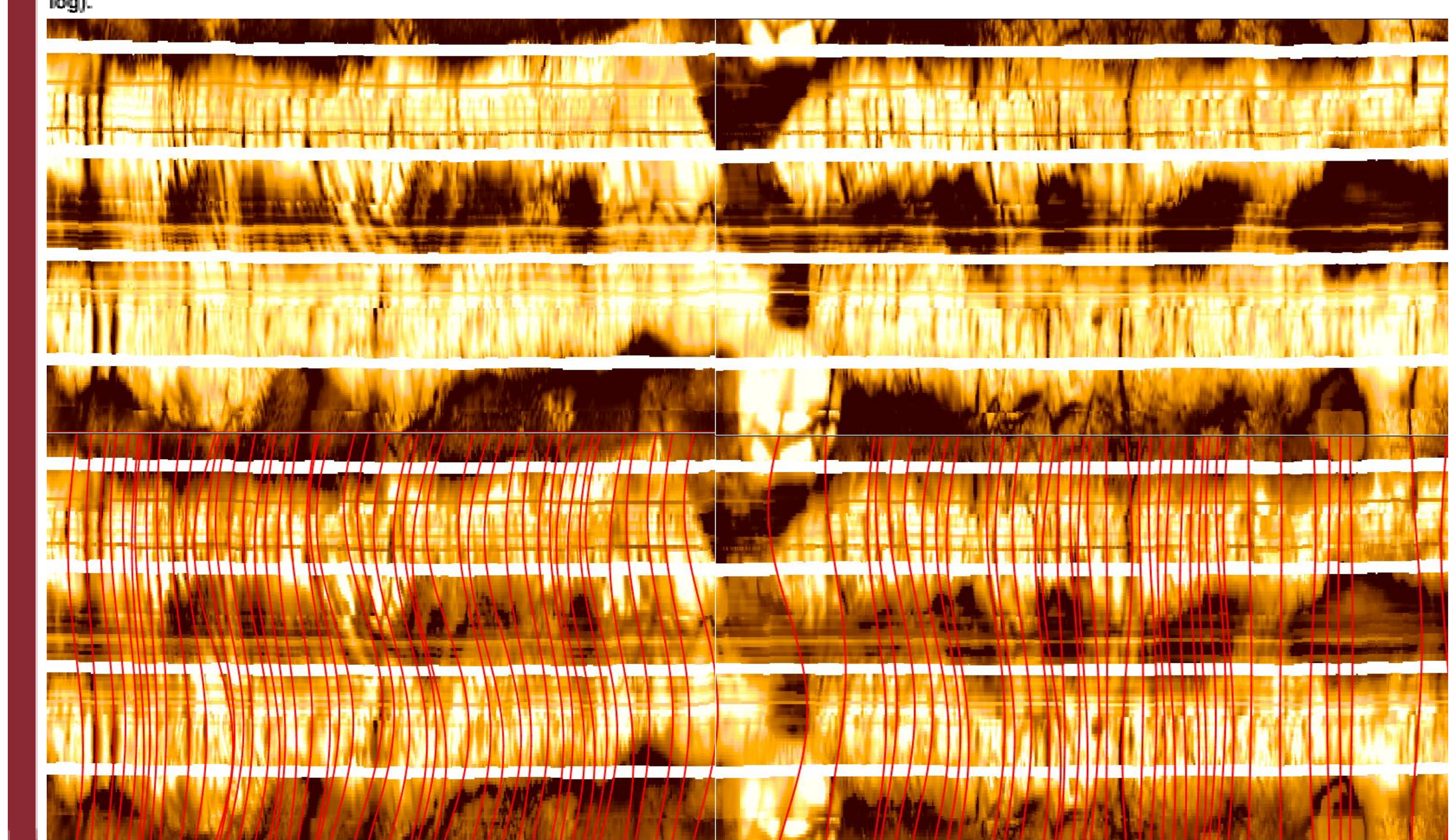


Figure 3

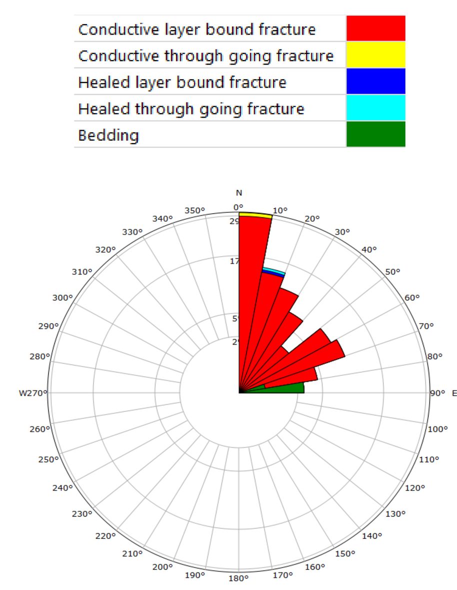
Figure 1 is a stratigraphy column from Osage County, Oklahoma with a red arrow pointing to the Mississippian zone of interest. Modified after Reeves, Guo et al., 1995. Figure 2 is a paleogeographic map of the North American continent as it looked in the Mississippian Period. The red arrow points to the area where Oklahoma would be in present day. Modified after Blakely, 2009.Figure 3 is a present day analog of the Mississippian lime. Oolitic carbonate mud lobes travel down slope into Exuma Sound, Bahamas Platform. After Loucks, Kerans, Jansen, 2003.

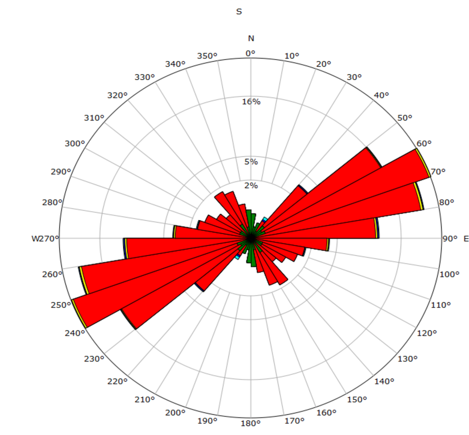
Borehole Analysis

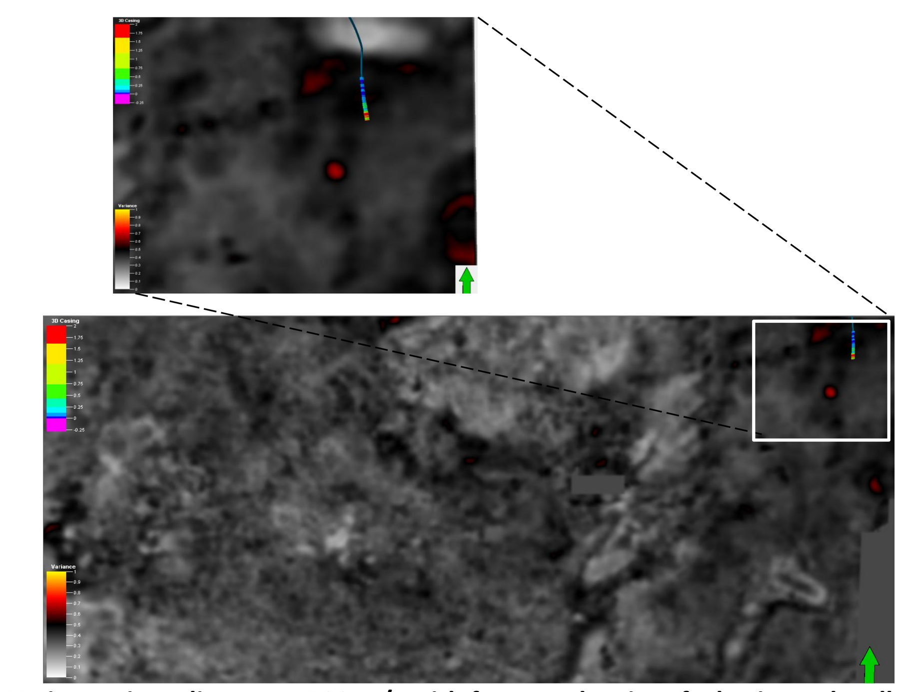
Image logs are utilized to interpret dip orientation, fracture density, and bedding plane curvature in the subsurface. Fracture density was calculated using the formula $F_{dens}=\frac{nF}{100ft}$. These image logs from a horizontal well targeting the Mississippian Lime in Osage County, Oklahoma are shown without interpretation (below top) and interpreted with conductive layer bound fractures with red sinusoids (below bottom). The lowest point in the sinusoid is the dip direction. The section shown is 2ft long and increases in depth to the left. Image logs are viewed as though the borehole has been sliced down the radius of the cylinder through the top of the borehole and unwrapped so the middle of the image log is the bottom (horizontal image log).



