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Seismic geometric attribute analysis for fracture characterization: New methodologies and applications

Haibin Di

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**SEISMIC GEOMETRIC ATTRIBUTE ANALYSIS FOR FRACTURE
CHARACTERIZATION: NEW METHODOLOGIES AND APPLICATIONS**

Haibin Di

Dissertation submitted
to the Eberly College of Arts and Sciences
at West Virginia University

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in
Geology

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Morgantown, West Virginia
2016

Keywords: Seismic Attribute; Discontinuity; Curvature; Flexure; Fault Detection; Fracture
Characterization

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Abstract

Seismic Geometric Attribute Analysis for Fracture Characterization: New Methodologies and Applications

Haibin Di

In 3D subsurface exploration, detection of faults and fractures from 3D seismic data is vital to robust structural and stratigraphic analysis in the subsurface, and great efforts have been made in the development and application of various seismic attributes (e.g. coherence, semblance, curvature, and flexure). However, the existing algorithms and workflows are not accurate and efficient enough for robust fracture detection, especially in naturally fractured reservoirs with complicated structural geometry and fracture network. My Ph.D. research is proposing the following scopes of work to enhance our capability and to help improve the resolution on fracture characterization and prediction.

For discontinuity attribute, previous methods have difficulty highlighting subtle discontinuities from seismic data in cases where the local amplitude variation is non-zero mean. This study proposes implementing a gray-level transformation and the Canny edge detector for improved imaging of discontinuities. Specifically, the new process transforms seismic signals to be zero mean and helps amplify subtle discontinuities, leading to an enhanced visualization for structural and stratigraphic details. Applications to various 3D seismic datasets demonstrate that the new algorithm is superior to previous discontinuity-detection methods. Integrating both discontinuity magnitude and discontinuity azimuth helps better define channels, faults and fractures, than the traditional similarity, amplitude gradient and semblance attributes.

For flexure attribute, the existing algorithm is computationally intensive and limited by the lateral resolution for steeply-dipping formations. This study proposes a new and robust volume-based algorithm that evaluate flexure attribute more accurately and effectively. The algorithms first volumetrically fit a cubic surface by using a diamond 13-node grid cell to seismic data, and then compute flexure using the spatial derivatives of the built surface. To avoid introducing interpreter bias, this study introduces a new workflow for automatically building surfaces that best represent the geometry of seismic reflections. A dip-steering approach based on 3D complex seismic trace analysis is implemented to enhance the accuracy of surface construction and to reduce computational time. Applications to two 3D seismic surveys demonstrate the accuracy and efficiency of the new flexure algorithm for characterizing faults and fractures in fractured reservoirs.

For robust fracture detection, this study presents a new methodology to compute both magnitude and directions of most extreme flexure attribute. The new method first computes azimuthal flexure; and then implements a discrete azimuth-scanning approach to finding the magnitude and azimuth of most extreme flexure. Specially, a set of flexure values is estimated and compared by substituting all possible azimuths between 0 degree (Inline) and 180 degree (Crossline) into the newly-developed equation for computing azimuthal flexure. The added value of the new algorithm is demonstrated through applications to the seismic data set from Teapot Dome of Wyoming. The results indicate that most extreme flexure and its associated azimuthal

directions help reveal structural complexities that are not discernible from conventional coherence or geometric attributes.

Given that the azimuth-scanning approach for computing maximum/minimum flexure is time-consuming, this study proposes fracture detection using most positive/negative flexures; since for gently-dipping structures, most positive is similar to maximum flexure while most negative flexure to minimum flexure. After setting the first reflection derivatives (or apparent dips) to be zero, the localized reflection is rotated to be horizontal and thereby the equation for computing azimuthal flexure is significantly simplified, from which a new analytical approach is proposed for computing most positive/negative flexures. Comparisons demonstrate that positive/negative flexures can provide quantitative fracture characterization similar to most extreme flexure, but the computation is 8 times faster than the azimuth-scanning approach.

Due to the overestimate by using most positive/negative flexure for fracture characterization, 3D surface rotation is then introduced for flexure extraction in the presence of structural dip, which makes it possible for solving the problem in an analytical manner. The improved computational efficiency and accuracy is demonstrated by both synthetic testing and applications to real 3D seismic datasets, compared to the existing discrete azimuth-scanning approach.

Last but not the least, strain analysis is also important for understanding structural deformation, predicting natural fracture system, and planning well bores. Physically, open fractures are most likely to develop in extensional domains whereas closed fractures in compressional ones. The beam model has been proposed for describing the strain distribution within a geological formation with a certain thickness, in which, however, the extensional zone cannot be distinguished from the compression one with the aid of traditional geometric attributes, including discontinuity, dip, and curvature. To resolve this problem, this study proposes a new algorithm for strain reconstruction using apparent dips at each sample location within a seismic cube.

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Chapter 1: Introduction

Detecting faults and fractures from three-dimensional (3D) seismic data is one of the most significant tasks in subsurface exploration, and effective fracture characterization is useful for highlighting the boundaries of fault blocks, stratigraphic units, and hydrocarbon reservoirs. In the past few decades, great efforts have been made and significant advances have been achieved in the development and application of various seismic attributes (e.g. coherence, semblance, curvature, and flexure) to aid such process. Specifically, coherence and semblance, here denoted as discontinuity attributes, measure lateral changes in seismic waveform and amplitude, and the result is often normalized for an enhanced vertical resolution; thereby, seismic discontinuity attribute is a partial and qualitative description of faults and fractures. Quantitative fracture detection can be achieved by using seismic geometric attributes, including curvature and flexure, and such attributes measure lateral changes in reflector geometry which are physically related to structural deformation.

The concept and methodology of discontinuity detection were first proposed by Bahorich and Farmer (1995), which measures the localized waveform similarity of one seismic trace to its adjacent traces by performing a time-lagged crosscorrelation operator; however, the first-generation algorithm involves only three neighboring traces, causing its major limitation of high sensitivity to seismic noises. The signal/noise ratio in the generated discontinuity images is improved by incorporating more traces into waveform similarity estimates, and such an algorithm was the eigenstructure-based coherence approach presented by Gersztenkorn and Marfurt (1996, 1999), which extracts an analysis cube enclosing an arbitrary number of traces and constructs a covariance matrix by crosscorrelating any two waveforms within the cube. Marfurt et al. (1999) proposed an improved eigenstructure-based algorithm that takes into

account the effect of structural dip on accurate attribute estimates. To avoid the time-consuming computation of large covariance matrix, Cohen and Coifman (2002) defined a smaller correlation matrix (4×4) formed from the crosscorrelations of four subvolumes in an analysis cube, and then seismic local structural entropy (LSE) was measured as a discontinuity indicator. While producing similar results to the eigenstructure-based algorithm, the LSE method also fails to take into account the effect of dip on estimating local discontinuities. However, these traditional algorithms provide no robust detection for discontinuities, across which waveform remains the same but amplitude changes sharply due to the presence of gas, because the crosscorrelation operator fails to take into account the amplitude difference between two seismic traces. Tingdahl and de Rooij (2005) then presented a solution by using a similarity operator.

Besides seismic waveform, lateral changes in seismic amplitude are also indicative of local seismic discontinuities. Luo et al. (1996) proposed to compute amplitude gradient as a discontinuity attribute to aid the interpretation of faults and stratigraphic boundaries using 3D seismic surveys. Marfurt et al. (1998) computed semblance for subsurface discontinuity detection. One major limitation of the two traditional methods is the assumption of seismic signals being zero mean, from which discontinuity magnitude can be measured in an accurate manner, 1.0 for discontinuities and 0.0 for continuous portions, or vice versa. In most cases, however, mean of localized amplitude variation rarely is zero, and performing discontinuity detection on such data will undesirably underestimate the values of discontinuity attribute. Therefore, the lateral resolution is limited for subtle faults and stratigraphic boundaries existing in seismic reflectors with non-zero mean.

Since the emergence of Gauss curvature in 3D seismic interpretation as a new attribute of seismic data (Lisle, 1994), curvature has been popular for characterizing fractures in a more

quantitative manner (Roberts, 2001; Sigismondi and Soldo, 2003; Al-Dossary and Marfurt, 2006; Sullivan et al., 2006; Blumentritt et al., 2006; Klein et al., 2008; Chopra and Marfurt, 2007a, 2007b, 2010, 2011). Roberts (2001) discussed the applications of different curvature attributes and presented a workflow for measuring curvature based on 3D interpreted horizons. However, horizon-based curvature estimates are very sensitive to the quality of seismic data. Any noise in seismic data adds to the difficulty for an interpreter to accurately and efficiently pick seismic horizons, which increases the risk of introducing interpreter bias into curvature analysis. With the development of computer-aided dip-steering algorithms (Marfurt et al., 1998; Marfurt and Kirlin, 2000; Marfurt, 2006; Barnes, 2007), Al-Dossary and Marfurt (2006) improved the process by calculating volumetric curvature. In particular, they applied a running window semblance-based method to volumetrically measure the first derivatives of a seismic reflector (also known as reflector apparent dips), and used an approach of fractional-order derivatives to compute the second derivatives of the reflector. For horizontal or gently-dipping horizons, the algorithm is close to accurate curvature estimates; however, for steeply-dipping horizons, the algorithm will “undesirably mix geology of different formations” (Al-Dossary and Marfurt, 2006). This limitation results from the fact that the fractional approach calculates the derivatives of dip on time slices as an approximation of the desired reflector second derivatives.

Flexure, or curvature gradient proposed by Gao (2013), defined as a spatial derivative of curvature attribute, is a third-order estimate of seismic reflector geometry and can complement curvature attribute for improved fracture characterization. Similar to seismic curvature, 3D flexure is dependent on the azimuthal direction, and at every sample within a 3D seismic volume, flexure could be evaluated along any given azimuth. Among those different azimuthal directions, four important azimuths for structure interpretation include the true dip direction, the

strike direction, and two principle directions that are associated with the maximum and minimum of all the flexure values, respectively. Physically, fractures are most likely to develop along the orientation of abnormal strains, and this orientation is often associated with most extreme flexure. Thus, a fracture network can be better detected by combining most extreme flexure with its azimuthal directions: using the magnitude and azimuthal direction of the attributes to predict fracture intensity and fracture orientation, respectively (Gao, 2013). Evaluation for most extreme curvature and most extreme curvature gradient is computationally intensive. The first generation of flexure algorithm (Gao, 2013) is to combine two gradient cubes of curvature measured along inline and crossline directions. However, this method assumes local linear nature of flexure attribute, which is not accurate in most cases. Thus, an efficient algorithm remains to be developed for computing most extreme flexure and most extreme flexure azimuth.

Besides fracture detection, quantifying strain is also important for understanding structural deformation and predicting natural fracture system, which is particularly helpful for hydraulic fracture simulation. A beam model was presented to describe the deformation of a reservoir formation with a certain thickness. As it bends to an anticline, extension increases towards the top, compression increases towards the base, and in the middle is a neutral surface where no strain occurs (Roberts, 2001). Physically, open fractures are most likely to develop in the extensional zone whereas closed fractures in the compressional one. Seismic curvature has been used to predict fracture intensity over a mapped horizon (Lisle, 1995; Stewart and Podolski, 1998; Roberts, 2001); however, such attribute cannot discriminate the extensional zone from the compressional one, leading to its major limitation for characterizing fracture mode. Therefore, it is of great importance to propose an algorithm for reconstructing strain field across the reservoir in the subsurface.

This dissertation combines the work of five peer-review journal papers and one SEG expanded abstract focusing on seismic geometric attribute extraction. I have improved and/or developed algorithms for computing seismic discontinuity and flexure attributes, and applied them to fracture characterization in fractured reservoirs. My dissertation is organized in a form of a list of scientific papers.

In Chapter 2, I present a new discontinuity algorithm by combining gray-level transformation and the Canny edge detector for qualitative fault detection, which transforms seismic signals to be zero mean and provides an enhanced visualization for structural and stratigraphic details. This Chapter has been published in *Computer & Geosciences*.

In Chapter 3, I present new algorithms for computing 3D seismic curvature and flexure attribute along the dip direction. It builds a cubic surface using a 13-node grid cell to fit seismic reflection, so that dip flexure can be evaluated more accurately and effectively, especially for steeply-dipping formations. This Chapter has also been published in *Computer & Geosciences*.

In Chapter 4, I present new algorithms for computing most extreme curvature and most extreme flexure, which are considered most effective for structural analysis and fracture characterization. In particular, they are computed by an analytical approach and a discrete azimuth-scanning approach, respectively. Part of this Chapter is published in *Geophysics*.

In Chapter 5, I present new algorithms for computing most positive/negative curvature and flexure, which provide an edge-type display of faults and fractures and can greatly facilitate fracture interpretation from curvature/flexure images. Moreover, they are computed by analytical algorithms with significant improvement in computation efficiency. This Chapter has been published in *Geophysical Prospecting*.

