Volumetric aberrancy to map subtle faults and flexures
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Summary

One of the key takes of a seismic interpreter is to map lateral changes in surfaces, including faults, folds, and flexures, but also incisements, diapirism, and dissolution features. Volumetrically, coherence provides rapid visualization of faults while curvature provides rapid visualization of folds and flexures. Aberrancy measures the lateral change (or gradient) of curvature along a picked or inferred surface. Aberrancy is complementary to curvature and coherence. In normally faulted terrains, the aberrancy anomaly will track the coherence anomaly and fall between the most-positive curvature anomalies defining the footwall and the most-negative curvature anomalies defining the hanging wall. Aberrancy can delineate faults whose throw falls below seismic resolution, or is distributed across a suite of smaller conjugate faults, which do not exhibit a coherence anomaly.

Previously limited to horizon computations, we extend aberrancy to uninterpreted seismic data volumes. The seismic survey of this study is located in Fort Worth Basin of TX. We will show and compare the results of aberrancy, curvature, and coherence attributes displayed in both seismic time slices and several cross sections.

Introduction

Well known to mathematicians (Schot, 1978), aberrancy has only recently been applied to 3D seismic surveys. Gao, 2013 defines aberrancy as measures the deformation of a surface. Aberrancy measures the lateral change (or gradient) of the curvature of a picked or inferred surface. For example, in two-dimensional space, if the curvature at a neighboring sample point is the same, the same circle would fit both points, and the magnitude of aberrancy would be zero. In three-dimensional space, aberrancy is defined as the vector described by its magnitude and azimuth. The magnitude defines the intensity of surface deformation, while the azimuth indicates the direction in which the curvature decreases. This definition provides as azimuth consistent with that of fault plane azimuths.

Gao and Di, 2015 state that aberrancy is complementary to curvature. In normally faulted terrains, the aberrancy anomaly will track the coherence anomaly and fall between the most-positive curvature anomalies defining the footwall and the most-negative curvature anomalies defining the hanging walls (Chopra and Marfurt, 2007). Unlike coherence which measures lateral changes in waveform and/or amplitude, aberrancy measures lateral changes in curvature, and as such provides not only an indication of the strength of the normal faulting (the magnitude of the vector), but also the direction of the downthrown side (the azimuth of the vector). The value of aberrancy is that it may delineate faults whose throw falls below seismic resolution, or is distributed across a suite of smaller conjugate faults, which do not exhibit a coherence anomaly (Di and Gao, 2016) (Figure 1). For this reason, we hypothesize that aberrancy will be quite useful in correlating surface seismic data to fractures associated with faults that are commonly seen in image logs from horizontal wells.

![Figure 1: Comparison of aberrancy with coherence using two synthetic structure models. (a) Finite offset across a fault usually results in a strong coherence anomaly. (b) In contrast, if the offset is distributed over a zone of conjugate faults, or if the offset falls below seismic resolution, the now continuous reflector no longer gives rise to a coherence anomaly. Curvature would result in two anomalies, a positive anomaly on the footwall indicated by the red circles, and a negative anomaly on the hanging wall indicated by the blue circles. Aberrancy measures the change in curvature which in this example is towards the east, and is displayed as a red-magenta aberrancy anomaly.](image)

We apply our volumetric aberrancy calculation to a data volume acquired over the Barnett Shale gas reservoir of Fort Worth Basin, Texas. In this area, the Barnett Shale is bound on the top by the Marble Falls Limestone and the bottom by the Ellenburger Dolomite. Basement faulting controls karstification in the Ellenburger, resulting in the well-known “string of pearls” pattern seen on coherence images.

Theory and Method

Apparent dip, curvature, and aberrancy

Geoscientists define a locally planar surface by its dip magnitude, $\theta$, and dip azimuth, $\phi$, where $\theta$ is sometimes called the “true dip” to distinguish it from the apparent dip at an azimuth $\beta$. Introducing the dip vector, $p$, measured in dimensionless units of km/km or ft/ft, the apparent dip components along the $x_1$ and $x_2$ axes are...
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$p_1 = \tan \theta \cos \varphi$,  
$p_2 = \tan \theta \sin \varphi$,

while the apparent dip component $p_\beta$ and apparent dip angle $\theta_\beta$ along the azimuth $\beta$ are

\[ p_\beta = \tan \theta \cos \beta, \]
\[ \theta_\beta = \tan^{-1} p_\beta. \]