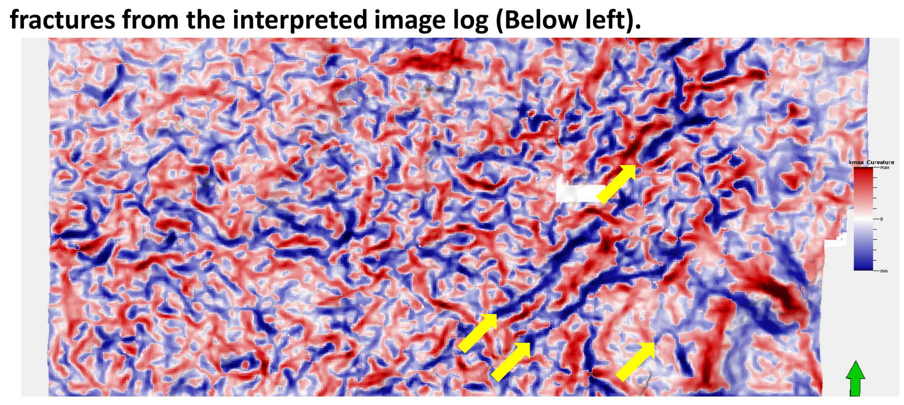
Stereonet illustrating dip of fractures and bedding planes (Below Top). Stereonet illustrating strike of fractures and bedding planes (Below Bottom).







Variance time slice at t= -580 m/s with fracture density of a horizontal well displayed in close up (Above). AASPI generated kmax curvature (Below) on the Mississippian Lime horizon showing a dominant NE-SW trend of lineaments (arrows pointing down strike)correlating with the strike of fractures from the interpreted image log (Below left).