In Chapter 6, I present new analytical algorithms for computing most extreme curvature and most extreme flexure based on 3D surface rotation. The new algorithm is more computational efficient compared to the previous discrete-scanning algorithm, and moreover the results are more accurate in the presence of structural dip. This Chapter has been published in *Geophysics*.

In Chapter 7, I present a preliminary algorithm for strain analysis from 3D seismic, which is a challenging topic and more work is expected on testing and improving it in the further. This Chapter has been accepted for presentation at 2015 SEG annual meeting.

Each of the above Chapters is followed by the appropriate references.

It is necessary to add a concise clarification of the “fracture” term used through the dissertation to avoid confusion and/or misunderstanding about fracture characterization from 3D seismic. Whenever “fracture” is mentioned, it refers to the localized zone where fractures are more likely to develop, instead of a single lineament usually considered in geology as well as core analysis. Such limitation results from the limited resolution of seismic surveying varying from several meters to several hundred meters, especially for post-stack data that is often used seismic interpretation. High-frequency signals are required for discerning each single fracture at the scale of millimeter or even micrometer; unfortunately, such signals cannot be well preserved after seismic data collection and processing.

Chapter 2: Gray-level Transformation and Canny Edge Detection for 3D Seismic

Discontinuity Enhancement

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Abstract

In 3D seismic survey, detection of seismic discontinuity is vital to robust structural and stratigraphic analysis in the subsurface. Previous methods have difficulty highlighting subtle discontinuities from seismic data in cases where the local amplitude variation is non-zero mean. This study proposes implementing a gray-level transformation and the Canny edge detector for improved imaging of discontinuity. Specifically, the new process transforms seismic signals to be zero mean and helps amplify subtle discontinuities, leading to an enhanced visualization for structural and stratigraphic details. Applications to various 3D seismic datasets demonstrate that the new algorithm is superior to previous discontinuity-detection methods. Integrating both discontinuity magnitude and discontinuity azimuth helps better define channels, faults and fractures, than the traditional similarity, amplitude gradient and semblance attributes.

Introduction

Recognizing subsurface structural and stratigraphic discontinuities is crucial in subsurface exploration, and an effective workflow for discontinuity detection from seismic is useful for highlighting boundaries of fault blocks, stratigraphic units, and hydrocarbon reservoirs (e.g., Bahorich and Farmer, 1995; Marfurt et al., 1998; Bakker, 2003; Blumentritt et al., 2003; Wang and Carr, 2012; Zheng et al., 2014). Previously, great efforts have been made and significant

advances have been achieved in the development and application of various discontinuity-detection algorithms to aid subsurface exploration (e.g., Bahorich and Farmer, 1995-; Haskell, et al., 1995; Luo et al., 1996; Marfurt et al., 1998; Gersztenkorn and Marfurt, 1996, 1999; Marfurt et al., 1999; Marfurt and Kirlin, 2000; Chopra, 2002; Cohen and Coifman, 2002; Blumentritt et al., 2003; Lu et al., 2003; Luo et al., 2003; Lu et al, 2005; Tingdahl and de Rooij, 2005). The coherence algorithm for discontinuity detection were first proposed by Bahorich and Farmer (1995), which measures the localized waveform similarity of one seismic trace to its adjacent traces by performing a time-lagged cross-correlation operator; however, the first-generation algorithm involves only three neighboring traces, causing the algorithm extremely sensitive to seismic noises. The signal/noise ratio in the generated discontinuity images is improved by incorporating more traces into waveform similarity estimates, and such an algorithm was the eigenstructure-based coherence approach presented by Gersztenkorn and Marfurt (1996, 1999). The algorithm extracts an analysis cubic window enclosing an arbitrary number of traces and constructs a covariance matrix by crosscorrelating any two waveforms within the window. Marfurt et al. (1999) proposed an improved eigenstructure-based algorithm that takes into account the effect of structural dip on accurate attribute estimates. To avoid the time-consuming computation of large covariance matrix, Cohen and Coifman (2002) defined a smaller correlation matrix (4×4) formed from the crosscorrelations of four subvolumes in an analysis cube, and then local structural entropy (LSE) was measured as a discontinuity indicator. While producing similar results to the eigenstructure-based algorithm, the LSE method also fails to take into account the effect of dip on estimating local discontinuities. In addition, these traditional algorithms provide no robust detection for discontinuities, across which waveform remains the same but amplitude changes sharply due to the presence of gas, because the crosscorrelation

operator fails to take into account the amplitude difference between two seismic traces. Tingdahl and de Rooij (2005) then presented a solution by using a similarity operator (Equation 1).

$$c(t, l, 2w) = \frac{\sqrt{\sum_{\tau=-w}^{+w} [u(t-\tau) - v(t-\tau+l)]^2}}{\sqrt{\sum_{\tau=-w}^{+w} u^2(t-\tau) + \sum_{\tau=-w}^{+w} v^2(t-\tau+l)}} \quad (1)$$

where u and v denote two trace segments. l is the temporal lag of trace v relative to trace u , and $2w$ is the length of the vertical analysis window.

In addition to seismic waveform, lateral changes in seismic amplitude are also indicative of local seismic discontinuities. Luo et al. (1996) used amplitude gradient as a discontinuity attribute to aid the interpretation of faults and stratigraphic boundaries. Marfurt et al. (1998) used semblance for discontinuity detection. Basically, both schemes first retrieve seismic amplitude within a spatial analysis window centered about a given sample location, and then perform edge detection in the inline (x-) and crossline (y-) directions on the retrieved seismic amplitude data (Equation 2).

$$c = (f_x * u)^2 + (f_y * u)^2 \quad (2)$$

where u denotes the seismic amplitude data. Asterisk $*$ denotes convolution. f_x and f_y denote a set of edge detectors in the x- and y-directions, respectively, and the set of edge detectors could be any detector used in image processing. Specifically, the amplitude-gradient algorithm uses the simplified Sobel operator with 9 traces (Equation 3) and the semblance algorithm uses the mean operator with arbitrary traces (Equation 4).

$$F_x = \frac{1}{2} \begin{bmatrix} 0 & 0 & 0 \\ -1 & 0 & +1 \\ 0 & 0 & 0 \end{bmatrix}, \text{ and } f_y = \frac{1}{2} \begin{bmatrix} 0 & +1 & 0 \\ 0 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} \quad (3)$$

$$f_x(x_j, y_j) = f_y(x_j, y_j) = \frac{1}{J} \quad (4)$$

in which J denotes the spatial analysis window size.

In 3D seismic interpretation, these amplitude-based methods often implement two additional operations to improve the quality of discontinuity cubes (Equation 5). One is to use a vertical analysis window through which attribute is summed to improve the signal/noise ratio; and the other is to normalize the discontinuity value from Equation 2 by the intensity of local seismic reflections within the analysis window to enhance the vertical resolution of weak seismic reflections.

$$c(t, p, q, 2w) = \frac{\sum_{\tau=-w}^{+w} \left\{ \left[\sum_{j=1}^J f_x(x_j, y_j) \cdot u(t+\tau+px_j+qy_j) \right]^2 + \left[\sum_{j=1}^J f_y(x_j, y_j) \cdot u(t+\tau+px_j+qy_j) \right]^2 \right\}}{\sum_{\tau=-w}^{+w} \left\{ \sum_{j=1}^J |f_x(x_j, y_j)| \cdot [u(t+\tau+px_j+qy_j)]^2 + \sum_{j=1}^J |f_y(x_j, y_j)| \cdot [u(t+\tau+px_j+qy_j)]^2 \right\}} \quad (5)$$

where p and q denote the apparent reflector dips along inline (x-) and crossline (y-) directions. x_j and y_j denote the distance along x-and y-directions, measured from the centered sample location to the j th sample location within the detectors.

Robust discontinuity detection using Equation 1 or Equation 5 relies on the assumption that the input seismic amplitude should vary with zero mean, from which 1.0 and 0.0 are evaluated for discontinuities and continuous portions, or vice versa. However, when the features of interest fail to be zero mean, both equations provide an underestimate of the discontinuity attribute and such estimates would decrease the lateral resolution on defining subtle faults and stratigraphic boundaries that are vital for understanding subsurface geology. We use the 3D seismic dataset from the Stratton field in Texas to demonstrate the limitation. The shallow unit in this area is dominated by a fluvial depositional system. A west-east meandering channel is clearly depicted at 844 ms (Figure 2-1a). The amplitude volume is processed with three different traditional discontinuity-detection algorithms, and the corresponding attribute images are displayed with Figure 2-1b from the similarity scheme (Tingdahl and de Rooij, 2005), Figure 2-1c from the

amplitude-gradient scheme (Luo et al., 1996), and Figure 2-1d from the semblance scheme (Marfurt et al., 1998). All methods define the western portion of the channel system, across which we notice amplitude variation from -1500 to 1500, close to be zero mean (denoted by rectangle 1); however, channels become difficult to define in the eastern portion, where amplitude varies from -1500 to 300 (denoted by rectangle 2).

To resolve the problem, this study presents a new algorithm for better discontinuity detection by performing a gray-level transformation on localized amplitude data, and the Canny edge detector is introduced from classical 2D image analysis to capture subtle amplitude changes in a more efficient manner. The new algorithm is then applied to 3D seismic datasets from the Stratton field (Texas), Teapot Dome (Wyoming), and the offshore Netherlands (North Sea).

New methodology

Our method is based on a mathematic operation that transforms localized seismic signal with non-zero mean to be zero mean. One straightforward approach is to subtract the non-zero mean from all amplitude samples enclosed in the spatial analysis window.

$$u_{new} = u - u_{mean} \quad (6)$$

where u denotes seismic amplitude data, and u_{mean} denotes its mean. An alternative approach is to rescaling Equation 7 by gray levels (Di and Gao, 2013).

$$g = Round(\frac{u - u_{min}}{\delta}) - N \quad (7)$$

where u_{max} and u_{min} denote the amplitude maximum and minimum within the analysis window, respectively. $\delta = \frac{1}{2N} (u_{max} - u_{min})$ denotes the interval between two adjacent gray levels. $2N + 1$ denotes the number of gray levels. For example, Figure 2-2 demonstrates the gray-level transformation with five levels ($N = 2$). The advantage of applying Equation 7 over Equation 6

is to re-characterize localized features using the same scale, regardless of whether the amplitude changes within the features is apparent or subtle. In the case of the Stratton data, the stratigraphic features denoted by both rectangles in Figure 2-1 are extracted and displayed in Figure 2-3a and Figure 2-3b, respectively. Using the regular amplitude scale, it is apparent that amplitude changes more sharply in the west (from -1500 to 1500 in Figure 2-3a) than the east (from -1500 to 300 in Figure 2-3b). After applying the gray-level transformation with 41 levels ($N = 20$), both features become zero mean, and the amplitude changes in the east (Figure 2-3d) are enhanced to the same scale as those in the west (Figure 2-3c). Consequently, the channel boundaries in the eastern portion can be better captured by performing edge detection from the transformed data. Our experiments indicate that better approximation of local features can be achieved by using 41 gray levels ($N = 20$) or more, without introducing non-seismic artifacts signals.

An efficient edge detector is also crucial in robust detection and characterization of seismic discontinuities. Besides the simplified Sobel operator (Equation 3) and the mean operator (Equation 4), studies in 2D image processing have developed several other powerful edge detectors for capturing edges in a digital image, such as the full Sobel operator (Equation 8), the Roberts operator (Equation 9) (Roberts, 1963), the Prewitt operator (Equation 10) (Prewitt, 1970), and particularly the Canny detector (Equation 11) (Canny, 1986), which is evaluated as the partial derivatives of the Gaussian filter along x- and y-directions, respectively (Figure 2-4).

$$f_x = \frac{1}{8} \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix}, \text{ and } f_y = \frac{1}{8} \begin{bmatrix} +1 & +2 & +1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} \quad (8)$$

$$f_x = \frac{1}{2} \begin{bmatrix} +1 & 0 \\ 0 & -1 \end{bmatrix}, \text{ and } f_y = \frac{1}{2} \begin{bmatrix} 0 & +1 \\ -1 & 0 \end{bmatrix} \quad (9)$$

$$f_x = \frac{1}{6} \begin{bmatrix} -1 & 0 & +1 \\ -1 & 0 & +1 \\ -1 & 0 & +1 \end{bmatrix}, \text{ and } f_y = \frac{1}{6} \begin{bmatrix} +1 & +1 & +1 \\ 0 & 0 & 0 \\ -1 & -1 & -1 \end{bmatrix} \quad (10)$$

$$f_x = \frac{\partial G}{\partial x} = -\frac{x}{\sigma^2} \cdot G, \text{ and } f_y = \frac{\partial G}{\partial y} = -\frac{y}{\sigma^2} \cdot G \quad (11)$$

where G denotes the Gaussian filter, in which σ is the standard deviation.

$$G = \exp\left(-\frac{x^2+y^2}{2\sigma^2}\right) \quad (12)$$

All six detectors are tested and the results are shown in Figure 2-6. For fair comparison, the amplitude-gradient slice (Figure 2-6a) and the semblance slice (Figure 2-6b) are generated from a gray-level transformed data, instead from the traditional amplitude. The comparison demonstrates that the Canny edge detector (Figure 2-6f) produces best results when applied to 3D seismic discontinuity analysis.

