

Prologue

The following paper will form a major part of Yanxia Guo's M.S. thesis. A shorter version of this paper has been submitted to the SEG as an expanded abstract for 2010 Annual Meeting. I provide this preliminary work as an illustration of a modern attribute-assisted interpretation workflow, and to provide the flavor of the content (and sources!) of my attribute short course. – Kurt J. Marfurt, April 24, 2010.

Seismic attribute illumination of Woodford Shale faults and fractures, Arkoma Basin, OK *Yanxia Guo, Kui Zhang, Jeremy Fisk, and Kurt J. Marfurt, The University of Oklahoma*

Summary

The Woodford Shale formation of western and southern Oklahoma is a hydrocarbon-rich shale that has served as the source rock for many Oklahoma oil and gas plays over the past century. Today, the Woodford Shale is an unconventional resource play similar in age and depositional environment to the prolific Barnett Shale to the south. Like the Barnett, the Woodford Shale contains a large amount of healed natural fractures, has very low permeability, and is amenable to production through hydraulic fracturing. Unlike the Barnett, the Woodford shale can also produce significant amounts of oil as well as gas. The characterization of natural fracture intensity and orientation has a direct impact on horizontal well orientation and completion strategies.

In the study, we use volumetric seismic attributes to map the structural deformation of the Woodford Shale. Coherence allows us to map major faults that appear to have a wrench component, while curvature allows us to map more subtle folds and flexures within the Woodford and overlying Hunton Limestone formations. Analysis of the production data indicates that the best-producing wells correlate to zones associated with k_2 most negative principal curvature (valley-shaped) anomalies. Furthermore, we find a strong correlation between low-impedance lineaments with structural lineaments, strongly suggesting natural fracture-enhanced production.

Introduction

Shale gas is one of the most promising unconventional resources for hydrocarbon exploration and production. Open fractures in shale provide critical porosity and permeability, while healed fractures can be opened for hydrocarbon flow through carefully-designed hydraulic fracturing programs. Recent technical and economic advancement in horizontal drilling techniques have

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made the Mississippian and Devonian Woodford Shale deposited over a large portion of the Midcontinent a significant hydrocarbon play.

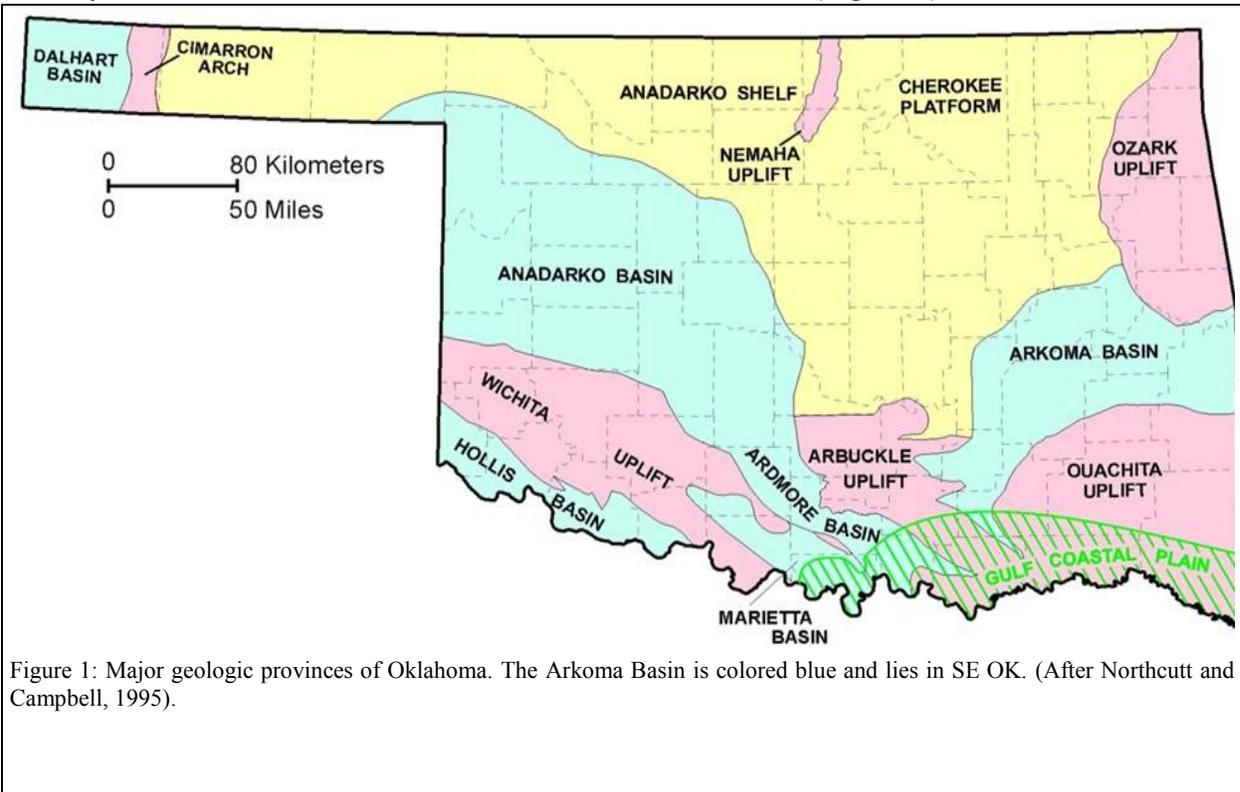
To date, the major use of 3D seismic data in the study of shale gas reservoir has focused on (1) mapping natural fractures (and karst) that can provide enhanced conduits for hydrocarbons (and in the Barnett shale for water from the underlying Ellenberger), and (2) mapping geo-mechanical brittleness and horizontal stress directions for effective hydraulic fracture stimulation. For effective fracability studies, core data and lab measurements of rock samples are critical, providing calibration of elastic parameters extracted from seismic data to identify fracture-prone zones (Goodway et al., 2006; 2007a). Direct measures of fractures include Amplitude vs. Azimuth (AVAZ) (Ruger, 1998; Goodway et al., 2007b), and azimuthal velocity anisotropy (Sicking et al., 2007; Roende et al., 2008; Jenner, 2001).

Indirect methods of fracture prediction from post-stack data include geometric attributes such as coherence and curvature (Chopra et al., 2007; Blumentritt et al., 2006; Chopra et al., 2008). In this study, we applied a suite of post-stack seismic attributes to the Woodford Shale, and find that volumetric curvature-based attributes offer a very promising opportunity to delineate both large and small wavelength fracture lineaments.

Geologic context

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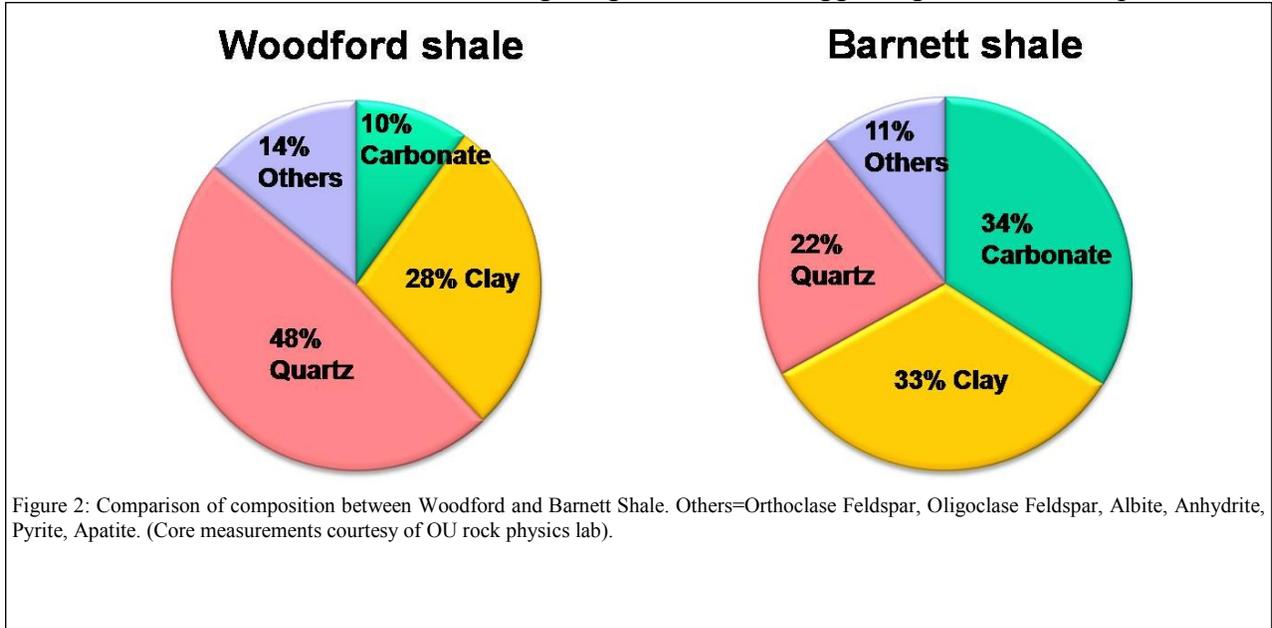
Due to the recent advancements in geology, geophysics, and engineering, the Woodford Shale of the Midcontinent U.S.A. has become an important unconventional resource play. The area under the study is located in the Arkoma basin in southern Oklahoma (Figure 1). The late Devonian to