Subsurface Analysis

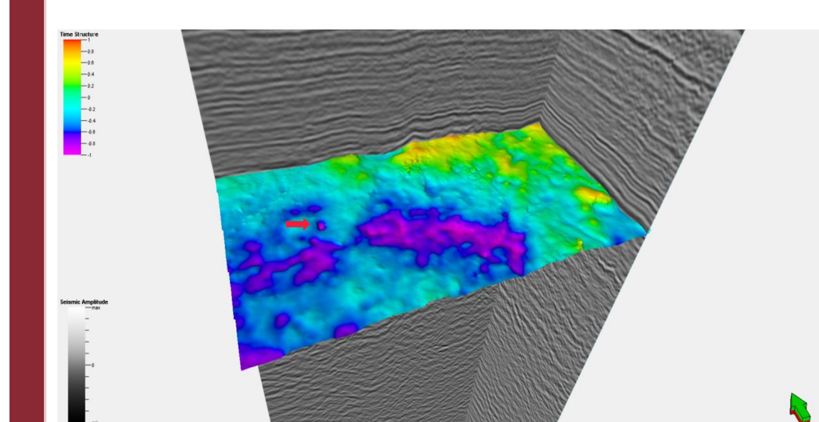


Figure 1

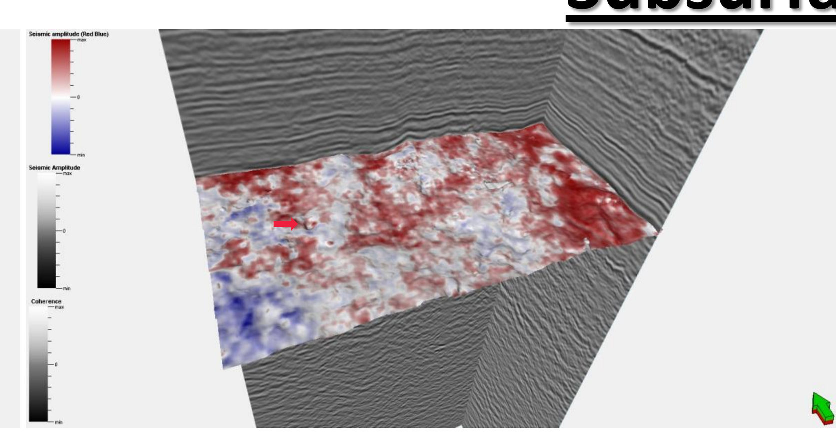


Figure 2

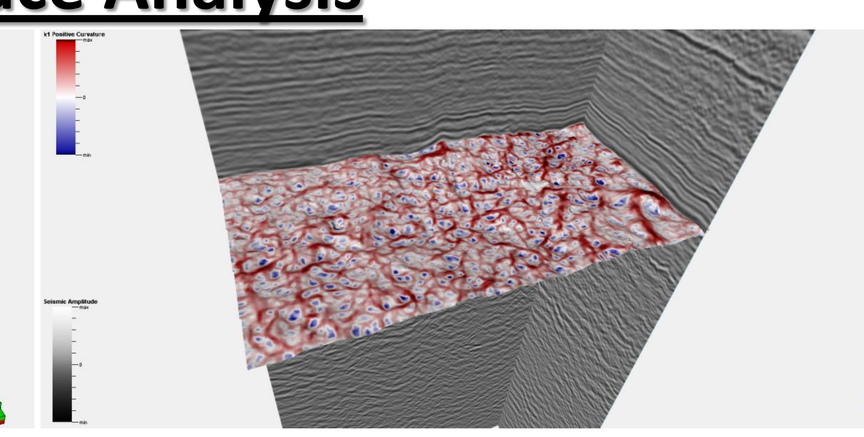


Figure 3

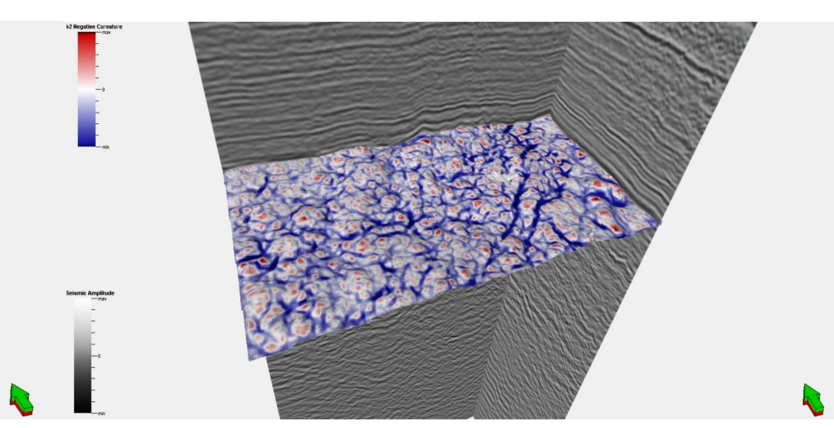


Figure 4

Figure 1 is a time structure volume on the Mississippian Lime top horizon with a vertical exaggeration of 1:10. The time structure map uses a thermal color bar where structural highs are rendered in warmer colors like red, orange and yellow and the lows in green, blue and purple. Figure 2 is a seismic amplitude volume co-rendered with coherence on the Mississippian Lime top horizon. The coherence accentuates relief on the surface. Note the karst feature in both figures marked by the arrow. Figure 3 is the k1 positive short wavelength curvature and Figure 4 is the k2 negative short wavelength curvature. Both attributes have been generated by AASPI on the Mississippian Lime top horizon. Short wavelength curvature is used to illuminate localized karst topography and collapse features (Chopra and Marfurt, 2007). For the scope of this study it can be used to map the intersection of relatively small positive or negative lineaments where fracture density is assumed to be the highest and use them for a preliminary visual correlation between the fracture density measured in the image logs and the intensity of the curvature (Figure 5). Figure 6 is the AASPI generated k1 magnitude vs strike. This helps to further break down the lineaments with high curvature values into smaller sets based on their azimuthal orientation. With more image logs providing well control we can begin to correlate, provided there is a correlation, which azimuthal set of high curvature values corresponds to high fracture density. The next step in this workflow first described by Nissen et. al (2005,2009) is a correlation between fracture density interpreted from image logs and the AASPI generated attribute azimuthal intensity shown in figures 7 ,8, and 9 that is generated using the k1 or k2 curvature volumes and their corresponding magnitude vs strike volumes . This attribute will generate multiple volumes relating an area's lineaments to a specific azimuthal direction, 30° for instance. Azimuthal intensity also uses a thermal color bar where warmer colors indicate areas of lineaments similar to whatever specific azimuthal volume you are using. So for instance we don't see much of a correlation between high OR low fracture density in this well and -60° azimuthal intensity in Figure 7. We can interpret Figure 8 as having a negative correlation between fracture density in this well since as the fracture density's thermal color bar gets cold the azimuthal intensity's color bar gets hot. Figure 9 shows what can best be described as a weak positive correlation between fracture density in this well and a 0° azimuthal intensity as both increase and decrease in intensity in the same direction but seemingly not at the same rate.