Implementing the gray-level transformation (Equation 7) coupled with the Canny edge detector (Equation 11) leads to an improved algorithm for discontinuity detection, which produces two attribute cubes with one being discontinuity magnitude and the other being discontinuity azimuth which are defined to be $c(t, p, q, 2w)$ and $\theta(t, p, q, 2w)$, respectively.

$$c(t, p, q, 2w) = \frac{\sum_{\tau=-w}^{+w} \left\{ \left[\sum_{j=1}^J f_x(x_j, y_j) \cdot g(t+\tau+px_j+qy_j) \right]^2 + \left[\sum_{j=1}^J f_y(x_j, y_j) \cdot g(t+\tau+px_j+qy_j) \right]^2 + \right.}{\sum_{\tau=-w}^{+w} \left\{ \left[\sum_{j=1}^J f_x(x_j, y_j) \cdot g^H(t+\tau+px_j+qy_j) \right]^2 + \left[\sum_{j=1}^J f_y(x_j, y_j) \cdot g^H(t+\tau+px_j+qy_j) \right]^2 + \right.} \quad (13a)$$

$$\theta(t, p, q, 2w) = \text{atan} \left[\frac{\sum_{\tau=-w}^{+w} \sum_{j=1}^J f_x(x_j, y_j) \cdot g(t+\tau+px_j+qy_j)}{\sum_{\tau=-w}^{+w} \sum_{j=1}^J f_y(x_j, y_j) \cdot g(t+\tau+px_j+qy_j)} + \frac{\sum_{\tau=-w}^{+w} \sum_{j=1}^J f_x(x_j, y_j) \cdot g(t+\tau+px_j+qy_j)}{\sum_{\tau=-w}^{+w} \sum_{j=1}^J f_y(x_j, y_j) \cdot g(t+\tau+px_j+qy_j)} \right] \quad (13b)$$

where g and g^H denote the gray-level data computed from the real seismic amplitude u and its Hilbert transform (or quadrature amplitude) u^H , respectively. The use of the analytic trace helps obtain robust estimates of amplitude variation even about the zero crossings of seismic reflectors

(Marfurt et al., 1998). Figure 2-5 demonstrates the workflow with four steps: first, to define a set of the Canny edge detectors in inline (x-) and crossline (y-) directions (Equation 11); second, at a given sample in a seismic volume, to retrieve localized seismic amplitude u and compute its Hilbert transform u^H within a spatial analysis window centered about the given sample; third, to generate the gray-level data g and g^H by processing the retrieved amplitude u and u^H with gray-level transformation (Equation 7); finally, to perform the defined Canny detectors on the generated g and g^H for discontinuity computation (Equation 13). The workflow is repeatedly executed from one sample to another. Consequently, a seismic amplitude volume is transformed into two attribute volumes, one being discontinuity magnitude and the other being discontinuity azimuth.

Applications

The 3D seismic dataset over the Stratton field of Texas is re-processed by the new algorithm, and the corresponding discontinuity slice at 844 ms is displayed in Figure 2-6f. Comparisons of Figure 2-6f to Figure 2-1b-d demonstrate the added value of the gray-level transformation and the Canny edge detector in delineating the eastern portion of the meandering channel (denoted by arrows), without causing any distortion or exaggeration of the channel in the west. Such exaggeration often happens if we simply increase the color contrast in Figure 2-1b-d for highlighting the subtle channel boundaries in the east. Additionally, the azimuth slice (Figure 2-7) clearly depicts the spatial orientation of both channel boundaries (denoted by dashed curves). Here an analysis window involving 49 traces is used for the Stratton data.

In addition to stratigraphic features, two fractured reservoirs are used for demonstrating the added value of the new algorithm for fault detection. The first one is a time-migrated dataset from the offshore Netherlands North Sea, where subsurface structures are dominated by a salt

dome as well as associated faults and fractures. As a baseline, the time slice at 1728 ms is shown in Figure 2-8, and the corresponding discontinuity slices from three traditional algorithms (Luo et al., 1996; Marfurt et al., 1998; Tingdahl and de Rooij, 2005) are shown in Figure 2-9a through Figure 2-9c, demonstrating the faults parallel as well as perpendicular to bedding. After processing the amplitude volume using the new algorithm, lateral resolution of seismic discontinuity is further enhanced with more structural details. In particular, faults parallel to bedding are better recognized (denoted by arrows in Figure 2-9d), and the fault orientation is mapped out by discontinuity azimuth (Figure 2-10). Here an analysis window involving 81 traces is used for the North Sea data.

The second is a Kirchhoff prestack depth-migrated dataset Teapot Dome (Wyoming) computed by Aktepe (2006). The subsurface structure is dominated by a northwest-trending Laramide-age anticline, and the hinge zone is populated with bend-induced fractures (Cooper et al., 2002; Cooper et al., 2006). The western edge of the structure is bounded by a major west-convergent upthrust fault (Cooper et al., 2001), and in association with the northwest-trending regional folds and thrusts are northeast-trending faults and fractures (Cooper et al., 2001; Cooper et al., 2002). Figure 2-11 displays the depth slice at 4800 ft, and the corresponding discontinuity slices using three traditional schemes (Luo et al., 1996; Marfurt et al., 1998; Tingdahl and de Rooij, 2005) and the new scheme are displayed in Figure 2-12a through Figure 2-12d, which depicts the northwest-trending anticline and thrusts. Comparison demonstrates that the new method helps reveal more structural details over the anticline hinge (denoted by circles). The azimuth image of seismic discontinuity from the new algorithm is shown in Figure 2-13, which defines two sets of faults and fractures: one for northeast-trending (in green to blue) and the other for northwest-trending (in red to yellow). Furthermore, we perform an ant-tracking processing

on the four discontinuity cubes (Figure 2-14a through Figure 2-14d). Apparently, more structural details (denoted by arrows) are identified based on the new algorithm, which have been confirmed by outcrop studies and image log analysis (Sterns and Friedman, 1972; Cooper et al., 2006; Schwartz, 2006). Here an analysis window involving 49 traces is used for the Teapot Dome data.

Discussion

The quality of input seismic data has a significant impact on discontinuity detection. Integrating current fracture detection methods with other techniques could help enhance the signal/noise ratio and resolution of seismic signal for improved seismic discontinuity detection. For example, combining a structure-oriented filter (Fehmers and Hocker, 2003; Chopra and Marfurt, 2007) with fracture detection could help minimize the impact of noises on discontinuity extraction. Combining texture model regression (TMR) method (Gao, 2004, 2011) with discontinuity detection could help enhance structural resolution and signal/noise ratio.

Effective discontinuity detection relies on lateral amplitude changes and an effective edge detector. First, gray-level transformation is one of the effective algorithms that enhance amplitude gradient without bit resolution reduction and amplitude truncation, which is advantageous over many other amplitude contrast enhancement and gain control techniques. Second, the Canny edge detector is one of the most effective methods for detecting image edges in 2D image analysis, and application to 3D seismic interpretation contributes the characterization of subsurface seismic discontinuities. Basically, the detector used for image processing is two dimensional, and better depict of seismic discontinuities is expected by the use of three-dimensional edge detectors.

Applying the gray-level transformation helps enhance the signal of subtle amplitude changes, but with could also magnify non-seismic random noises. The increased artifacts in the resulting discontinuity cubes could lead to interpretational bias or even misinterpretation of subsurface faults and stratigraphic features. This problem can be partially resolved by enlarging the edge detector to enclose more seismic traces; however, an enlarged detector needs to process more amplitude data in a large analysis window at each sample location, thus increasing computational time. A practical solution to that problem is to run the algorithm within the interval and area of interest. In fractured reservoirs formed by tectonic deformation, seismic discontinuity attribute is a partial and qualitative description of reservoir structures. The discontinuity attribute measures relative changes in reflection coherency or seismic amplitude; thereby the magnitude for various seismic datasets is always between 0.0 and 1.0. For example, however, raw seismic data indicates more strong deformation at Teapot Dome of Wyoming (Figure 2-11) than that at the Stratton field of Texas (Figure 2-1). Physically, structural deformation of reservoir formations is more related to lateral changes in reflection geometry than reflection coherency. A more quantitative characterization for fractured reservoirs can be achieved by using geometric attributes, such as curvature and curvature gradient, whose magnitude and azimuth are physically related to deformation intensity and azimuth, respectively (Gao, 2013; Di and Gao, 2014).

Conclusions

In 3D seismic interpretation, lateral amplitude changes are often evaluated for delineating structural or stratigraphic discontinuities in the subsurface. The traditional discontinuity-detection techniques are based on the assumption of localized amplitude variation being zero mean, and thus limited for delineating faults and fractures from regular seismic amplitude data

with non-zero mean. This study proposes implementing a gray-level transformation and the Canny edge detection into the workflow for enhanced discontinuity characterization. The gray-level transformation generates new zero-mean data for re-characterizing localized seismic features with non-zero mean amplitude variation, and the Canny edge detection helps more effectively capture the amplitude changes associated with discontinuities. The added value of the new algorithm is verified through applications to a fluvial channel system in Stratton field (Texas) and two fractured reservoirs at Teapot Dome (Wyoming) and the offshore Netherlands (North Sea). Compared to the traditional similarity scheme, amplitude-gradient scheme, and semblance scheme, the new algorithm produces better images of channels, faults, and fractures along with their orientation in the subsurface.

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Chapter 3: A New Algorithm for Evaluating 3D Curvature and Flexure for Improved Fracture Detection

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Abstract

In 3D seismic interpretation, both curvature and flexure are useful seismic attributes for structure characterization and fault detection in the subsurface. However, the existing algorithms are computationally intensive and limited by the lateral resolution for steeply-dipping formations. This study presents new and robust volume-based algorithms that evaluate both curvature and flexure attributes more accurately and effectively. The algorithms first volumetrically fit a local surface to seismic data and then compute attributes using the spatial derivatives of the built surface. Specifically, the curvature algorithm constructs a quadratic surface by using a rectangle 9-node grid cell, whereas the flexure algorithm builds a cubic surface by using a diamond 13-node grid cell. To avoid introducing interpreter bias, this study presents workflows for automatically building surfaces that best represent the geometry of seismic reflectors. A dip-steering approach based on 3D complex seismic trace analysis is implemented to enhance the accuracy of surface construction and to reduce computational time. Applications to two 3D seismic surveys demonstrate the accuracy and efficiency of the new curvature and flexure algorithms for characterizing faults and fractures in fractured reservoirs.

Introduction

Discontinuity attributes such as seismic coherence have been widely used to visualize and highlight major faults that are already discernable from seismic data (Bahorich and Farmer, 1995; Luo et al., 1996; Marfurt et al., 1998; Gerstzenkorn and Marfurt, 1999; Marfurt et al., 1999; Cohen and Coifman, 2002); however, these attributes cannot be used to detect faults and fractures that fall below the seismic resolution. Since the emergence of Gauss curvature in 3D seismic interpretation as a new attribute of seismic data (Lisle, 1994), curvature has been popular for characterizing fractures in a more quantitative manner (Roberts, 2001; Sigismondi and Soldo, 2003; Al-Dossary and Marfurt, 2006; Sullivan et al., 2006; Blumentritt et al., 2006; Klein et al., 2008; Chopra and Marfurt, 2007, 2010, 2011). Roberts (2001) discussed the applications of different curvature attributes and presented a workflow for measuring curvature based on 3D interpreted horizons. However, horizon-based curvature estimates are very sensitive to the quality of seismic data. Any noise in seismic data adds to the difficulty for an interpreter to accurately and efficiently pick seismic horizons, which increases the risk of introducing interpreter bias into curvature analysis. With the development of computer-aided dip-steering algorithms (Marfurt et al., 1998; Marfurt and Kirlin, 2000; Marfurt, 2006; Barnes, 2007), Al-Dossary and Marfurt (2006) improved the process by calculating volumetric curvature. In particular, they applied a running window semblance-based method to volumetrically measure the first derivatives of a seismic reflector (also known as reflector apparent dips), and used an approach of fractional-order derivatives to compute the second derivatives of the reflector. For horizontal or gently-dipping horizons, the algorithm is close to accurate curvature estimates; however, for steeply-dipping horizons, the algorithm will “undesirably mix geology of different formations” (Al-Dossary and Marfurt, 2006). This limitation results from the fact that the

fractional approach calculates the derivatives of dip on time slices as an approximation of the desired reflector second derivatives.

Seismic flexure, or curvature gradient (Gao, 2013), defined as a new spatial derivative of curvature attribute, is a different indicator of seismic reflector geometry and compliments curvature attribute for improved fracture characterization. Following a description of its concept, Gao (2013) presented the first equation of computing flexure in 2D space. For 3D flexure, he implemented an approximation algorithm, in which two gradients of a curvature cube along inline and crossline directions are combined to evaluate the flexure value with reduced computational time. However, this method assumes local linear nature of curvature gradient, which is not accurate in most cases.