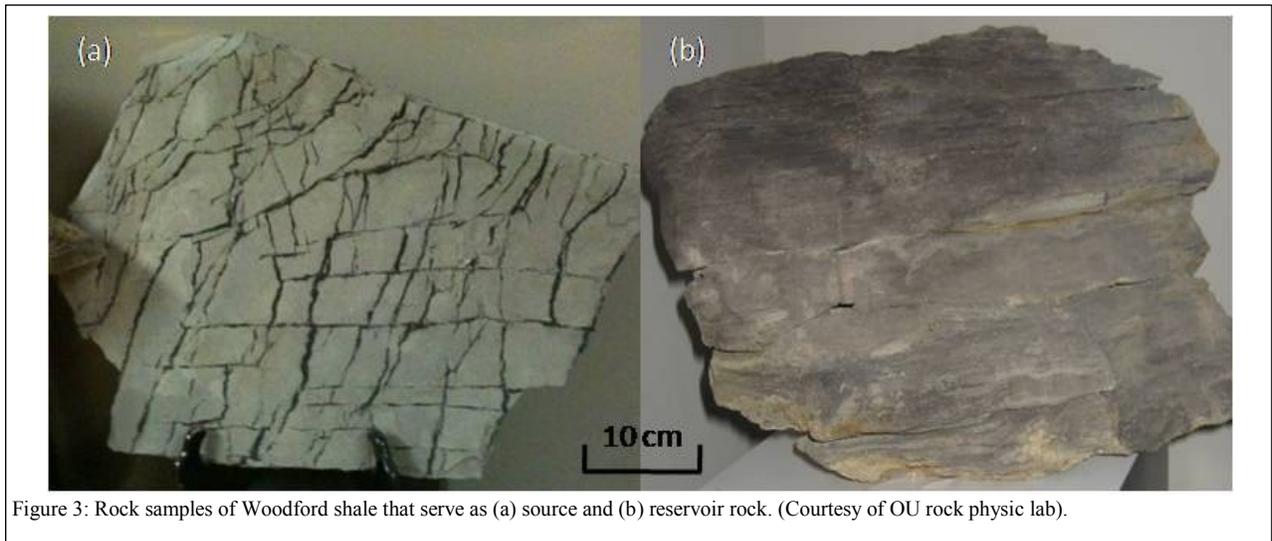
early Mississippian Woodford Shale lies between 6000 to 12000 ft (2000-4000 m) in depth, with thicknesses ranging between 120 and 280 ft (40 and 95 m). The Woodford Shale formation is an organic-rich, fissile black shale which is thought to have been deposited in a deep marine environment, under highly anoxic conditions. Compared to the Barnett Shale (Figure 2), we note

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that the Woodford Shale also contains high organic content suggesting its value as a petroleum



source rock (Figure 3a), as well as a major quartz component which allows it to be fractured. Since gas production in the Woodford Shale is majorly controlled by natural and hydraulic fractures (Figure 3b), the studies of the local stress field and fracture distribution is essential (Miller and Young, 2007).



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Method

In recent years, seismic attributes have proven to be a powerful aid in mapping, qualitatively or even quantitatively, subsurface geological features. When calibrated with wells, seismic attributes sometimes can detect subtle but important structural or stratigraphic components or be statistically correlated with production.

Figure 4 shows a time structure map of the Woodford horizon. In addition to a major wrench fault cutting the horizon into a shallower northern and deeper southern section, we note a fault indicated by the block yellow arrow in the image. Figure 5 shows a conventional RMS amplitude image, calculated using a ± 10 ms window about the Woodford horizon. RMS amplitude attribute calculations are fast and easy to compute. Often, RMS amplitude images can differentiate high amplitude vs. low amplitude reflectivity, even when the reflectors are chaotic, with no easily picked peak or trough. Unfortunately, no significant geologic features are highlighted.

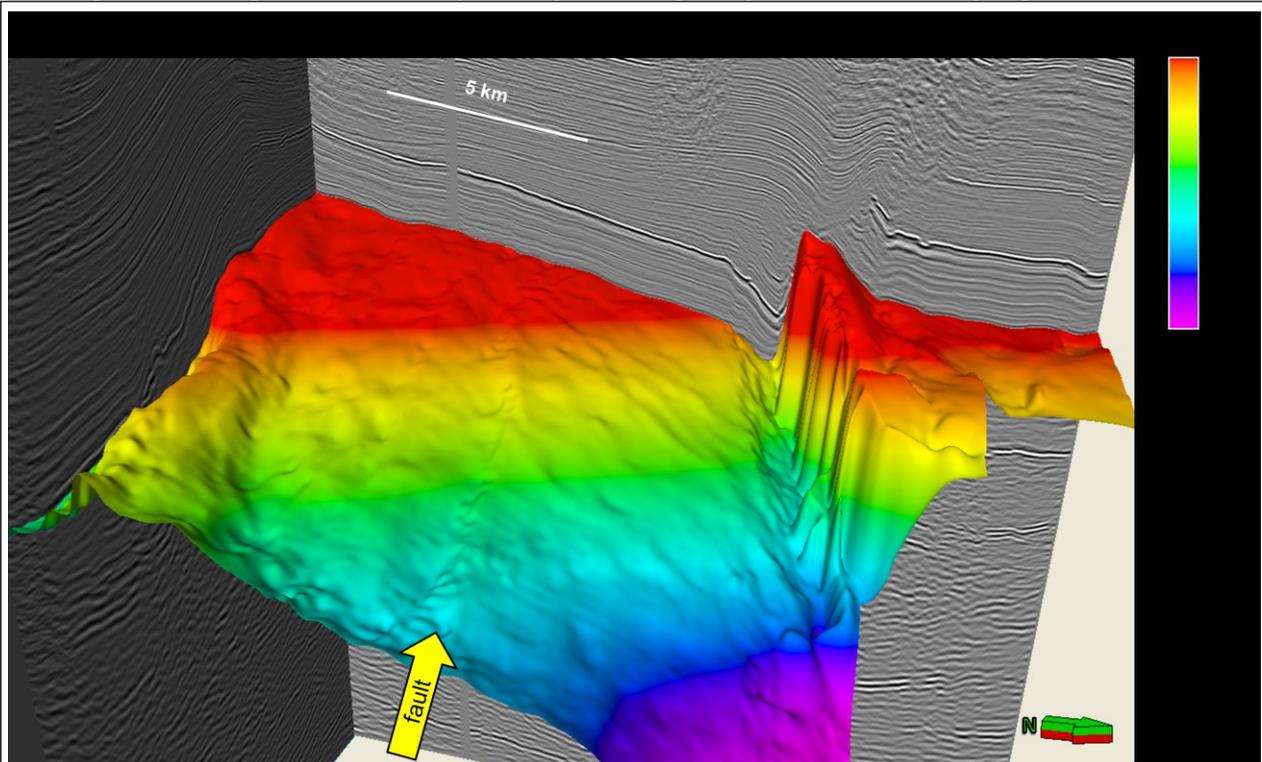
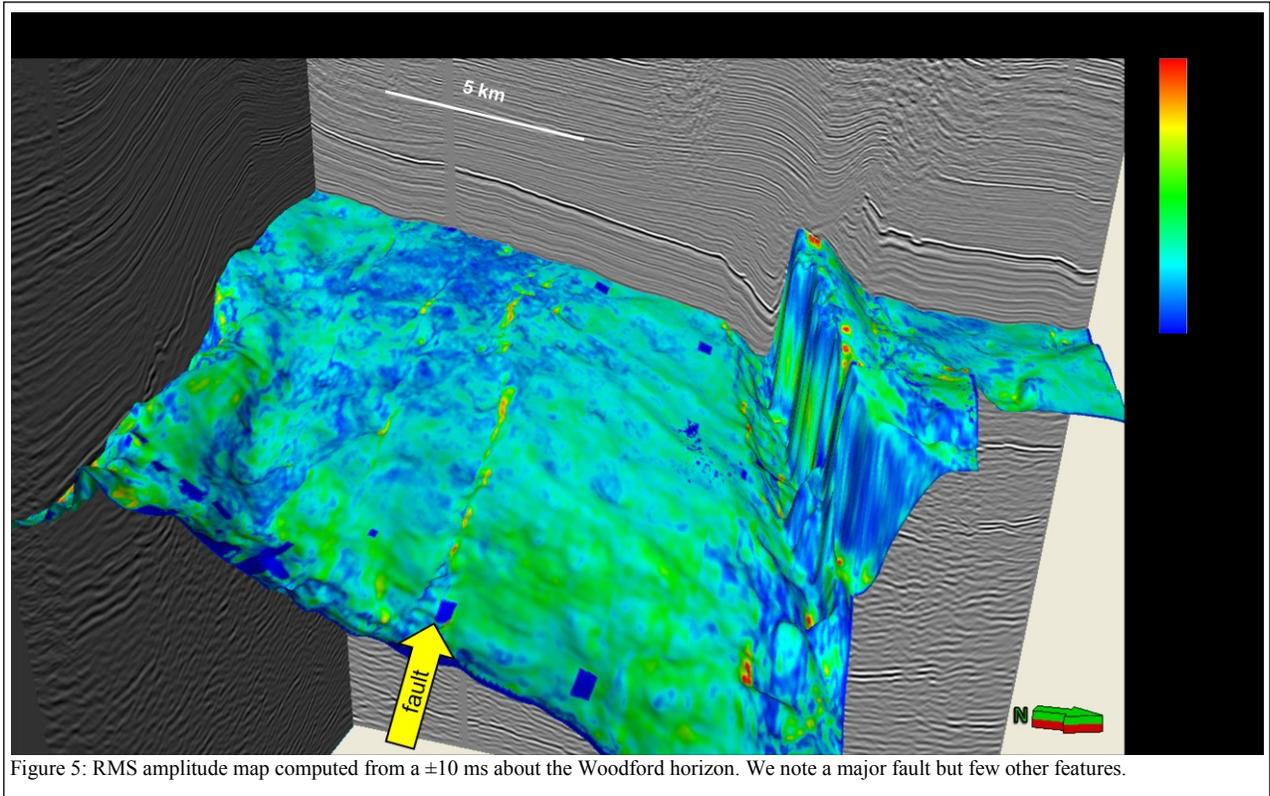