Most geoscientists are also familiar with the two principal (most-positive and most-negative) curvature values, $k_1$ and $k_2$, and their corresponding strikes, $\gamma_1$ and $\gamma_2$, where Rich and Marfurt (2013) shows that they are the eigenvalues and eigenvectors of a solid geometry problem. Somewhat less familiar is the apparent curvature at a given azimuth, or Euler curvature, $k_\beta$, at strike $\beta$ defined as

\[ k_\beta = k_1 \cos^2 (\beta - \gamma_1) + k_2 \sin^2 (\beta - \gamma_1). \]

Di and Gao (2014) show that one can compute the most-positive and most-negative principal curvatures by searching for extrema of the Euler or apparent curvatures. This search is significantly simplified if one first locally flattens the data about the vector dip at the analysis point. While this approach is somewhat less efficient than the more commonly used eigenvector curvature solution, it provides not only physical insight into the meaning of the principal curvatures, it also provides a means to compute the extrema of aberrancy (Figure 2).

\[ f_\beta = \frac{\partial^2 p_\beta}{\partial x_i \partial x_i} \cos^2 \psi + \frac{3}{2} \left( \frac{\partial^2 p_\beta}{\partial x_i \partial x_j} \right) \cos \psi \sin \psi 
+ \frac{3}{2} \left( \frac{\partial^2 p_\beta}{\partial x_i \partial x_j} \right) \cos \psi \sin \psi \]

where the primes indicate the volumetric dip component, $p'(x', y', z')$ in the rotated coordinate system.

The extrema of the aberrancy are computed by minimizing the value of $f_\beta$ with respect to $\psi$. Note that vector dip is computed using the first derivative of the surface, $z$, and has one extremum, the dip magnitude, and the dip azimuth, which define a single dip vector. Curvature is computed using the second derivatives of the surface $z$ and has two extrema, the most-positive and most-negative principal curvatures and their strikes. Aberrancy is computed using the third derivatives (equation 4) of the surface $z$ and therefore will have in general three extrema. We will call these extrema the maximum, intermediate, and minimum aberrancy vectors expressed by its magnitude, $f_\beta$ and its azimuth $\psi$. The numerical roots of the minimization problem are in terms of $\tan \psi$, such that initially $\psi$ ranges between $\pm 90^\circ$. Inserting these roots into equation 4 may provide negative values of aberrancy $f_\beta$. It is obvious that a negative flexure to the north is equivalent to a positive flexure to the south. For this reason, in our implementation, we define our resulting maximum, intermediate, and minimum aberrancy magnitudes, $f_{\text{max}}$, $f_{\text{int}}$, and $f_{\text{min}}$, to be strictly positive, with the corresponding azimuths $\psi_{\text{max}}$, $\psi_{\text{int}}$, and $\psi_{\text{min}}$ ranging between $\pm 180^\circ$. The analysis and display

![Diagram](image-url)
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of three roots can be cumbersome, although we hypothesize non-zero values of $f_{\text{min}}$, and $f_{\text{max}}$, represent intersecting flexures which may be indicators of increased shear strain. We leave such quantitative analysis to future work which will require image logs calibration. In this extended abstract paper, we will examine total vector aberrancy, $f_{\text{tot}}$, which is simply the sum of the three aberrancy vectors.

Geologic background

The Fort Worth basin is a shallow, north-south-elongated foreland basin extended to around 15,000 mi² (38,100 km²) in north-central Texas (Montgomery et al., 2005). The Ouachita thrust-fold belt, Llano uplift, Bend arch, and the Muensier arch bounds the basin to the east, south, west, and north, correspondingly (Figure 1). Preserved fill in the Fort Worth basin reaches a maximum of about 12,000 ft (3660 m) in the northeast corner, adjacent the Muensier arch (Montgomery et al., 2005). Deposits consist of about 4000-5000 ft (1200-1500 m) of Ordovician-Mississippian carbonates and shales; 6000-7000 ft (1800-2100 m) of Pennsylvanian clastics and carbonates; and, in the eastern parts of the basin, a thin layer of Cretaceous rocks (Montgomery et al., 2005).

The structures in the Fort Worth basin include both major and minor faulting, local folding, fracturing, and karst-related collapse features (Montgomery et al., 2005; Qi et al., 2014). Thrust-fold structures are presented mostly in the easternmost parts of the basin. Studies have shown that the fault exerted significant control on the depositional patterns and thermal history of the Barnett. The small-scale faulting and local subsidence control karstification in the Ellenburger, resulting in the well-known “string of pearls” pattern seen on seismic coherence images (Schuelke et al., 2011).