In this study, we develop new algorithms to compute 3D volumetric curvature and flexure attributes that are accurate and computationally efficient. Our algorithms first construct local surfaces to represent the geometry of 3D seismic reflectors at each sample within a seismic volume. As a second-derivative-related geometric attribute, curvature is measured using a quadratic surface defined by a rectangle 9-node grid cell. As a third-derivative-related geometric attribute, flexure is measured using a cubic surface defined by a diamond 13-node grid cell. Then curvature and flexure are computed using newly-developed equations. Following a description of the new algorithms, they are applied to two 3D seismic surveys of fractured reservoirs from the Stratton field in Texas and from Teapot Dome in Wyoming. Both new algorithms generate attribute cubes that better define potential faults and fractures in fractured reservoirs. Appendices A and B provide a detailed derivation of the analytical equations for computing 3D curvature and 3D flexure along the dip direction, respectively.

3D curvature

Curvature k is evaluated as the ratio of dip angle change with respect to the arc length at a given point on a curve. In 3D space, a seismic volume is often described using an x-y-z coordinate system, in which x-, y- and z-coordinates denote the inline, crossline and depth/time directions, respectively. Using this system, a seismic reflector can be locally fit by a three-dimensional surface, which is often denoted as $z = z(x, y)$. On the surface, numerous types of seismic curvature can be evaluated at each sample. Roberts (2001) presented nine different curvatures, among which dip curvature is one of the most effective to represent the structural geometry and to detect geological features. Here, we present a detailed mathematical derivation (See Appendix A), which results in the equation (Equation 1) for computing 3D seismic curvature along the dip direction.

$$k_{3D} = \frac{1}{[1+A_1^2+A_2^2]^{3/2}} \cdot \frac{1}{(A_1^2+A_2^2)} \cdot [A_1^2 \cdot B_1 + A_2^2 \cdot B_2 + 2 \cdot A_1 \cdot A_2 \cdot B_3] \quad (1)$$

where $A_1 = \frac{dz}{dx}$ and $A_2 = \frac{dz}{dy}$ represent the reflector first derivatives, or apparent dips, along inline (x-) and crossline (y-) directions, respectively; $B_1 = \frac{d^2z}{dx^2}$, $B_2 = \frac{d^2z}{dy^2}$ and $B_3 = \frac{d^2z}{dxdy}$ represent the reflector second derivatives, or derivatives of vector dip.

Based on Equation 1, we develop a new algorithm to compute 3D volumetric curvature accurately and efficiently. The curvature algorithm consists of three steps (Figure 3-1). First, at a given sample in a seismic volume, a local quadratic 9-node surface is constructed to represent the 3D geometry of the seismic reflector at that point, based on volumetric estimates of reflector apparent dips. Then, the new algorithm calculates the derivative terms required in Equation 1, including both the first and second derivatives of the quadratic surface. Finally, 3D curvature at the target sample is estimated by substituting Equation 1 with these derivatives. The above steps

are repeatedly executed from one sample to another. Consequently, a regular amplitude volume is transformed into a volume of seismic curvature.

In the new curvature algorithm, automatic construction of a quadratic surface is the key to accurate volumetric curvature estimates. Curvature is a second order geometric attribute, and thus the built surface should be quadratic to calculate the reflector second derivatives. As shown in Figure 3-2, to build such a quadratic surface that represents the reflector geometry centered at sample *A*, the algorithm uses a rectangle 9-node grid cell (Roberts, 2001). Figure 3-3 illustrates the workflow for automatically building a quadratic surface within the 9-node grid cell shown in Figure 3-2. Specifically, construction of the quadratic surface is achieved by extending the corresponding reflector from the target trace to its neighboring traces. At the given sample *A*, backward and forward apparent dips are used for locating the reflector at its neighboring traces. For example, to find sample *B* that is on the same reflector as *A*, the apparent dip at sample *A* toward the previous trace along the inline (x-) direction, here denoted as the inline backward apparent dip θ_{xB} , is measured; similarly, the inline forward apparent dip θ_{xF} is used to locate sample *C* (Figure 3-4). The use of backward and forward apparent dips guarantees that the curve linking three samples *A*, *B*, and *C* represents the target reflector well. Consequently, in 3D space, its eight neighboring samples, *B*, *C*, *D*, *E*, *G*, *H*, *J*, and *K*, can be located, all of which lie on the same reflector as sample *A*, and linking all the nine samples leads to the desired 3D quadratic surface that well represents local reflector geometry, which can be illustrated by the following equation (Modified from Roberts, 2001).

$$z = \frac{1}{2}B_1x^2 + \frac{1}{2}B_2y^2 + B_3xy + A_1x + A_2y \quad (2)$$

The workflow illustrated in Figure 3-3 indicates that the efficiency of the new algorithm depends strongly on volumetric dip estimates. There are several approaches for measuring reflector dips, including discrete scanning (Finn, 1986; Marfurt et al., 1998; Marfurt and Kirlin, 2000; Marfurt, 2006), plane-wave destructor (Fomel, 2002), and 3D complex seismic trace analysis (Taner et al., 1979; Scheuer and Oldenburg, 1988; Barnes, 2007). Among these, 3D complex seismic trace analysis is computationally most efficient and convenient for implementation. Generally, this method uses a 3D generalization of instantaneous frequency, and reflector dip is rapidly evaluated as the negative ratio of spatial frequency and instantaneous frequency (Barnes, 2007).

$$\tan \theta = -\frac{f_x}{f_z} \quad (3)$$

where f_x denotes the spatial frequency and f_z denotes the instantaneous frequency.

The new curvature algorithm implements the method of 3D complex seismic trace analysis into measuring the required 12 apparent dips (shown in Figure 3-3). Additionally, to avoid numeric instability, we average a set of spatial frequencies and instantaneous frequencies within a vertical window. For example, the inline backward and forward apparent dips θ_{xB} and θ_{xF} at sample $A(x,y,z)$ (shown in Figure 3-4) are evaluated as

$$\tan \theta_{xB} = -\frac{f_{xB}}{f_z} \quad (4a)$$

$$\tan \theta_{xF} = -\frac{f_{xF}}{f_z} \quad (4b)$$

where $f_z = \frac{1}{N} \cdot \sum_{i=0}^N \frac{1}{4\pi i \Delta z} \cdot \left[\arg \left(\frac{Z(x,y,z+i\Delta z)}{Z(x,y,z)} \right) + \arg \left(\frac{Z(x,y,z)}{Z(x,y,z-i\Delta z)} \right) \right]$

$$f_{xF} = \frac{1}{12\pi N \Delta x} \cdot \sum_{i=0}^N \left[\arg \left(\frac{Z(x+\Delta x,y,z-i\Delta z)}{Z(x,y,z-i\Delta z)} \right) + \arg \left(\frac{Z(x+\Delta x,y,z)}{Z(x,y,z)} \right) + \arg \left(\frac{Z(x+\Delta x,y,z+i\Delta z)}{Z(x,y,z+i\Delta z)} \right) \right]$$

$$f_{xB} = \frac{1}{12\pi N \Delta x} \cdot \sum_{i=0}^N \left[\arg \left(\frac{Z(x-\Delta x,y,z-i\Delta z)}{Z(x,y,z-i\Delta z)} \right) + \arg \left(\frac{Z(x-\Delta x,y,z)}{Z(x,y,z)} \right) + \arg \left(\frac{Z(x-\Delta x,y,z+i\Delta z)}{Z(x,y,z+i\Delta z)} \right) \right]$$

in which $Z(x, y, z)$ denotes the complex or analytic traces at sample A ; $\arg()$ denotes the argument of a complex number; Δz denotes sampling interval; Δx denotes the spatial interval along inline direction; $2N + 1$ denotes the vertical analysis window size.

Next, our algorithm computes the quadratic coefficients of the surface equation (Equation 2) as the desired reflector second derivatives used in Equation 1. Using the rectangle 9-node grid cell shown in Figure 3-2, three sets of the reflector first and second derivatives can be calculated, and averaging these three sets by Equation 5 and Equation 6 leads to a stable estimate of all the five derivative terms used in Equation 1. Test comparison indicates that not only the results are more accurate and noise resistant, but also the process is computationally more efficient.

$$A_1 = \frac{dz}{dx} = \text{ave}\left(\frac{z_C - z_B}{2\Delta x}, \frac{z_K - z_H}{2\Delta x}, \frac{z_J - z_G}{2\Delta x}\right) \quad (5a)$$

$$A_2 = \frac{dz}{dy} = \text{ave}\left(\frac{z_E - z_D}{2\Delta y}, \frac{z_K - z_J}{2\Delta y}, \frac{z_H - z_G}{2\Delta y}\right) \quad (5b)$$

$$B_1 = \frac{d^2z}{dx^2} = \text{ave}\left(\frac{z_C + z_B - 2z_A}{\Delta x^2}, \frac{z_K + z_H - 2z_E}{\Delta x^2}, \frac{z_J + z_G - 2z_D}{\Delta x^2}\right) \quad (6a)$$

$$B_2 = \frac{d^2z}{dy^2} = \text{ave}\left(\frac{z_E + z_D - 2z_A}{\Delta y^2}, \frac{z_K + z_J - 2z_C}{\Delta y^2}, \frac{z_H + z_G - 2z_B}{\Delta y^2}\right) \quad (6b)$$

$$B_3 = \frac{d^2z}{dxdy} = \frac{z_K - z_H - z_J + z_G}{4\Delta x\Delta y} \quad (6c)$$

where $z_i (i = A, B, C, D, E, G, H, J, K)$ refers to the values at 9 nodes in the grid cell. Δx and Δy are the spatial intervals along inline (x-) and crossline (y-) directions, respectively. $\text{ave}()$ denotes an averaging operator. Roberts (2001) presented similar equations based on 3D picked horizons.

3D flexure

Flexure f (Gao, 2013) is defined as the spatial derivative of curvature with respect to the arc length. Here, we develop what we feel to be the first accurate and applicable equation for computing 3D flexure along the dip direction (See Appendix B).

$$f_{3D} = -3 \cdot \frac{1}{(1+A_1^2+A_2^2)^3} \cdot \frac{1}{(A_1^2+A_2^2)^{3/2}} \cdot (A_1^2 \cdot B_1 + A_2^2 \cdot B_2 + 2 \cdot A_1 \cdot A_2 \cdot B_3)^2 + \frac{1}{(1+A_1^2+A_2^2)^2} \cdot \frac{1}{(A_1^2+A_2^2)^{3/2}} \cdot [A_1^3 \cdot C_1 + A_2^3 \cdot C_2 + 3 \cdot A_1^2 \cdot A_2 \cdot C_3 + 3 \cdot A_1 \cdot A_2^2 \cdot C_4] \quad (7)$$

where $C_1 = \frac{d^3z}{dx^3}$, $C_2 = \frac{d^3z}{dy^3}$, $C_3 = \frac{d^3z}{dx^2dy}$, and $C_4 = \frac{d^3z}{dxdy^2}$ represent the reflector third derivatives.

Based on Equation 7, we develop a new algorithm to compute 3D volumetric flexure accurately and efficiently. The flexure algorithm consists of three steps (Figure 3-5). First, at a given sample in a seismic volume, the algorithm constructs a cubic surface to represent the local geometry of seismic reflectors. Then, it computes not only the first and second derivatives, but also the third derivatives of the cubic surface. Finally, 3D flexure is evaluated by substituting Equation 7 with these derivatives. The above steps are repeatedly executed from one sample to another. Consequently, a seismic amplitude volume is transformed into a volume of seismic flexure.

By comparing the flexure equation (Equation 7) to the curvature equation (Equation 1), we notice that the algorithm for 3D flexure is much more complicated than that for 3D curvature. In particular, flexure is related to not only the first and second derivatives but also to the third derivatives of a seismic reflector. Thus, the computation of flexure needs a cubic surface, instead of a quadratic one used in the curvature algorithm, because flexure is related to the reflector third derivatives while a quadratic surface is only accurate enough to evaluate the second derivatives.

Consequently, a more advanced grid cell than the rectangle one (shown in Figure 3-2) should be used for constructing this cubic surface. Figure 3-6 demonstrates a diamond grid cell with 13 nodes. Figure 3-7 illustrates the workflow for building the cubic surface (Equation 8) within the diamond grid cell, which requires a total of 16 estimates of apparent dips.

$$z = \frac{1}{6}C_1x^3 + \frac{1}{6}C_2y^3 + \frac{1}{2}C_3x^2y + \frac{1}{2}C_4xy^2 + \frac{1}{2}B_1x^2 + \frac{1}{2}B_2y^2 + B_3xy + A_1x + A_2y \quad (8)$$

To facilitate the construction of a cubic surface, the flexure algorithm also implements 3D complex seismic trace analysis for volumetric dip estimates.