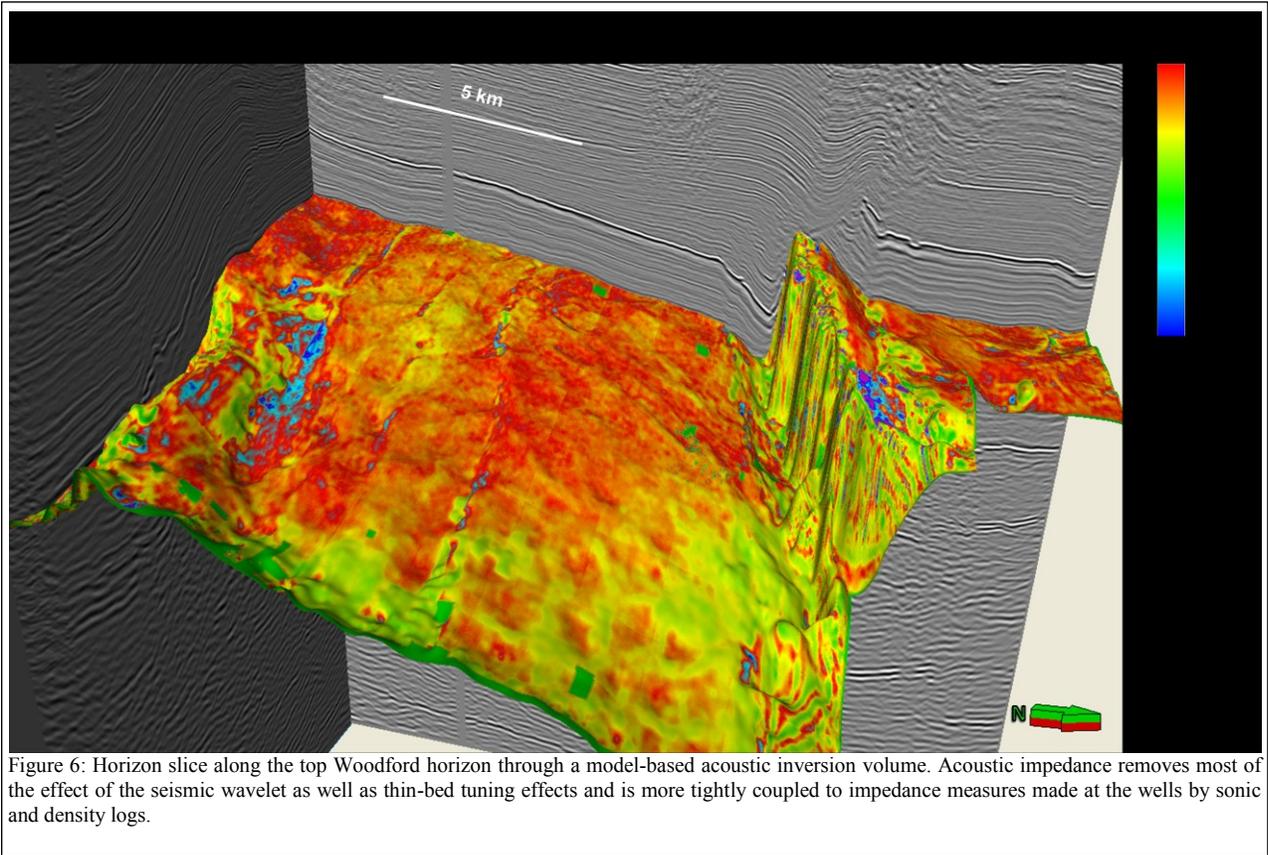
Figure 4: Time structure map of the top Woodford horizon, Arkoma Basin, OK, U.S.A. (Seismic data courtesy of CGG-Veritas).

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A much more sophisticated and time-consuming measure of lithology is acoustic impedance. In Figure 6, we used a model-based acoustic impedance algorithm, which required picking a suite of horizons, tying all the well logs, kriging a background impedance model, and estimating a wavelet. Given the amount of work involved, model-based inversion is usually not considered to be an attribute, although simpler impedance estimates using band-limited and colored inversion usually are. In general, P-impedance, S-impedance, and AVO or AVAz estimates of subsurface properties are combined with simpler attributes such as time-structure, shape, and spectral components through either visualization or through clustering, neural network, or geostatistical analysis. In this paper we will restrict ourselves to visualization. P-impedance removes the effect of the seismic wavelet and most tuning effects. In general, P-impedance is the ‘attribute’ most sensitive to porosity.

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In Figure 7 we display a horizon slice through the coherence volume. In this case, the coherence was computed by taking the ratio of the coherent energy computed using a structure-oriented KL filter to that of the unfiltered (or total energy) within a 9-trace, ± 10 ms analysis window. Coherence does an excellent job of delineating the faults seen on the previous images as well as many smaller faults. We also note several circular incoherent features which we interpret to be collapse features in the underlying Hunton Limestone formation.