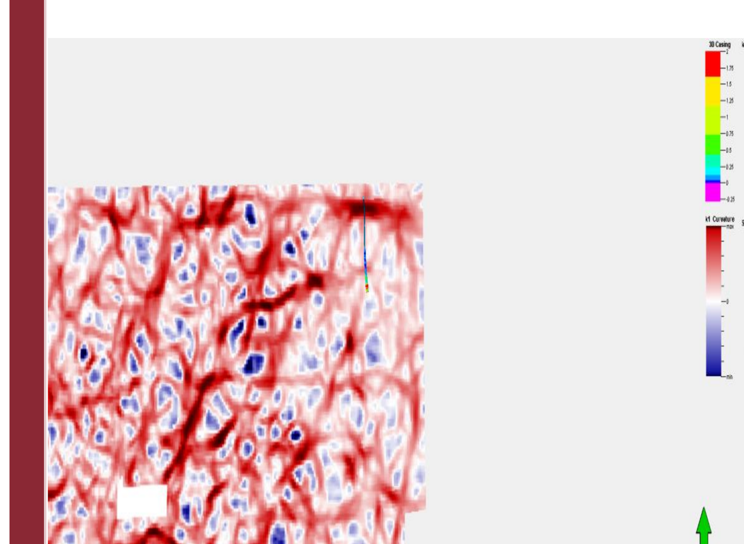


Figure 5

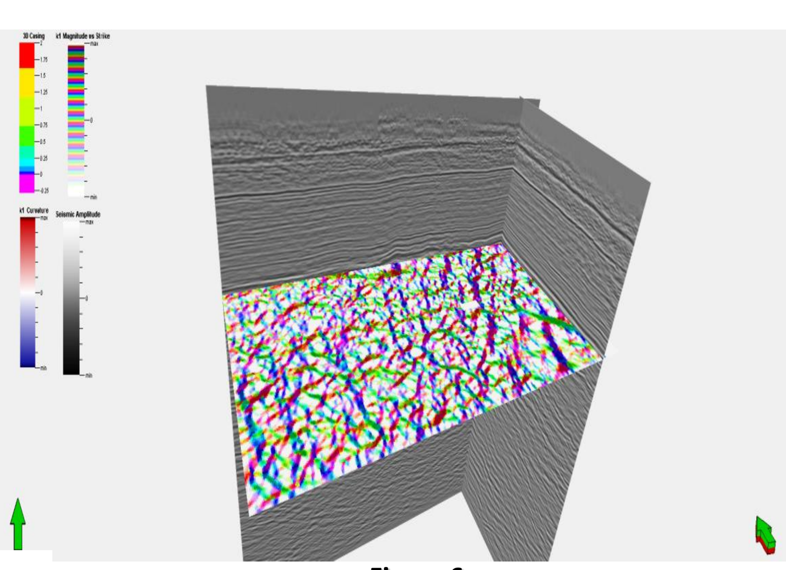


Figure 6

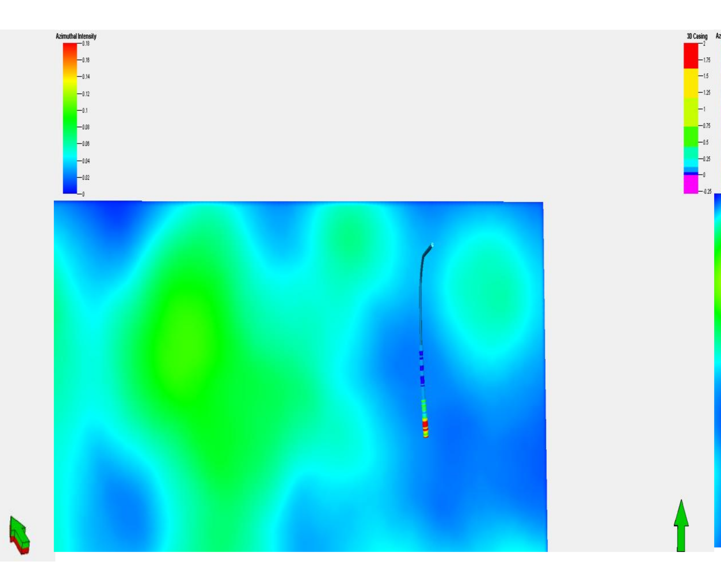


Figure 7

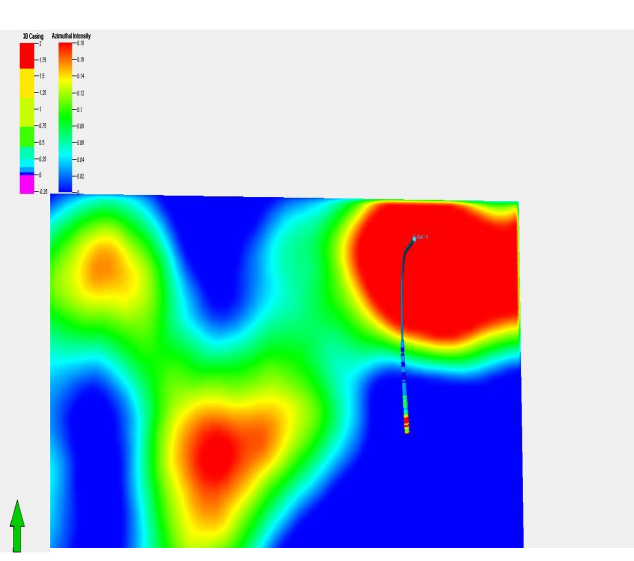


Figure 8

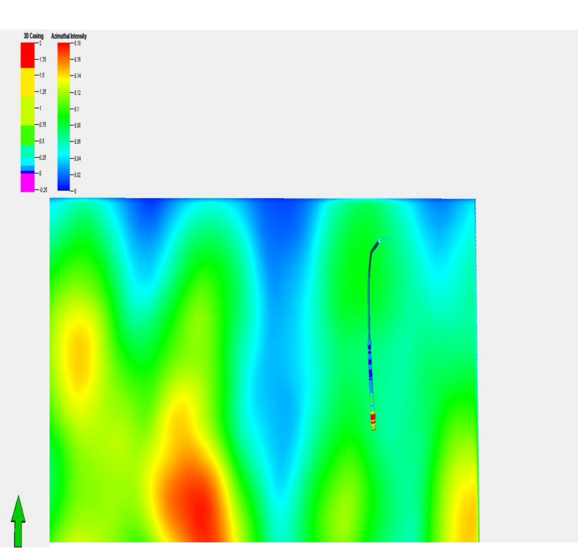


Figure 9

Continuing Research

In order to completely understand the results of the research completed so far the AASPI team must generate both stratigraphic and structural models of both the Mississippian Lime interval and the Osage County region as a whole. Methods that have proved effective in previous research include laboratory clay modeling experiments to observe curvature's relationship to fracture patterns, analog outcrop analysis using LIDAR to observe fracture patterns and bedding plane curvature and their application to the structural model, and a stratigraphic analysis of the Mississippian Lime interval through core and outcrop studies. We must continue our described research in other wells in the region to attain a higher degree of well control and fine tune our calibration between our well data and seismic attribute results. With enough data it's possible that in the future a discrete fracture characterization of the Mississippian Lime interval in the area can be produced that can then be compared to production data in the Osage County region.

References

Al-Dossary, S., and Marfurt, K.J., 2006, 3D volumetric multispectral estimates of reflector curvature and rotation: Geophysics, v. 71, p. P41-P51.
Chopra, S., and Marfurt, K.J., 2010, Integration of coherence and volumetric curvature images: The Leading Edge, v. 29, p. 1092-1107.