Next, using the diamond grid cell of 13 nodes (Figure 3-6), the algorithm computes two linear coefficients of the cubic surface equation as the first derivatives (Equation 9), three quadratic coefficients as the second derivatives (Equation 10), and four cubic coefficients as the third derivatives (Equation 11)

$$A_1 = \frac{dz}{dx} = ave\left(\frac{z_C - z_B}{2\Delta x}, \frac{z_K - z_H}{2\Delta x}, \frac{z_J - z_G}{2\Delta x}, \frac{z_N - z_M}{4\Delta x}\right) \quad (9a)$$

$$A_2 = \frac{dz}{dy} = ave\left(\frac{z_E - z_D}{2\Delta y}, \frac{z_K - z_J}{2\Delta y}, \frac{z_H - z_G}{2\Delta y}, \frac{z_Q - z_P}{4\Delta y}\right) \quad (9b)$$

$$B_1 = \frac{d^2z}{dx^2} = ave\left(\frac{z_C + z_B - 2z_A}{\Delta x^2}, \frac{z_K + z_H - 2z_E}{\Delta x^2}, \frac{z_J + z_G - 2z_D}{\Delta x^2}, \frac{z_N + z_M - 2z_A}{4\Delta x^2}\right) \quad (10a)$$

$$B_2 = \frac{d^2z}{dy^2} = ave\left(\frac{z_E + z_D - 2z_A}{\Delta y^2}, \frac{z_K + z_J - 2z_C}{\Delta y^2}, \frac{z_H + z_G - 2z_B}{\Delta y^2}, \frac{z_Q + z_P - 2z_A}{4\Delta y^2}\right) \quad (10b)$$

$$B_3 = \frac{d^2z}{dxdy} = \frac{z_K - z_H - z_J + z_G}{4\Delta x\Delta y} \quad (10c)$$

$$C_1 = \frac{d^3z}{dx^3} = \frac{z_N - z_M - 2z_C + 2z_B}{2\Delta x^3} \quad (11a)$$

$$C_2 = \frac{d^3z}{dy^3} = \frac{z_Q + z_P - 2z_E + 2z_D}{2\Delta y^3} \quad (11b)$$

$$C_3 = \frac{d^3z}{dx^2dy} = \frac{z_K - z_J + z_H - z_G - 2z_E + 2z_D}{\Delta x^2\Delta y} \quad (11c)$$

$$C_4 = \frac{d^3z}{dxdy^2} = \frac{z_K + z_J - z_H - z_G - 2z_C + 2z_B}{\Delta x\Delta y^2} \quad (11d)$$

where $z_i (i = A, B, C, D, E, G, H, J, K, M, N, P, Q)$ refers to values at 13 nodes in the grid cell.

Results

To verify the value of the new curvature and flexure algorithms, we calculate both attributes for two 3D seismic datasets, one being time data from the Stratton field in Texas and the other being depth data from Teapot Dome in Wyoming. In the Stratton data, the reservoir structure is dominated by a north-trending listric fault and associated rollover anticlines as well as fracture systems subparallel to the fold hinge. As a baseline, the structure contour map of the horizon at approximately 1850 ms is shown in Figure 3-8a, indicating that the formation gradually dips from the eastern portion towards the west. In order to highlight the potential faults and fractures resulting from the roll-over bending, the seismic volume was processed using the proposed curvature and flexure algorithms. For the convenience of visualization and comparison, both attributes are displayed on the same seismic reflector (Figure 3-8). In the attribute maps, four major north-trending faults are clearly depicted from the steeply-dipping horizon (denoted by dotted lines), verifying the accuracy of our algorithms on highlighting faults and fractures. Specifically, faults are delimited by the juxtaposition of positive curvature and negative curvature (Figure 3-8b), which are directly delineated by flexure (Figure 3-8c). Perspective chair displays of curvature and flexure images, along with a seismic line, help better illustrate the expressions of faults and fractures by the two attributes (Figure 3-9). Positive and negative curvature highlight the upthrown and downthrown fault blocks, respectively (Figure 3-9b), whereas the fault planes are directly highlighted by flexure (Figure 3-9c). Here, integrating curvature with flexure helps differentiate structural features of reservoir formations, which is instrumental in fractured reservoir characterization.

In the second example, we use Kirchhoff prestack depth-migrated data in Teapot Dome computed by Aktepe (2006). Figure 3-10a displays the structure contour map of the horizon at approximately 4600 ft, which depicts the northwest-trending anticline and the northeast-trending cross-regional transfer faults. Figure 3-10b and Figure 3-10c display the corresponding curvature and flexure images, respectively. Compared to curvature, flexure helps characterize the subtle fractures that are not easily discernable from curvature attribute (Figure 3-10c). At a deeper horizon of approximately 6000 ft in the Tensleep reservoir interval, flexure better defines two sets of lineaments (Figure 3-11c). One set trends to the northwest and is subparallel to the regional folds that have been well documented in previous studies (Cooper et al., 2006). The other set trends obliquely to the hinge of the fold, which have also been confirmed by outcrop studies and image log analysis (Sterns and Friedman, 1972; Cooper et al., 2006; Schwartz, 2006).

Then we test and compare the results and the computational efficiency of our algorithms with the traditional algorithms, using the 3D Stratton data which contains 100 inlines, 200 crosslines, and 1500 samples per trace with an sampling interval of 2 ms. As the first test, two different methods for dip estimates, 3D complex seismic trace analysis and discrete scanning, are implemented to construct the quadratic surface used in the new curvature algorithm and the cubic surface used in the new flexure algorithm. Both results for curvature and curvature gradient are shown in Figure 3-12 and Figure 3-13, respectively. As demonstrated, the results are very similar, but the computational time of discrete scanning is 10 times more than that of 3D complex seismic trace analysis (Table 3-1). Next, the curvature cube from our algorithm is compared to that from the traditional curvature algorithm by Al-Dossary and Marfurt (2006). As shown in Figure 3-14, curvature estimates from both algorithms are similar for the eastern area

where the reflector is horizontal, whereas our algorithm provides a better delineation in the west where the reflector dips steeply. Finally, Figure 3-15 displays the comparison of flexure from our new algorithm and the approximation algorithm by Gao (2013), and more accurate estimates of flexure are produced by the new algorithm as denoted by arrows.

Discussion

The success of our algorithms depends mainly on the accuracy of surface construction. At each sample in a seismic volume, building a 9-node quadratic and 13-node cubic surface requires a total of 12 and 16 dip estimates, respectively. Rapid and accurate volume-based evaluation of reflector dip plays a critical role in enhancing both the accuracy and computational efficiency of the new curvature and flexure algorithms. Compared to the discrete scanning dip estimate (Finn, 1986; Marfurt et al., 1998; Marfurt and Kirlin, 2000; Marfurt, 2006) and plane-wave destruction filter (Fomel, 2002), 3D complex seismic trace analysis is computationally more efficient and convenient for implementation (Taner et al., 1979; Scheuer and Oldenburg, 1988; Barnes, 2007). However, numeric instability is a major concern and should be addressed when applying this approach. More work is expected for developing efficient dip-steering method, based on which the accuracy of automatic surface construction can be further improved and thereby our algorithms can produce even better estimates of seismic curvature and flexure attributes.

Curvature and flexure attributes are both dependent on the measuring direction on a surface in 3D space. The focus of our algorithm description lies on dip curvature and dip flexure, which represent the attributes measured along the true dip direction, one of the important direction for subsurface structural interpretation. Nevertheless, the new algorithms can be easily extended to other important directions, such as strike direction and two principle directions, by developing the corresponding applicable equations.

In the new algorithms, the rectangle 9-node grid cell and the diamond 13-node grid cell are the simplest but eligible cell for constructing a quadratic surface and a cubic surface, respectively. A cell with less than 9 nodes cannot provide the required information about the reflector second derivatives to compute curvature attribute, and a cell with less than 13 nodes cannot provide the required information about the reflector third derivatives to compute flexure attribute. The algorithms would become more robust if a larger and more complicated grid cell, for example a rectangle 25-node cell, is used. However, surface construction at every sample using the 25-node grid cell needs a total of 40 estimates of reflector apparent dip, which would lead to a fourfold increase in computation time.

Conclusions

We have developed new and efficient algorithms for robust estimate of 3D volumetric curvature and flexure attributes. Both algorithms consist of two steps: 1) to automatically construct a local surface representing the geometry of a seismic reflector, and 2) to compute attributes using the coefficients of the built surface equation. The new 3D curvature algorithm constructs a quadratic surface using a 9-node grid cell, whereas the new flexure algorithm constructs a cubic surface using a more complicated 13-node grid cell. Dip estimate is accomplished using the method of 3D complex seismic trace analysis, yet averaging instantaneous and spatial frequency within a vertical analysis window is applied to keep computation stability. The major advantages of our algorithms over the existing ones are the enhanced accuracy and efficiency for delineating faults and fractures in 3D space. Applications of the new algorithms to both time and depth data from two 3D seismic surveys over the Stratton field in Texas and Teapot Dome in Wyoming indicate that both new algorithms help better

define and detect faults and fractures in an analytically more accurate and computationally more efficient manner.

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Appendix A

Derivation of equations for computing 3D curvature along the dip direction

In 3D space, curvature along the dip direction k_{3D} , is defined as the derivative of dip angle with respect to arc length along the dip direction on a surface (Roberts, 2001; Sigismondi and Soldo, 2003).

$$k_{3D} = \frac{d\theta}{ds} \quad (\text{A-1})$$

where θ denotes the reflector dip and s denotes the arc length along the dip direction.

In the x-y-z coordinate system, Equation A-1 becomes applicable using the chain rule of derivative

$$k_{3D} = \frac{\partial \theta}{\partial x} \cdot \frac{dx}{ds} + \frac{\partial \theta}{\partial y} \cdot \frac{dy}{ds} \quad (\text{A-2})$$

Let a surface be described using a function $z = z(x, y)$. Then, as shown in Figure 3-A1, dip angle θ is represented by

$$\theta = \tan^{-1} \sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2} \quad (\text{A-3})$$

where $\frac{dz}{dx}$ and $\frac{dz}{dy}$ denote the apparent dips along x and y directions, respectively (Modified from Marfurt, 2006; Gao, 2013).

By taking a derivative of Equation A-3 with respect to x and y, $\frac{\partial \theta}{\partial x}$ and $\frac{\partial \theta}{\partial y}$ are evaluated as

$$\frac{\partial \theta}{\partial x} = \frac{\partial}{\partial x} \left[\tan^{-1} \sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2} \right] = \frac{1}{1 + \left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2} \cdot \frac{1}{\sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2}} \cdot \left(\frac{dz}{dx} \cdot \frac{d^2 z}{dx^2} + \frac{dz}{dy} \cdot \frac{d^2 z}{dx dy} \right) \quad (\text{A-4a})$$

$$\frac{\partial \theta}{\partial y} = \frac{\partial}{\partial y} \left[\tan^{-1} \sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2} \right] = \frac{1}{1 + \left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2} \cdot \frac{1}{\sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2}} \cdot \left(\frac{dz}{dy} \cdot \frac{d^2 z}{dy^2} + \frac{dz}{dx} \cdot \frac{d^2 z}{dx dy} \right) \quad (\text{A-4b})$$

Geometric knowledge provides

$$dx = ds \cdot \cos \theta \cdot \cos \varphi \quad (\text{A-5a})$$

$$dy = ds \cdot \cos \theta \cdot \sin \varphi \quad (\text{A-5b})$$

where θ denotes true dip and φ denotes dip azimuth.

Rearranging Equation A-5 leads to

$$\frac{dx}{ds} = \frac{dz}{dx} \cdot \left[\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2 \right]^{-1/2} \left[1 + \left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2 \right]^{-1/2} \quad (\text{A-6a})$$

$$\frac{dy}{ds} = \frac{dz}{dy} \cdot \left[\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2 \right]^{-1/2} \left[1 + \left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2 \right]^{-1/2} \quad (\text{A-6b})$$

Substituting Equation A-2 with Equation A-4 and Equation A-6 leads to

$$k_{3D} = \frac{1}{[1 + A_1^2 + A_2^2]^{3/2}} \cdot \frac{1}{(A_1^2 + A_2^2)} \cdot [A_1^2 \cdot B_1 + A_2^2 \cdot B_2 + 2 \cdot A_1 \cdot A_2 \cdot B_3] \quad (\text{A.7})$$

Appendix B

Derivation of equations for computing 3D flexure along the dip direction

In 3D space, flexure along the dip direction f_{3D} , is defined as the derivative of curvature with respect to arc length along the dip direction on a surface (Gao, 2013).

$$f_{3D} = \frac{dk_{3D}}{ds} \quad (B-1)$$

where k_{3D} denotes 3D curvature along the dip direction (Equation A-7) and s denotes the arc length along the dip direction.