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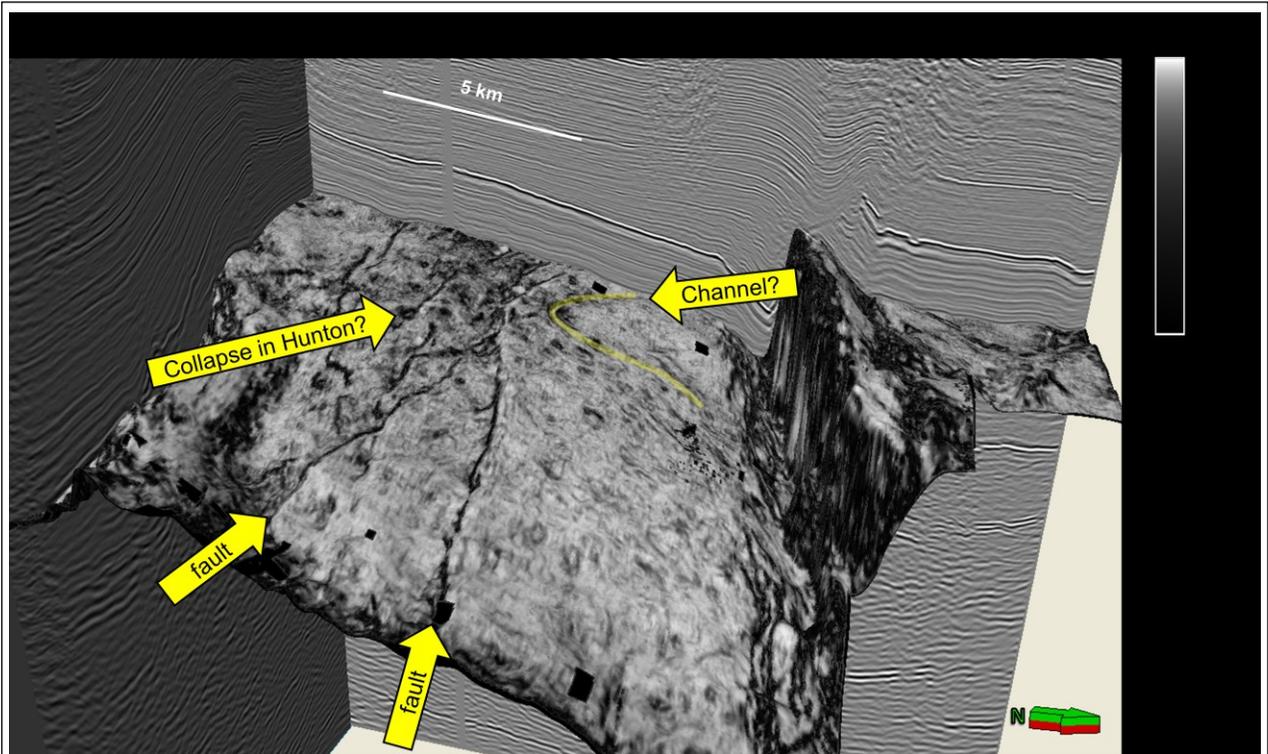
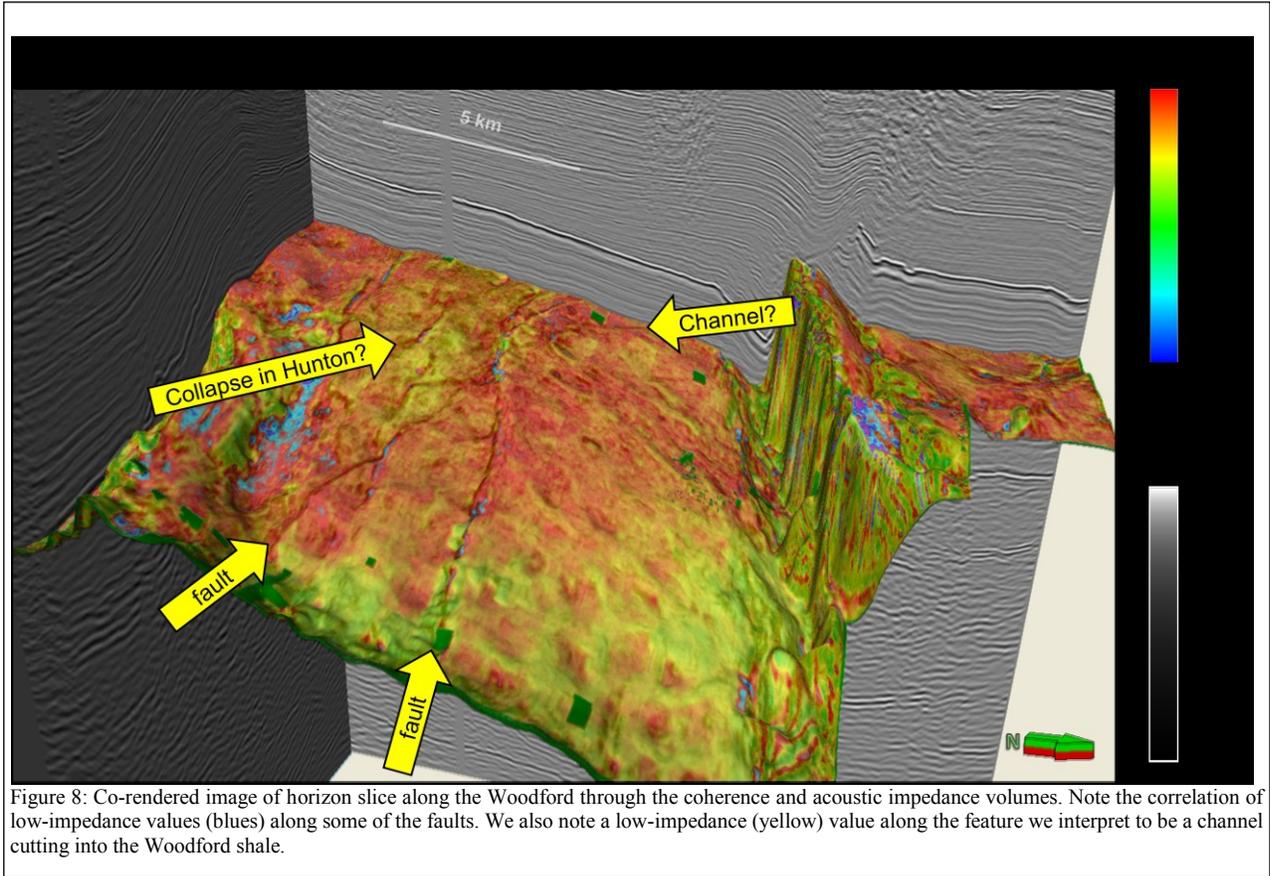


Figure 7: Horizon slice along the Woodford through the coherence volume. We note several other faults, what we interpret to be a collapse feature in the underlying Hunton Limestone, and a possible channel feature through the Woodford shale.

In Figure 8, we co-render the previous two images using transparency. We note that several of the low-coherence (blue) anomalies line up with the faults seen on the coherence image. We also note a low coherence (yellow) trend following the feature we interpreted to be a channel on the coherence image.

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Curvature is another attribute that can be correlated to fractures. Curvature is mathematically independent of coherence and impedance, though similar features may appear in all three attribute images due to coupling through the geology. In 2D, curvature, k , is defined to be the inverse of the radius of curvature, R , and is positive for an anticline, negative for a syncline, and zero for a planar feature (Figure 9). Curvature is computed as

$$k = \frac{1}{R} = \frac{d\theta}{ds} = \frac{dx}{ds} \frac{d}{dx} \left[\arctan \left(\frac{dz}{dx} \right) \right] = \frac{\frac{d^2z}{dx^2}}{\left[1 + \left(\frac{dz}{dx} \right)^2 \right]^{3/2}}, \quad (1)$$

where θ is the angle of the normal from the horizontal, z is the elevation, x is the lateral position, and s the length along the irregular surface. In 3D, we have two perpendicular components of curvature, which we illustrate through the use of a University of Oklahoma football (Figure 10).

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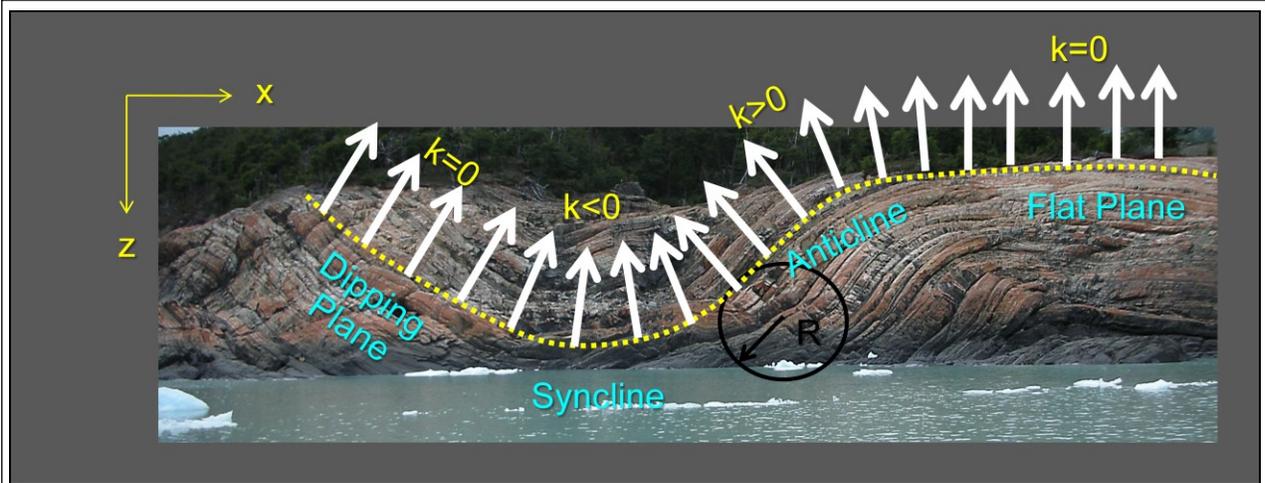


Figure 9: Photo of an outcrop in Lago de Argentina illustrating curvature of a picked horizon (yellow dotted line). The curvature, k , is the reciprocal of the radius of curvature, R . By construction, anticlines have positive curvature, synclines negative curvature, and planar features, zero curvature. (Photo by K. J. Marfurt).