The Barnett Shale of the Fort Worth Basin, Texas, has played an important role in a gas-shale play in North America. Recent studies estimate that the Barnett Shales may hold as much as 39 trillion cubic feet of gas (tcf) undiscovered (Bruner and Smosna, 2011). The Barnett Shale of the Fort Worth Basin, Texas formed during the late Paleozoic Ouachita Orogeny, generated by the convergence of Laurasia and Gondwana (Bruner and Smosna, 2011). Generalized stratigraphy column of the Fort Worth basin is shown in Figure 2. The Barnett Shale is an organic-rich, petrolierous black shale of middle-late Mississippian age, bounded between Lower Marble Falls and Ellenburger Group (Figure 2). The Marble Falls Formation is conformably overlying the Barnett Shale on top. It typically includes two parts, an upper limestone interval and a lower member of interbedded dark limestone and gray-black shale (Montgomery et al., 2005). The top of Ellenburger Group is an erosional surface (second-order Sauk-Tippecanoe erosional unconformity) commonly characterized by solution-collapse features (Montgomery et al., 2005). We expect to see major and/or minor faulting, local folding, fracturing, and karst-related collapse features within our study area.

Discussion of Results

Seismic data

In 2006, Marathon Oil Company acquired 3D wide-azimuth seismic survey to image the Barnett Shale using 16 live receiver lines with a nominal 16 × 16 m (55 × 55 ft) CDP bin size (Khatiwada et al., 2013). The overall data quality is excellent, with a poststack data-conditioning workflow including edge-preserving structure oriented filtering and spectral balancing performed by Qi et al. (2014) further improving the continuity and vertical resolution. The top Marble Falls Limestone is an easy-to-pick horizon that lies immediately above the Barnett Shale at approximately 0.7 s two-way time (TWT) (Figure 3).

Figure 3. Top of Marble Falls time structure with three crossline AA’, BB’, and CC’. AA’ go across the area where we observe the coherence limitation from North to South, BB’ cut across several major faults from West to East, and CC’ diagonal line cut across karst features.

Aberrancy

After a comparison among the maximum, intermediate, and minimum aberrancy, we decided to use the vector sum of the above three vectors for the following analysis (Figure 4).

Because both aberrancy and coherence are edge-detecting attributes, for a better comparison, we displayed them
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under the same cross sections (Figure 5). Due to the length of this extended abstract, we only show the cross section BB’. In cross section BB’, the faults in the aberrancy image appear as relatively vertically continuous thin lines, while, it appeared as stair step blotches in coherence image.

**Conclusions**

Aberrancy is a new edge-detecting geometric seismic attribute. High order derivatives derivation and multi-step coordinate rotations make the computational of aberrancy in 3D space quite challenging. Because the computation of aberrancy involves higher order derivatives, aberrancy image provides more detailed information regarding surface change compared with coherence.

We demonstrated the value of aberrancy through one case study. The survey of the case study is located in Fort Worth Basin, Texas, where the basement faulting controls karstification in the Ellenburger, resulting in the well-known “string of pearls” pattern seen on coherence images. By comparison among maximum, intermediate, and minimum aberrancy vectors from the synthetic models, we feel that the total aberrancy vector is the most appropriate for structural interpretation; however, the intermediate and minimum aberrancy indicate zones of conflicting flexure, and depending on the tectonic model, may potentially indicate areas of more intense natural fracturing.

Results from the case study show that aberrancy vector may be less sensitive to chaotic zones and thus provide more continuous images that will help delineate structure changes. In the case study, we also showed that coherence is complementary to aberrancy, providing additional insight into the interpretation. The causes of the coherence limitation can be due to either geology (a single fault becoming a flexure, fault splay) or to data quality issues (limit of seismic resolution of a fault offset, or insufficient statics and velocities limiting the lateral resolution of the image). There are more works left need to be done, such as a deeper understanding of the roots to the cubic equation and calibrating the aberrancy with fracture data.

**Acknowledgments**

We thank the industrial sponsors of the Attribute Assisted Seismic Processing and Interpretation (AASPI) Consortia at the University of Oklahoma for their technical guidance and financial support of this work. Dustin Dewett of BHPBilliton and Jamie Rich of Devon Energy both provided particular geological motivation and encouragement. All computations were performed using the AASPI software package. We also thank Schlumberger for licenses for research and education to Petrel 2016 which we used for visualization.