In the x-y-z coordinate system, Equation B-1 becomes applicable using the chain rule of derivative

$$f_{3D} = \frac{\partial k_{3D}}{\partial x} \cdot \frac{dx}{ds} + \frac{\partial k_{3D}}{\partial y} \cdot \frac{dy}{ds} \quad (B-2)$$

and in order to simplify the computation of partial derivatives, the equation of 3D curvature (Equation A-7) can be written as

$$k_{3D} = \frac{1}{1+\tan^2(\varphi)} \cdot \frac{1}{\left[1+\left(\frac{dz}{dx}\right)^2+\left(\frac{dz}{dy}\right)^2\right]^{3/2}} \cdot \left[\frac{d^2z}{dx^2} + \frac{d^2z}{dy^2} \cdot \tan^2(\varphi) + 2 \cdot \frac{d^2z}{dxdy} \cdot \tan(\varphi)\right] \quad (B-3)$$

where $\varphi = \text{atan2}\left(\frac{dz}{dy}, \frac{dz}{dx}\right)$ denotes dip azimuth. Then let

$$A = \frac{1}{1+\tan^2(\varphi)} \quad (B-4a)$$

$$B = 1 + \left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2 \quad (B-4b)$$

$$C = \frac{d^2z}{dx^2} + \frac{d^2z}{dy^2} \cdot \tan^2(\varphi) + 2 \cdot \frac{d^2z}{dxdy} \cdot \tan(\varphi) \quad (B-4c)$$

Based on the derivative theory, Equation B-2 is represented as

$$f_{3D} = A \cdot \left[\left(\frac{\partial B^{-3/2}}{\partial x} \cdot C + B^{-3/2} \cdot \frac{\partial C}{\partial x} \right) \cdot \frac{dx}{ds} + \left(\frac{\partial B^{-3/2}}{\partial y} \cdot C + B^{-3/2} \cdot \frac{\partial C}{\partial y} \right) \cdot \frac{dy}{ds} \right] \quad (B-5)$$

Substituting Equation B-5 with Equation A-6 and Equation B-4 leads to

$$A \cdot \frac{\partial B^{-3/2}}{\partial x} \cdot C \cdot \frac{dx}{ds} = -3 \cdot B^{-3} \cdot \left[\left(\frac{dz}{dx} \right)^2 + \left(\frac{dz}{dy} \right)^2 \right]^{-3/2} \cdot C \cdot \left[\left(\frac{dz}{dx} \right)^2 \cdot \frac{d^2 z}{dx^2} + \frac{dz}{dx} \cdot \frac{dz}{dy} \cdot \frac{d^2 z}{dx dy} \right] \quad (\text{B-6a})$$

$$A \cdot \frac{\partial B^{-3/2}}{\partial x} \cdot C \cdot \frac{dy}{ds} = -3 \cdot B^{-3} \cdot \left[\left(\frac{dz}{dx} \right)^2 + \left(\frac{dz}{dy} \right)^2 \right]^{-3/2} \cdot C \cdot \left[\left(\frac{dz}{dy} \right)^2 \cdot \frac{d^2 z}{dy^2} + \frac{dz}{dx} \cdot \frac{dz}{dy} \cdot \frac{d^2 z}{dx dy} \right] \quad (\text{B-6b})$$

and

$$A \cdot B^{-3/2} \cdot \frac{\partial C}{\partial x} \cdot \frac{dx}{ds} = B^{-2} \cdot \left[\left(\frac{dz}{dx} \right)^2 + \left(\frac{dz}{dy} \right)^2 \right]^{-3/2} \cdot \left[\left(\frac{dz}{dx} \right)^3 \cdot \frac{d^3 z}{dx^3} + 2 \cdot \left(\frac{dz}{dx} \right)^2 \cdot \frac{dz}{dy} \cdot \frac{d^3 z}{dx^2 dy} + \frac{dz}{dx} \cdot \left(\frac{dz}{dy} \right)^2 \cdot \frac{d^3 z}{dx dy^2} \right] \quad (\text{B-7a})$$

$$A \cdot B^{-3/2} \cdot \frac{\partial C}{\partial y} \cdot \frac{dy}{ds} = B^{-2} \cdot \left[\left(\frac{dz}{dx} \right)^2 + \left(\frac{dz}{dy} \right)^2 \right]^{-3/2} \cdot \left[\left(\frac{dz}{dy} \right)^3 \cdot \frac{d^3 z}{dy^3} + 2 \cdot \frac{dz}{dx} \cdot \left(\frac{dz}{dy} \right)^2 \cdot \frac{d^3 z}{dx dy^2} + \left(\frac{dz}{dx} \right)^2 \cdot \frac{dz}{dy} \cdot \frac{d^3 z}{dx^2 dy} \right] \quad (\text{B-7b})$$

Finally, 3D flexure along the dip direction is evaluated as

$$f_{3D} = -3 \cdot \frac{1}{(1+A_1^2+A_2^2)^3} \cdot \frac{1}{(A_1^2+A_2^2)^{3/2}} \cdot (A_1^2 \cdot B_1 + A_2^2 \cdot B_2 + 2 \cdot A_1 \cdot A_2 \cdot B_3)^2 + \frac{1}{(1+A_1^2+A_2^2)^2} \cdot \frac{1}{(A_1^2+A_2^2)^{3/2}} \cdot [A_1^3 \cdot C_1 + A_2^3 \cdot C_2 + 3 \cdot A_1^2 \cdot A_2 \cdot C_3 + 3 \cdot A_1 \cdot A_2^2 \cdot C_4] \quad (\text{B-8})$$

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Figures & Tables

Figure 3-1: Flowchart of the 3D curvature algorithm. The input is a regular amplitude volume. At each sample, the algorithm calculates the curvature along the dip direction to create a curvature volume.

Figure 3-2: The rectangle 9-node grid cell for constructing a quadratic surface to represent the 3D geometry of the local seismic reflector centered at sample *A*.

Figure 3-4: Schematic diagram of forward and backward apparent dips along the inline (x-) direction at a sample location: θ_{xB} is the backward apparent dip from sample A to sample B , and θ_{xF} is the forward apparent dip from sample A to sample C .

Figure 3-5: Flowchart of the 3D flexure algorithm. The input is a regular amplitude volume. At each sample, the algorithm calculates the flexure along the dip direction to create a flexure volume.

Figure 3-6: The diamond 13-node grid cell for constructing a cubic surface to represent the 3D geometry of the local seismic reflector centered at sample *A*.

Note: θ_{xs}^* and θ_{xp}^* denote the backward and forward apparent dips along x-direction at a sample location, respectively; θ_{ys}^* and θ_{yp}^* denote the backward and forward apparent dips along y-direction at a sample location, respectively, where * represents 13 nodes in the diamond grid cell (shown in Fig. 6), A, B, C, D, E, G, H, J, K, M, N, P, and Q.

Figure 3-7: Flowchart of constructing a cubic surface using a diamond 13-point grid cell (shown in Figure 3-6). A total of 16 estimates of reflector apparent dips are required.

Figure 3-8: Application of the new algorithms to the 3D seismic volume over the Stratton field in Texas. (a) Structure contour map of the horizon at approximately 1850 ms, gradually dipping from the eastern area toward the west. (b) The corresponding curvature image generated from the proposed curvature algorithm. (c) The corresponding flexure image generated from the proposed flexure algorithm. Four north-trending faults (denoted by dotted lines) are highlighted to demonstrate their spatial relationship to curvature and flexure.

Figure 3-9: Perspective chair display of (a) structure contour, (b) curvature attribute, and (c) flexure attribute along with a seismic line. White lines indicate three major north-trending faults interpreted in Figure 3-8.

Figure 3-10: Application of the new algorithms to the 3D seismic volume over Teapot Dome in Wyoming. (a) Structure contour map of a deformed horizon at approximately 4600 ft, demonstrating a northwest-trending anticline and associated faults perpendicular to the fold hinge. (b) The corresponding curvature image generated from the proposed curvature algorithm. (c) The corresponding flexure image generated from the proposed flexure algorithm. More structural details are revealed by flexure than curvature.

Figure 3-11: (a) Structure contour map of the Tensleep Formation in the Teapot Dome survey. (b) The corresponding curvature image generated from the proposed curvature algorithm. (c) The corresponding flexure image generated from the proposed flexure algorithm. Two sets of lineaments are well defined by flexure.

Figure 3-12: Comparison of the new curvature algorithm using two different dip-steering methods for quadratic surface construction. (a) 3D complex seismic trace analysis. (b) Discrete scanning.

Figure 3-13: Comparison of the new flexure algorithm using two different dip-steering methods for cubic surface construction. (a) 3D complex seismic trace analysis. (b) Discrete scanning.

Figure 3-14: Comparison of (a) the new curvature algorithm and (b) the traditional curvature algorithm. Both algorithms provide similar results in the eastern area where the reflector is horizontal, whereas (a) shows a better expression for the west where the reflector dips steeply.

Figure 3-15: Comparison of (a) the new flexure algorithm and (b) the existing flexure algorithm. Both results are generally similar, but different in details (denoted by arrows).

Figure 3-A1: Schematic diagram of defining reflector dip: θ_x is apparent dip in the x-direction, θ_y is apparent dip in the y-direction, θ is reflector dip, and ϕ is dip azimuth (Modified from Marfurt, 2006).

Algorithm	3D Complex seismic trace analysis	Discrete scanning
Curvature	5 min 47 sec	53 min 35 sec
Flexure	8 min 17 sec	79 min 26 sec

Table 3-1: Comparison of computational time between 3D complex seismic trace analysis and discrete scanning.

**Chapter 4: Most Extreme Curvature and Most Extreme Flexure Analysis for Fracture
Characterization from 3D Seismic: New Analytical and Discrete Azimuth-Scanning
Algorithms**

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Abstract

Seismic curvature and flexure attributes evaluate the variation of reflection geometry from three-dimensional (3D) seismic and have great potential for efficient structure analysis and fracture detection in the subsurface. However, such attributes are dependent on their measuring direction, and little has been published for finding the most effective ones that best facilitate fracture characterization and network modeling. This study focuses on most extreme curvature and most extreme flexure that are considered effective at detecting fractures and presents new algorithms for computing both magnitude and azimuth of these attributes. Our method starts with azimuthal curvature and azimuthal flexure along any given direction in 3D space; and then implements analytical and azimuth-scanning approaches for most extreme curvature and most extreme flexure extraction, respectively. In particular, we build and solve a quadratic equation for computing most extreme curvature; for computing most extreme flexure, a set of flexure values is first estimated along all possible azimuths and then compared to find the largest absolute value. We demonstrate the added value of our algorithms through applications to a seismic survey over Teapot Dome of Wyoming. The results demonstrate that the new algorithms

help resolve structural details that are otherwise not easily discernible from regular amplitude and conventional attributes. Most importantly, the algorithms hold the potential to volumetrically detect and visualize fractures in an automatic and quantitative manner. We conclude that most extreme curvature and most extreme flexure attributes have important geologic implications for predicting fundamental fracture properties that are critical to fractured reservoir characterization in the subsurface.

Introduction

Detecting faults and fractures from three-dimensional (3D) seismic is one of the most significant tasks in subsurface exploration. The coherence attribute (Bahorich and Farmer, 1995) is a powerful tool and has been widely used for fracture detection (Luo et al., 1996; Marfurt et al., 1998; Gerstzenkorn and Marfurt, 1999; Marfurt et al., 1999; Cohen and Coifman, 2002; Di and Gao, 2014a). However, coherence is limited to detection of faults that are already discernable from seismic data. By evaluating local changes in the geometry of 3D seismic reflectors, curvature analysis (e.g. Lisle, 1994; Roberts, 2001; Sigismondi and Soldo, 2003; Al-Dossary and Marfurt, 2006; Sullivan et al., 2006; Blumentritt et al., 2006; Kleim et al, 2008; Chopra and Marfurt, 2007, 2010, 2011) and flexure (or curvature gradient) analysis (Gao, 2013) provide the potential to delimit faults and fractures in a more quantitative manner at both seismic and subseismic scale. By their definition, 3D curvature and flexure are both dependent on the direction for attribute extraction, and at every sample within a 3D seismic volume, curvature and flexure can be evaluated along any given azimuth. Among those different azimuthal directions, the most important azimuths for structure interpretation include the true dip direction, the strike direction, and the principle directions that are associated with the local maximum of all the attribute values. Roberts (2001) provided a detailed discussion of nine different types of

curvature. Gao (2013) reported that among various curvatures, most extreme (signed maximum) curvature is most effective for revealing a lot of information relating to faults and fractures. Besides most extreme curvature, Gao (2013) also proposed taking a new gradient of most extreme curvature and applying the generated flexure attribute to fractured reservoir characterization at Teapot Dome of Wyoming. Physically, fractures are most likely to develop along the orientation of abnormal strains, and this orientation is often associated with most extreme curvature and most extreme flexure. Thus, a fracture network can be better detected by integrating most extreme curvature and most extreme flexure: using the magnitude and azimuth of these attributes to predict fracture intensity and fracture orientation, respectively (Gao, 2013).