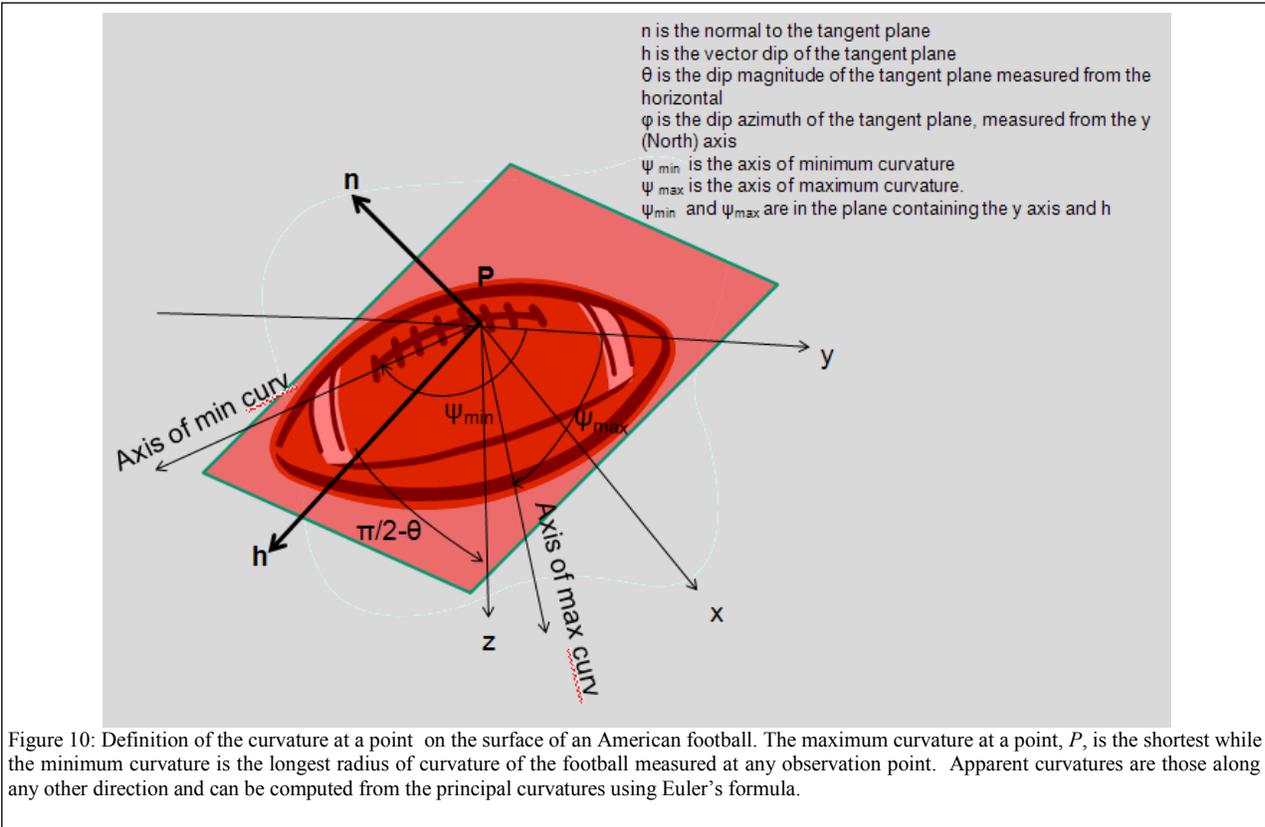


Figure 10: Definition of the curvature at a point on the surface of an American football. The maximum curvature at a point, P , is the shortest while the minimum curvature is the longest radius of curvature of the football measured at any observation point. Apparent curvatures are those along any other direction and can be computed from the principal curvatures using Euler's formula.

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Curvature has long been used as an indication of fractured reservoirs, with one of the earliest published examples being Murray's image of the Bakken Formation of North Dakota, U.S.A. (Figure 11). Like the Barnett and Woodford, the Bakken Shale is a hot play in North America. Unlike the Barnett and Woodford, the Bakken produces mainly oil rather than gas.

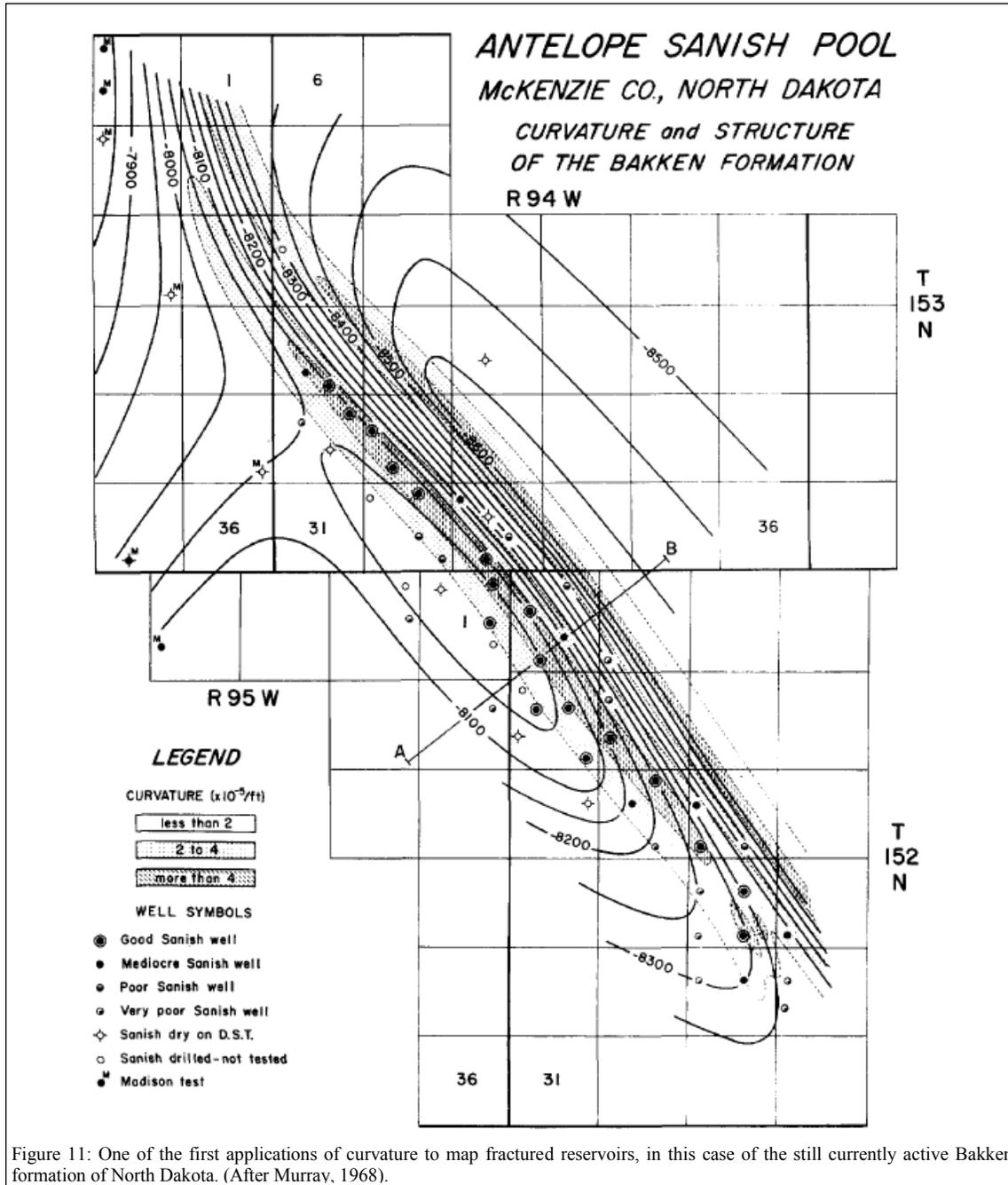


Figure 11: One of the first applications of curvature to map fractured reservoirs, in this case of the still currently active Bakken formation of North Dakota. (After Murray, 1968).

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Figures 12-15 show horizon slices through moderate and long-wavelength volumes of the most-positive and most-negative principal curvatures. In many fracture plays (e.g. Schnerk and Madeen, 2000), large through-going faults seen on coherence should be avoided since they may connect to underlying or overlying aquifers, while more subtle fractures associated with folding may be confined to the formation of interest.