Chopra, S., and Marfurt, K.J.,2008, Emerging and future trends in seismic attributes:The Leading Edge, v. 27, p. 298-318.
Chopra, S., and Marfurt, K.J., 2007, Seismic attributes for prospect identification and reservoir characterization: Tulsa, Oklahoma, Society of Exploration geophysicists, 464 p.
Hennings, P.H., Olsen, J.E. and Thompson L.E., 2000, Combining outcrop data and 3D structural models to characterize fractured reservoirs with outcrop fracture and fault data for reservoir characterization: AAPG Bullitin, v. 84,p. 830-849
Manger, W.L., 2011, Lower Mississippian sequence stratigraphy and depositional dynamics: Insights from the outcrops, Northwestern Arkansas and southwestern Missouri, Oklahoma Geological Survey: Mississippian Play Workshop Guidebook.
Loucks, R., Kerans C., and Janson, X. "Platform Interior Carbonate Depositional Environments." 2003. Web. Dec 4, 2011.
Reches, Z., 1988, Evolution of fault patterns in clay experiments: Tectonophysics, v. 145, p. 141-156.
Reeves, T.K., Johnson,W.I., Guo, G., Sharma, B., Chen, K.C., Carroll, H.B., July 1995, Exploration 3D seismic field test/native tribes initiative. U.S. Department of Energy.
Roberts, A., 2001, Curvature attributes and their application to 3D interpreted horizons. First Break, 19, 85-99.
Staples, E., Subsurface and experimental analysis of fractures and curvature, M.S. Thesis, U. of Oklahoma, 2011. print
Van der Plujim, B. and Marshak, S., 2004, Earth Structure, New York, NY, WW Norton & Company, 672 p.

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