Evaluation of most extreme curvature and particularly most extreme flexure is computationally intensive. The first generation of curvature algorithm is based on a horizon picked by an interpreter (Roberts, 2001); however, horizon-based curvature estimates are very sensitive to seismic noises and run the risk of introducing artifacts into curvature images. Al-Dossary and Marfurt (2006) present a fractional approach for efficiently computing 3D curvature at every sample in an uninterpreted cube, which helps avoid interpreter bias. A major limitation of this method is the undesired mixture of geology of different steeply-dipping formations. For computing most extreme flexure in 3D space, Gao (2013) proposed combining two flexure values measured along inline and crossline directions. However, this method assumes local linear nature of curvature gradient, which is not accurate in most cases. Di and Gao (2014b) present a computationally efficient algorithm to enhance the accuracy of computing 3D curvature and flexure; however, their method is major limited to attribute estimates along the direction of true reflector dip. Therefore, an efficient algorithm remains to be developed for computing most extreme curvature and most extreme flexure.

Although many authors have made great efforts to compute curvature and flexure from 3D seismic, extracting the principle attribute is often beyond the areas of research focus. Roberts (2001) gave a brief discussion about orientation of maximum curvature, but did not present a computational method for evaluating this property. Moreover, in many seismic surveys, fractures often develop associated with small magnitude of curvature and flexure; thereby they are difficult to define only by the magnitude of either most extreme curvature or most extreme flexure. In spite of their intensity, subtle fractures typically have a constant orientation in 3D space. Thus we propose to use azimuth of most extreme curvature/flexure to highlight subtle fractures, which are denoted as most extreme curvature azimuth and most extreme flexure azimuth.

This paper presents new efficient algorithms for computing both the magnitude and azimuth of most extreme curvature and most extreme flexure attributes. First, we present equations of computing azimuthal curvature and azimuthal flexure along any specified azimuth in 3D space. Then two computational approaches are implemented to find most extreme curvature and most extreme flexure, with enhanced computational efficiency. In particular, for curvature estimates, we develop an analytical approach which is both accurate and fast in computation: first takes a derivative of the azimuthal curvature equation with respect to azimuth; and then computes the roots of the generated quadratic equation. For most extreme flexure, we propose an azimuth-scanning approach of computing and comparing a set of all possible flexure values by scanning azimuth from 0 degree (North) to 180 degree (South), which helps reduce the computation time by half. We apply our proposed methods to a seismic survey from Teapot Dome in Wyoming, and demonstrate the added value of most extreme curvature and most extreme flexure as well as their associated azimuth for enhancing subtle fractures.

Most Extreme Curvature

Curvature, in two-dimensional space, is defined as the inverse of the radius of a circle that is tangent to the surface at any point of a curve (Roberts, 2001; Sigismondi and Soldo, 2003). For our purposes, we follow the sign convention of curvature and consider positive curvature to be concave downward; thereby, faults become recognizable with the downthrown and upthrown blocks of a fault demonstrating positive curvature and negative curvature, respectively (Figure 4-1). When extending to a 3D surface, curvature is dependent on the measuring direction. Numerous types of curvature could be determined at every point on a 3D surface, since there are an infinite number of circles in normal planes of different orientations that may be tangent to the surface at that point (Roberts, 2001). Specifically, the curvature of the tangent circle with the smallest radius in a normal plane is called maximum curvature, k_{max} , and the curvature of the tangent circle in the normal plane perpendicular to this has minimum curvature, k_{min} . Together, these two curvatures are known as the principle curvatures and the corresponding azimuths are the principle directions. Other important curvatures are dip curvature k_{dip} measured from the true dip direction and strike curvature k_{strike} measured from the strike direction (See Figure 4-2 and Roberts, 2001, for more detailed description). Among these, k_{max} and k_{min} are considered to be most helpful in seismic structure analysis to infer the direction in which there is the highest potential for fractures to develop (Gao, 2013); and most extreme curvature k_{xmt} is evaluated as the signed maximum of maximum curvature k_{max} and minimum curvature k_{min} (Chopra and Marfurt, 2007).

$$k_{xmt} = \begin{cases} k_{max} & \text{if } |k_{max}| \geq |k_{min}| \\ k_{min} & \text{if } |k_{max}| < |k_{min}| \end{cases} \quad (1)$$

Computation of most extreme curvature is available based on the equations presented in Roberts (2001) as well as in advanced mathematics books on geometry, whereas little attention has been

put on methods of extracting the associated azimuth. Here we present what we feel to be the first method for calculating most extreme curvature azimuth, and the new algorithm can simultaneously evaluate the magnitude and direction of most extreme curvature.

We begin with computing azimuthal curvature, which represents the curvature evaluated along any azimuthal direction in 3D space, and then maximum or minimum curvature can be estimated as the maximum or minimum of all azimuthal curvatures. Let φ be any given azimuth on a surface. Then the azimuthal curvature along azimuth φ is evaluated as

$$k_{\varphi} = \frac{d\theta_{\varphi}}{ds} \quad (2)$$

where ds denotes the arc length of the intersecting curve between the surface and the vertical plane along azimuth φ . And θ_{φ} denotes the apparent dip along the specified azimuth (Marfurt and Kirlin, 2000)

$$\theta_{\varphi} = \tan^{-1} \left(\frac{dz}{dx} \cdot \cos \varphi + \frac{dz}{dy} \cdot \sin \varphi \right) \quad (3)$$

where $\frac{dz}{dx}$ and $\frac{dz}{dy}$ denote the apparent reflector dips along inline (x-) and crossline (y-) directions, respectively (Figure 4-3).

After using the chain rule of derivative, Equation 2 becomes

$$k_{\varphi} = \frac{\partial \theta_{\varphi}}{\partial x} \cdot \frac{dx}{ds} + \frac{\partial \theta_{\varphi}}{\partial y} \cdot \frac{dy}{ds} \quad (4)$$

By taking a partial derivative of Equation 3 with respect to x and y, terms $\frac{\partial \theta_{\varphi}}{\partial x}$ and $\frac{\partial \theta_{\varphi}}{\partial y}$ are represented as

$$\frac{\partial \theta_{\varphi}}{\partial x} = \left[1 + \left(\frac{dz}{dx} \cos \varphi + \frac{dz}{dy} \sin \varphi \right)^2 \right]^{-1} \cdot \left(\frac{d^2z}{dx^2} \cos \varphi + \frac{d^2z}{dxdy} \sin \varphi \right) \quad (5a)$$

$$\frac{\partial \theta_{\varphi}}{\partial y} = \left[1 + \left(\frac{dz}{dx} \cos \varphi + \frac{dz}{dy} \sin \varphi \right)^2 \right]^{-1} \cdot \left(\frac{d^2z}{dxdy} \cos \varphi + \frac{d^2z}{dy^2} \sin \varphi \right) \quad (5b)$$

Geometric principle provides

$$dx = ds \cdot \cos \varphi \cdot \cos \theta_\varphi \quad (6a)$$

$$dy = ds \cdot \sin \varphi \cdot \cos \theta_\varphi \quad (6b)$$

Substituting Equation 4 with Equation 5 and 6 leads to

$$k_\varphi = \frac{1}{[1+A_1^2+A_2^2]^{1/2}} \cdot \frac{(B_1+B_2 \tan^2 \varphi + 2B_3 \tan \varphi)}{[(1+A_1^2)+(1+A_2^2)\tan^2 \varphi + 2A_1A_2 \tan \varphi]} \quad (7)$$

where $A_1 = \frac{dz}{dx}$ and $A_2 = \frac{dz}{dy}$ denote the first derivatives of the reflector along x- and y-directions,

also known as apparent dips, respectively. $B_1 = \frac{d^2z}{dx^2}$, $B_2 = \frac{d^2z}{dy^2}$ and $B_3 = \frac{d^2z}{dxdy}$ denote the second reflector derivatives.

Dip curvature and strike curvature could be treated as simplifications of Equation 7 when curvature is evaluated along the true dip direction and the strike direction, respectively. Specifically, for the direction of true dip,

$$\varphi_{dip} = \text{atan2}(A_2, A_1) \quad (8)$$

then Equation 7 becomes

$$k_{dip} = \frac{1}{[1+A_1^2+A_2^2]^{3/2}} \cdot \frac{1}{[A_1^2+A_2^2]} \cdot (A_1^2B_1 + A_2^2B_2 + 2A_1A_2B_3) \quad (9)$$

Similarly, when φ takes the strike direction perpendicular to the true dip,

$$\varphi_{strike} = \varphi_{dip} + 90 = -\text{atan2}(A_1, A_2) \quad (10)$$

Equation 7 is simplified into the equation for computing strike curvature

$$k_{strike} = \frac{1}{[1+A_1^2+A_2^2]^{1/2}} \cdot \frac{1}{[A_1^2+A_2^2]} \cdot (A_2^2B_1 + A_1^2B_2 - 2A_1A_2B_3) \quad (11)$$

At every point on a surface, when increasing the measuring azimuth φ from 0 to 360, Equation 7 provides us with a curve of all the azimuthal curvatures, and the curve indicates the

principle directions by which curvature reaches its local maximum and minimum (Figure 4-4). Moreover, by examining Equation 7, we notice that 3D curvature attribute is periodic with a period of 180 degree (shown in Figure 4-4a)

$$k(\varphi) = k(\varphi + 180) \quad (12)$$

In order to search for most extreme curvature and its associated azimuth, we propose an analytical approach that is both computationally efficient and accurate. After taking a derivative of Equation 7 with respect to azimuth φ , we obtain a quadratic equation

$$\frac{dK_\varphi}{d\varphi} = d \cdot [a \cdot \tan^2 \varphi + b \cdot \tan \varphi + c] \quad (13)$$

where $a = (A_1 A_2 B_2 - A_2^2 B_3 - B_3)$ is the quadratic coefficient;

$b = (A_1^2 B_2 - A_2^2 B_1 - A_1 + A_2)$ is the linear coefficient;

$c = (A_1^2 B_3 - A_1 A_2 B_1 + B_3)$ is the constant term; and

$d = \frac{1}{[1+A_1^2+A_2^2]^{1/2}} \cdot \frac{1}{[(1+A_1^2)+(1+A_2^2)\tan^2 \varphi + 2A_1 A_2 \tan \varphi]^2} \cdot \frac{1}{\cos^2 \varphi}$ is the scaling term.

As demonstrated in Figure 4-4, principle directions could be accurately evaluated by finding the roots of Equation 13. From the algebraic knowledge, the quadratic equation has two roots, one making Equation 7 to be maximum and the other to be minimum.

$$\varphi_{1,2} = \text{atan} \left(\frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \right) \quad (14a)$$

And two principle curvatures are

$$k_{1,2} = \frac{1}{[1+A_1^2+A_2^2]^{1/2}} \cdot \frac{(B_1+B_2 \tan^2 \varphi_{1,2} + 2B_3 \tan \varphi_{1,2})}{[(1+A_1^2)+(1+A_2^2)\tan^2 \varphi_{1,2} + 2A_1 A_2 \tan \varphi_{1,2}]} \quad (14b)$$

Finally, combination of two principle curvatures makes it possible to compute most extreme curvature

$$k_{xmt} = \begin{cases} k_1 & \text{if } |k_1| \geq |k_2| \\ k_2 & \text{if } |k_1| < |k_2| \end{cases} \quad (15a)$$

and its associated azimuth

$$\varphi_{xmt} = \begin{cases} \varphi_1 & \text{if } |k_1| \geq |k_2| \\ \varphi_2 & \text{if } |k_1| < |k_2| \end{cases} \quad (15b)$$

Figure 4-5 illustrates the workflow for computing 3D most extreme curvature and its associated azimuth, which consists of four steps: first, at any given sample location in a seismic volume, we compute the first and second derivatives of seismic reflectors; second, all the coefficients of the quadratic equation are evaluated; then we use Equation 14 to solve Equation 13 and estimate two principle curvatures and associated azimuths; finally, the use of Equation 15 provides us with most extreme curvature and most extreme curvature azimuth at the given sample. After repeatedly executing the above steps from one sample location to another, a seismic amplitude volume is transformed into two volumes, one of most extreme curvature and the other of most extreme curvature azimuth.