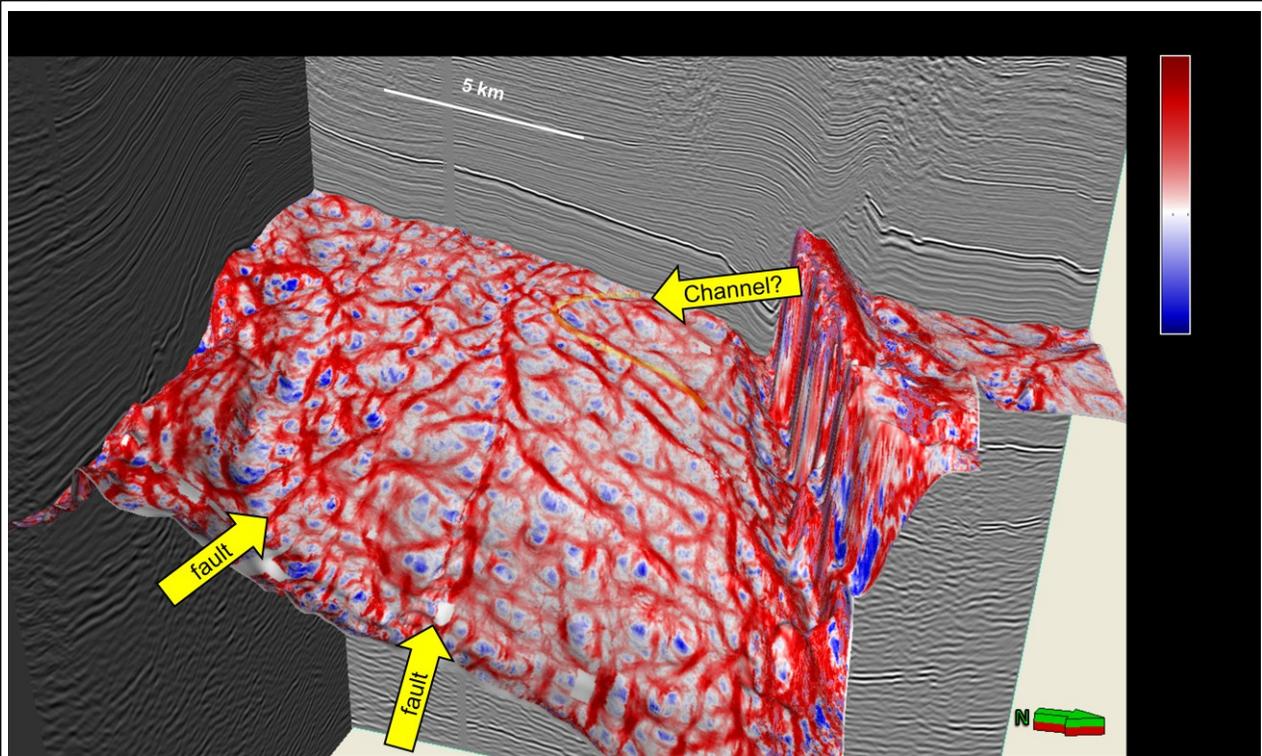
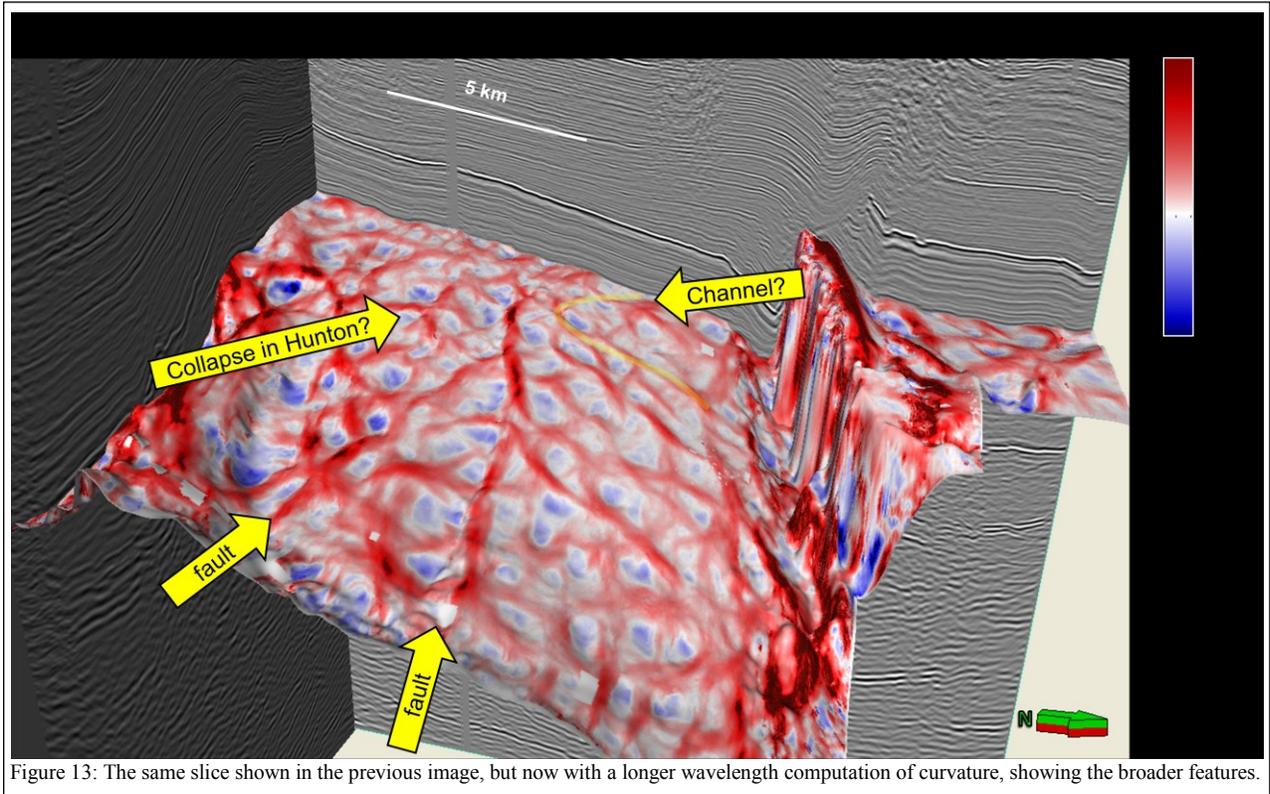
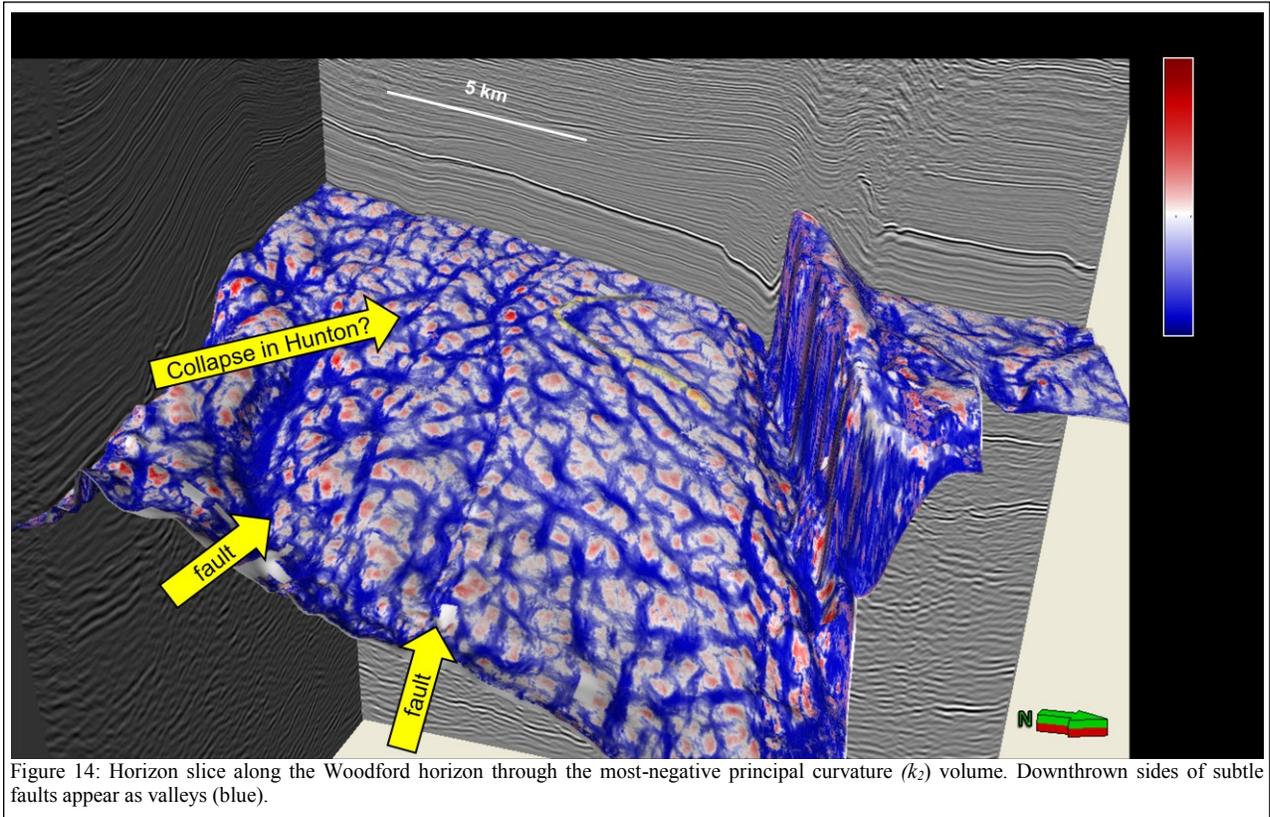


Figure 12: Horizon slice along the Woodford horizon through the most-positive principal curvature (k_1) volume. Upthrown sides of subtle faults appear as ridges (red). The channel shows as a structural high, implying that it is shale filled and has undergone less differential compaction than the surrounding shale.

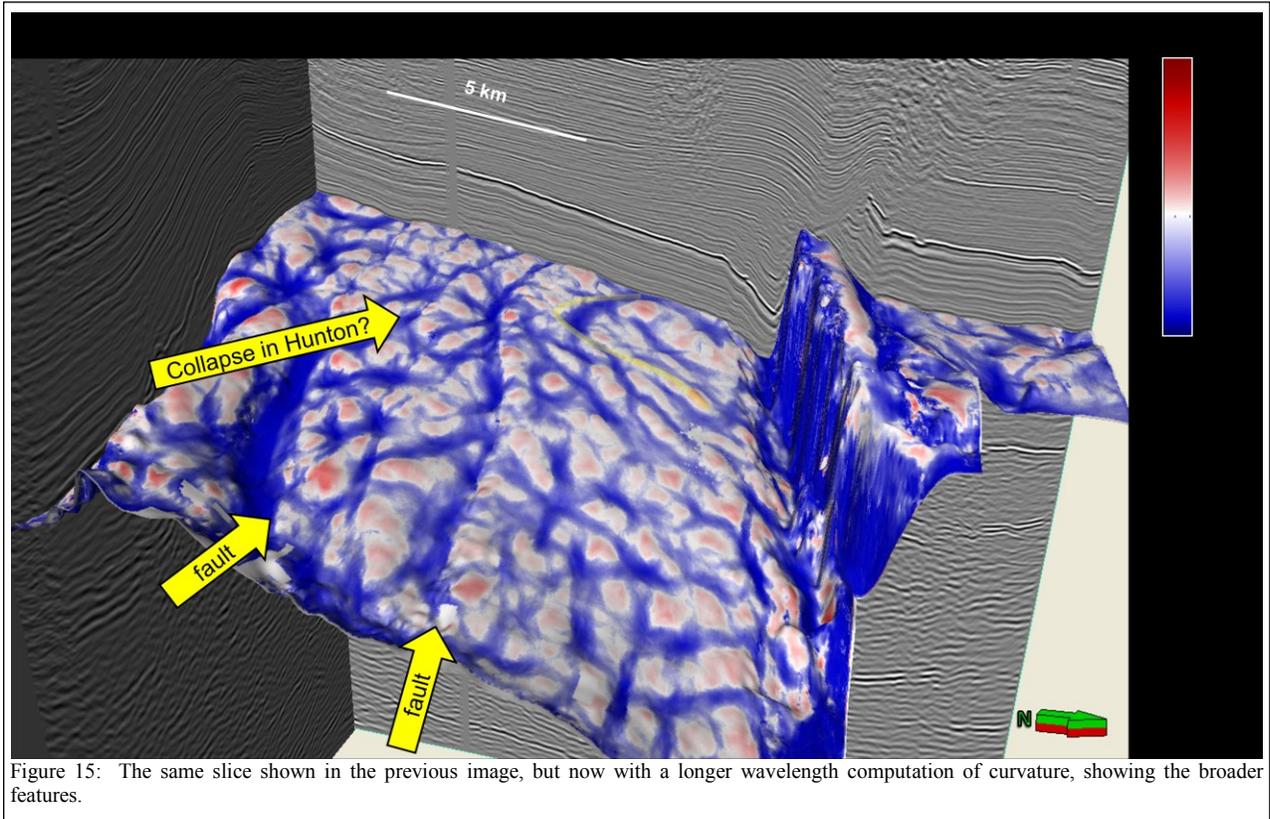
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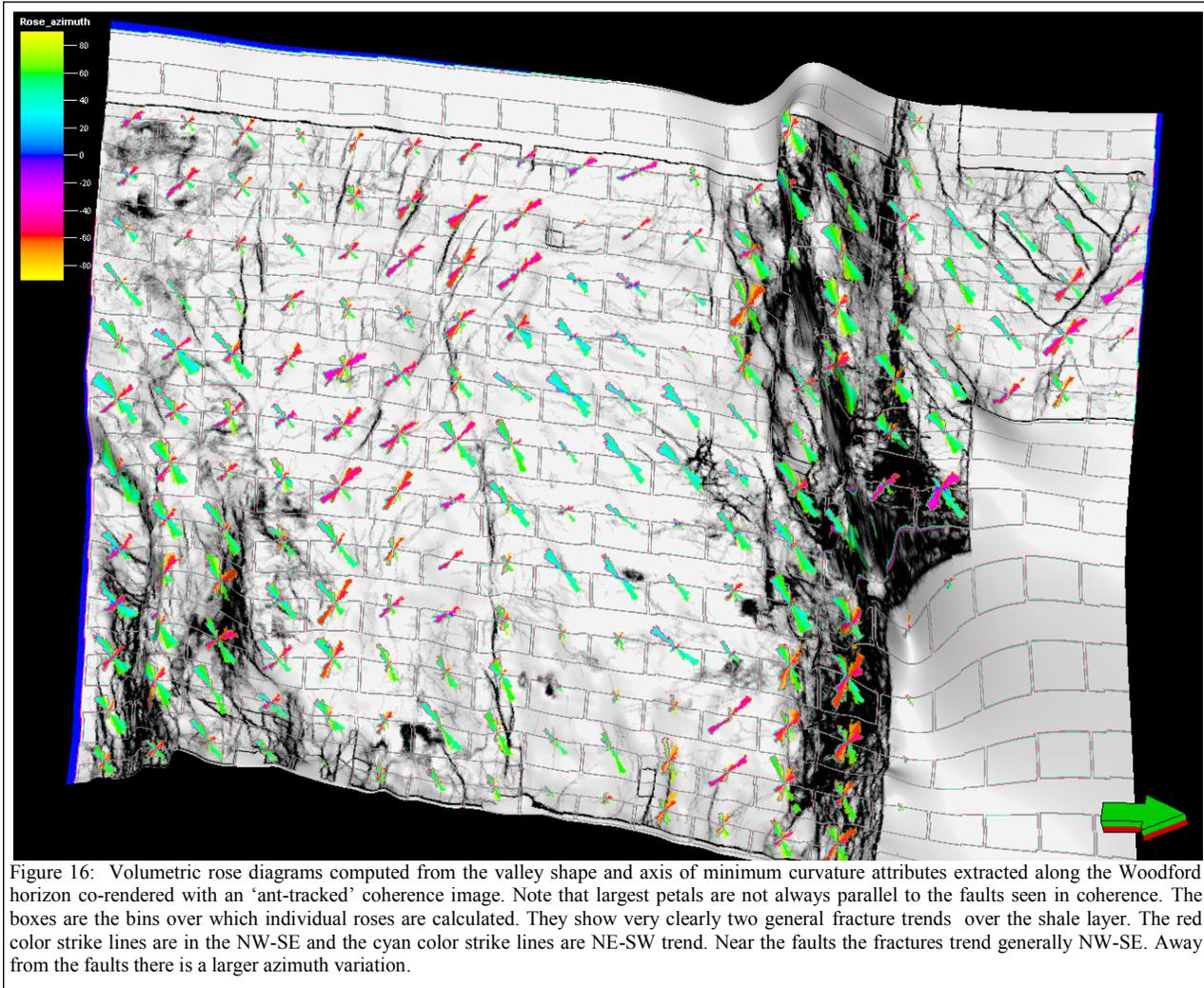


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From the two principal curvatures we can define a suite of quadratic shape components. The valley (synclinal) component can be combined with the azimuth of minimum curvature to form a volumetric rose diagram, such as shown in Figure 16 where we note a strong NE orientation of the structural lineaments.

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Structural curvature of a picked horizon is computed from second derivatives of an interpreted time-structure map. Volumetric structural curvature is quite similar, but is computed from the first derivatives of the volumetric inline and crossline dip components, thereby circumventing the need to pick any horizons. We can also compute second derivatives of other attributes. We do so in Figure 17, which is the most-negative curvature of the impedance image previously shown in Figure 6. We note that there is a strong correlation between lows in the most-negative curvature of impedance image, and the structural lows shown in Figure 14. Such correlations allow us to cluster mathematically independent attributes to come up with one or more geologic hypotheses that define the different measures. In this case, our hypothesis is that all three of these lineaments are consistent with a fractured shale (Figure 18). This correlation is consistent with fracture sweet spots associated with flexures that lower impedance, or alternatively fractures that

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either give rise to an overlying stress release and velocity push-down, or enhance diagenetic alteration and structural lows.

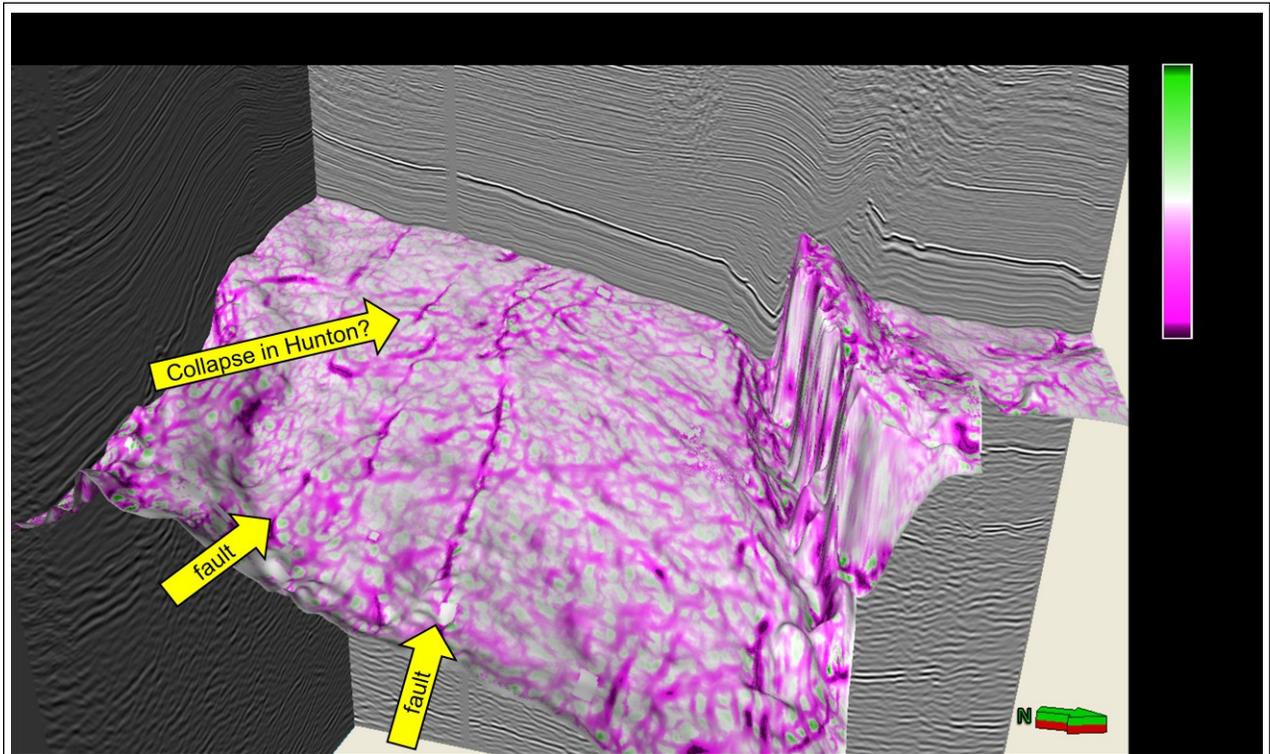
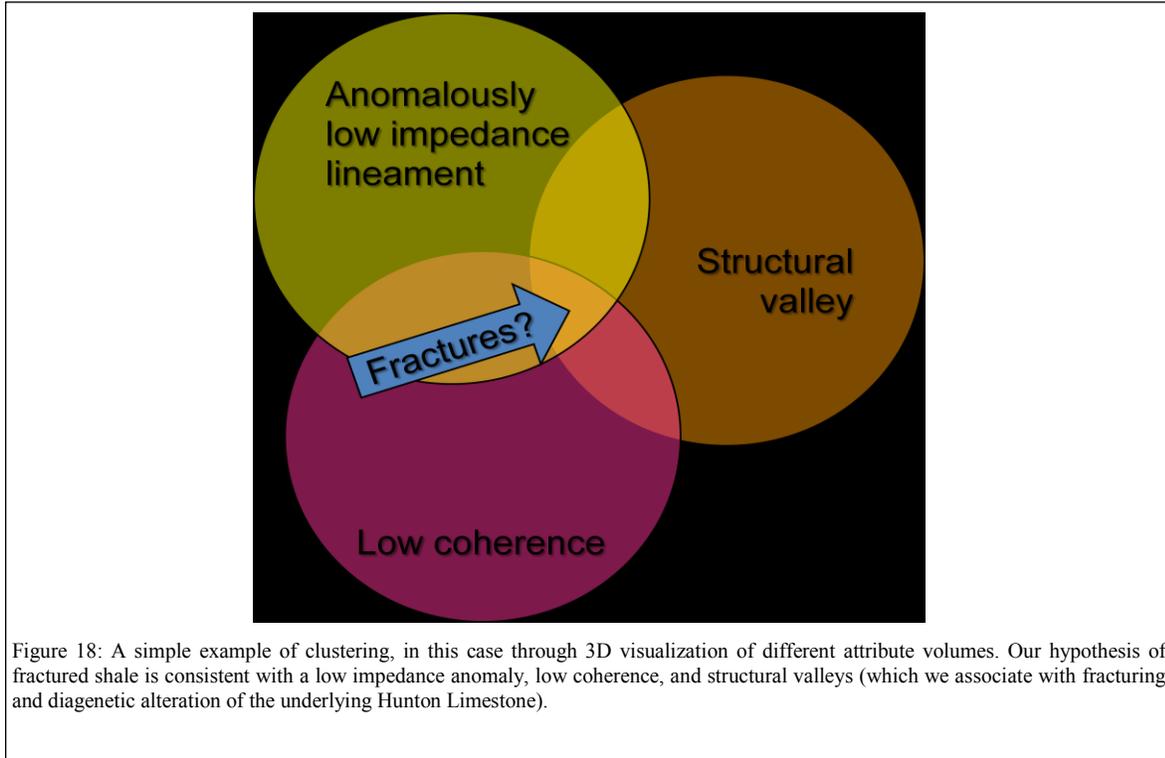


Figure 17: Horizon slice along the Woodford through the most-negative curvature (a 2nd derivative) of the acoustic impedance, highlighting low-impedance lineaments. Compare with the coherence image shown in Figure 7 and the most-negative principal (structural) curvature image shown in Figure 14.

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In Figure 19, we project the production wells onto coherence and k_2 most-negative principal curvature horizon slices, and find that most high oil and gas production wells are correlated with negative curvature anomalies. In contrast, there is no strong visual correlation between the coherence images and production. Red and green bubbles represent gas and oil production respectively with bubble size representing the gross revenue of the first 90 days of those wells calculated using \$4/MCF (thousand cubic feet) for gas and \$80/barrel for oil.

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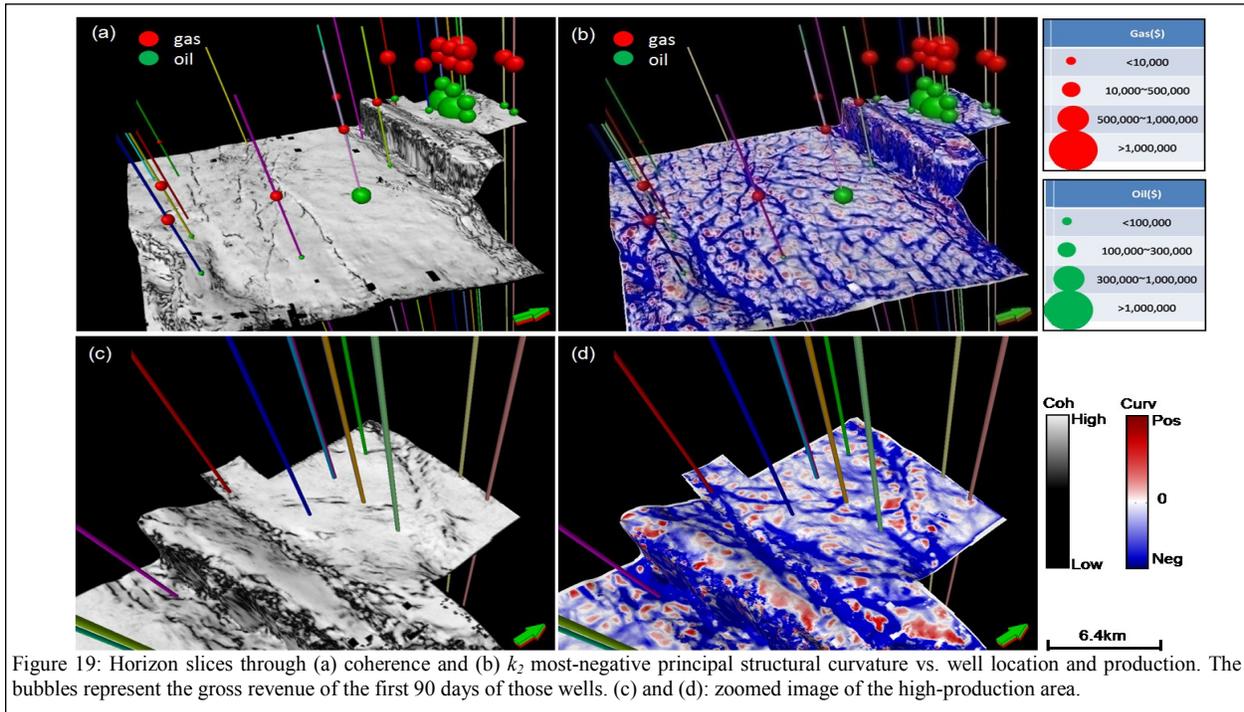


Figure 19: Horizon slices through (a) coherence and (b) k_2 most-negative principal structural curvature vs. well location and production. The bubbles represent the gross revenue of the first 90 days of those wells. (c) and (d): zoomed image of the high-production area.

Discussions and Conclusions

In the Woodford Shale, natural fractures provide a major component of porosity and permeability. For this reason, identification of fracture lineaments is essential to drilling, allowing us to map flexures, low-impedance trends, and azimuth of the minimum and maximum horizontal stress. In our study, volumetric curvature delineates subtle folds and flexures that are correlated to the production data, implying that they are associated with either natural fractures or zones of weakness that are more amenable to hydraulic fractures. We also found the second derivative (most negative curvature) of acoustic impedance shows a high correlation with coherence and most-negative structural curvature, suggesting the presence of either fractures or diagenetic alteration along these flexures. The correlation with production data shows that most of high production wells are close to negative curvature anomalies.

The full understanding of fracture distribution requires the integration of seismic attributes with core data, image logs, and microseismic data. Ongoing work includes correlation of production to mechanically brittle zones using $\lambda\rho$, $\mu\rho$, and λ/μ parameters extracted from AVO analysis.

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analysis. Thanks to Schlumberger and Hampson Russell for providing software licenses for use in research and education. Thanks to the sponsors of the University of Oklahoma Attribute-Assisted Seismic Processing and Interpretation Consortium (AASPI) for their support.

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