Most Extreme Flexure

Flexure, as a new geometric attribute of seismic data, is defined as a spatial derivative of seismic curvature along reflectors (Gao, 2013). At every point of a two-dimensional curve, flexure evaluates the changes in the radius of circles that are tangent to the curve with respect to the arc length at that point; thereby a fault is highlighted as a peak associated with two side-lobes of an opposite sign (Figure 4-6). Just like curvature attribute, in 3D space, flexure is also dependent on the measuring direction. Among all the possible azimuths, there is two directions along which flexure reaches its maximum f_{max} , and minimum f_{min} , respectively; also dip curvature gradient f_{dip} and strike curvature gradient f_{strike} can be measured along the direction

of true dip and strike (Figure 4-7). Similarly, we define and compute most extreme flexure f_{xmt} as the signed maximum of f_{max} and f_{min}

$$f_{xmt} = \begin{cases} f_{max} & \text{if } |f_{max}| \geq |f_{min}| \\ f_{min} & \text{if } |f_{max}| < |f_{min}| \end{cases} \quad (16)$$

In this paper, we first present a computational equation of azimuthal flexure, which represents the value measured along any given azimuth on a surface. Starting from Equation 7 of computing azimuthal curvature, azimuthal flexure f_φ is evaluated as

$$f_\varphi = \frac{dk_\varphi}{ds} = \frac{\partial k_\varphi}{\partial x} \cdot \frac{dx}{ds} + \frac{\partial k_\varphi}{\partial y} \cdot \frac{dy}{ds} \quad (17)$$

By taking a partial derivative of Equation 7 with respect to x and y, apparent flexures along x- and y-directions, $\frac{\partial k_\varphi}{\partial x}$ and $\frac{\partial k_\varphi}{\partial y}$, become

$$\begin{aligned} \frac{\partial k_\varphi}{\partial x} = & \frac{1}{[1+A_1^2+A_2^2]^{1/2}} \cdot \frac{(C_1+2C_3\tan\varphi+C_4\tan^2\varphi)}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]} - \frac{[A_1B_1+A_2B_3]}{[1+A_1^2+A_2^2]^{3/2}} \cdot \\ & \frac{[B_1+B_2\tan^2\varphi+2B_3\tan\varphi]}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]} - \frac{[A_1B_1+A_2B_3]}{[1+A_1^2+A_2^2]^{1/2}} \cdot \frac{2[A_1B_1+A_2B_3\tan^2\varphi+(A_1B_3+A_2B_1)\tan\varphi]}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]^2} \end{aligned} \quad (18a)$$

$$\begin{aligned} \frac{\partial k_\varphi}{\partial y} = & \frac{1}{[1+A_1^2+A_2^2]^{1/2}} \cdot \frac{(C_3+2C_4\tan\varphi+C_2\tan^2\varphi)}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]} - \frac{[A_1B_3+A_2B_2]}{[1+A_1^2+A_2^2]^{3/2}} \cdot \\ & \frac{[B_1+B_2\tan^2\varphi+2B_3\tan\varphi]}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]} - \frac{[A_1B_1+A_2B_3]}{[1+A_1^2+A_2^2]^{1/2}} \cdot \frac{2[A_1B_3+A_2B_2\tan^2\varphi+(A_1B_2+A_2B_3)\tan\varphi]}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]^2} \end{aligned} \quad (18b)$$

Finally, substituting Equation 17 with Equation 6 and 18 leads to a complicated but applicable equation of computing azimuthal flexure

$$\begin{aligned} f_\varphi = & \frac{\cos\varphi}{[1+A_1^2+A_2^2]} \cdot \frac{(C_1+3C_3\tan\varphi+3C_4\tan^2\varphi+C_2\tan^3\varphi)}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]} - \frac{\cos\varphi}{[1+A_1^2+A_2^2]^2} \cdot \frac{[B_1+B_2\tan^2\varphi+2B_3\tan\varphi]}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]^2} \cdot \\ & [(3A_1^3B_1 + A_1^2A_2B_3 + 2A_1A_2^2B_1 + 3A_1B_1 + A_2B_3) + (5A_1^3B_3 + 4A_1^2A_2B_1 + A_1^2A_2B_2 + \\ & 6A_1A_2^2B_3 + 5A_1B_3 + A_2B_2 + 2A_2B_1 + 2A_2^3B_1)\tan\varphi + (2A_1^3B_2 + 6A_1^2A_2B_3 + A_1A_2^2B_1 + \end{aligned}$$

$$4A_1A_2^2B_2 + A_1B_1 + 2A_1B_2 + 5A_2B_3 + 5A_2^3B_3)tan^2\varphi + (2A_1^2A_2B_2 + A_1A_2^2B_3 + A_1B_3 + 3A_2B_2 + 3A_2^3B_2)tan^3\varphi] \quad (19)$$

Specifically, when φ takes the direction of true dip (Equation 8), then Equation 19 measures dip flexure (Equation 11 in Di and Gao, 2014b)

$$f_{dip} = \frac{1}{[1+A_1^2+A_2^2]^2} \cdot \frac{1}{[A_1^2+A_2^2]^{3/2}} \cdot (A_1^3C_1 + A_2^3C_2 + 3A_1^2A_2C_3 + 3A_1A_2^2C_4) - 3 \cdot \frac{1}{[1+A_1^2+A_2^2]^3} \cdot \frac{1}{[A_1^2+A_2^2]^{3/2}} \cdot (A_1^2B_1 + A_2^2B_2 + 2A_1A_2B_3)^2 \quad (20)$$

Similarly, we can compute strike flexure

$$f_{strike} = \frac{1}{[1+A_1^2+A_2^2]} \cdot \frac{1}{[A_1^2+A_2^2]^{3/2}} \cdot (A_2^3C_1 - A_1^3C_2 - A_1A_2^2C_3 - A_1^2A_2C_4) - \frac{1}{[1+A_1^2+A_2^2]^2} \cdot \frac{1}{[A_1^2+A_2^2]^{3/2}} \cdot (A_1^2B_1 + A_2^2B_2 - 2A_1A_2B_3) \cdot (A_2^2B_3 - A_1^2B_3 + A_1A_2B_1 - A_1A_2B_2) \quad (21)$$

Using Equation 19, we can plot the curve of curvature gradient related to the azimuthal direction (Figure 4-8a). The curve shows that flexure is also a periodic attribute with a period of 180 degree; but unlike curvature, its sign reverses, since it measures the gradient from the opposite direction.

$$f(\varphi) = -f(\varphi + 180) \quad (22)$$

We can take a derivative of Equation 19 with respect to azimuth, but this leads to a fifth-order equation whose roots cannot be solved in an analytical way. Therefore, considering the periodic property of flexure attribute (Equation 22), we propose a simplified approach by scanning all possible azimuths between 0 degree (North) and 180 degree (South) to find most extreme flexure (Figure 4-8b), and then using Equation 22 to extend azimuth to the full range. This method helps reduce the computation time by half. By Equation 19, we can compute a set of flexure between 0 azimuth to 180 azimuth by a specified scanning interval, such as 1 or 5

degree, and take the signed maximum as the desired most extreme flexure, f_{xmt} , and the associated azimuth as the desired most extreme curvature-gradient azimuth, φ_{xmt} . In addition, φ_{xmt} is adjusted to the full azimuth range based on Equation 22

$$\varphi_{xmt} = \begin{cases} \varphi_{xmt} & \text{if } f_{xmt} \geq 0 \\ 180 + \varphi_{xmt} & \text{if } f_{xmt} < 0 \end{cases} \quad (23)$$

Figure 4-9 illustrates the workflow for computing 3D most extreme flexure and its associated azimuth, which consists of four steps: first, at any given sample location in a seismic volume, we compute the first, second and third derivatives of the seismic reflector; second, using Equation 19, a set of azimuthal flexures are calculated by increasing the measuring azimuth from 0 degree (North) to 180 degree (South); then we compare all the flexures, and output the signed maximum as most extreme flexure f_{xmt} and the associated azimuth as most extreme flexure azimuth φ_{xmt} ; finally, true flexure azimuth at the given sample is adjusted by the use of Equation 23. After repeatedly executing the above steps from one sample location to another, a seismic amplitude volume is transformed into two volumes, one of most extreme flexure and the other of most extreme flexure azimuth.

Application

To illustrate the added value of most extreme curvature and most extreme flexure along with their associated azimuth in fracture characterization, we apply our methods to a seismic survey over Teapot Dome of Wyoming. We begin by generating a suite of attribute cubes for Teapot Dome, Wyoming, and extracting the attribute values along an interpreted horizon approximately at 4400 ft. As a baseline, we plot the structure contour map of the picked horizon in Figure 4-10a, which clearly depicts the northwest-trending anticline and associated three

northeast-striking major faults (denoted by arrows). After processing the amplitude volume by the semblance-based coherence method (Marfurt et al., 1998), we display the corresponding coherence slice in Figure 4-10b, in which zones of low coherence correspond to the cross-regional faults that are already visible from the structure contour map. However, faults and fractures below the seismic scale are not discernable from the coherence slice.

Reflector dip, curvature and flexure evaluate first-, second- and third-order lateral changes in the geometry of seismic reflectors, respectively; thus, they are capable of providing an enhanced spatial resolution for imaging subseismic structural features. As the first derivative of a seismic reflector, dip attribute is often interpreted as being indicative of fractures. As the second reflector derivative, curvature attribute highlight a fault by the juxtaposition of a positive curvature and a negative curvature. As the third-order derivative of reflector geometry, flexure attribute directly highlights faults that are typically associated with local peaks (positive or negative). In Figure 4-11, we display the (a) reflector dip, (b) most extreme curvature, and (c) most extreme flexure corresponding to the structure map shown in Figure 4-10a. We notice that, besides the major northeast-striking faults, more detailed information about the structural deformation over the northwest-trending anticline crest is revealed by three attributes, and the spatial resolution increases from (a) to (c). Subtle structures and deformational fabrics that are not visible by either reflector dip or curvature become discernable with the aid of most extreme curvature gradient (denoted by arrows). This is particularly the case with the northeast-trending cross-regional faults that have been previously reported based on outcrops and well logs (Cooper et al., 2006; Schwartz, 2006)

In Figure 4-12, we display the (a) dip azimuth, (b) most extreme curvature azimuth, and (c) most extreme flexure azimuth, and these maps provide different perspectives on fracture

interpretation at Teapot Dome. Among these, dip azimuth has the lowest resolution, as shown in Figure 4-12a, and only delineates the major cross-regional faults. In contrast, most extreme curvature azimuth (Figure 4-12b) and most extreme flexure azimuth (Figure 4-12c) reveal structural complexities and details associated with the cross-strike lineaments. Although both attributes represent the most likely orientation of faults/fractures to develop, they should be interpreted to represent different mode of faults and fractures. Specifically, most extreme curvature azimuth reveals the SE140° orientation of extension over the anticline crest (highlighted in yellow-green). Additionally, we also notice northeast-oriented localized compression (highlighted in red), which has a high potential of developing subtle reverse fractures subparallel to the northwest-trending anticline; however, such fractures are not clearly characterized by the image of most extreme curvature azimuth. As shown in Figure 4-12c, azimuth of most extreme flexure reveals fractures both subparallel and perpendicular to the regional structure trend. Consistent with previous observations and prediction from outcrops and image logs (Cooper et al., 2006; Schwartz, 2006), these fractures can be divided into two sets: one primary set trends to the northeast, running across the hinge of the Dome; and the other set trends to the northwest and is subparallel to the regional folds. By integrating the images of most extreme flexure (Figure 4-11c) and its associated azimuth (Figure 4-12c), we interpret a total of fifty-one faults and fractures in the study area. These fractures are plotted in Figure 4-13a, in which each red line representing a lineament subparallel to fold hinge and each blue line for a cross-regional lineament. Then we collect the azimuth and length of all the picked fractures and display them in rose diagram (Figure 4-13b), which shows nearly orthogonal trends with a major N40°E trending set of faults and fractures. The interpretation fits the fracture model at Teapot Dome presented by Cooper et al. (2006) (shown in Figure 4-13c).

Discussions

Extracting the azimuth property of most extreme curvature and most extreme flexure provides us with useful information about fault/fracture orientation. First, the most extreme curvature occurs along the direction of local extensional strain, and interpreting maps of most extreme curvature azimuth can help us to predict local tensile fracture orientation (Gao, 2013). Second, the most extreme flexure might occur along the direction of local shear strain, and interpreting maps of most extreme curvature-gradient azimuth could help us to predict local shear fracture orientation (Gao, 2013). Differentiating tensile from shear faults/fractures and predicting their orientations are instrumental in fault/fracture characterization.

A concern about using flexure attribute is its sign and side-lobes. First, in maps of most extreme flexure, fault and fractures are often highlighted as lineaments with either positive or negative peaks, and the sign is dependent on whether such attribute is measured along or against the dip azimuth. In our algorithm, the measuring azimuth of this attribute is defined between 0 degree (North) and 180 degree (South). With this scanning range, a fault would have a negative flexure when it dips to the east, whereas the sign becomes positive for a western-dipping fault. Sign consistency is recommended for better interpretation of this attribute. However, due to geological complexity, there often occurs a mixture of positive flexures and negative ones in a study area. An effective technique for sign adjustment is the next step to make flexure attribute more practical and informative. Second, besides the peak, a fault often has two sidelobes with the opposite sign to the peak, and the sidelobes reduce the S/N ratio of flexure images and thereby interfere with the process of accurate fault recognition. We also expect to develop an effective sidelobe-suppression technique for improved fracture detection.

Our proposed azimuth-scanning approach has a major limitation in computational efficiency when applied to compute most extreme flexure. For a high resolution, azimuth scanning should run from 0 degree (North) to 180 degree (South) with a small interval, such as 0.5 or 1.0 degree, at each sample location through a seismic volume, and thus the process is computationally intensive for a large dataset. In an attempt to solve this problem, the algorithm typically use a scanning interval of 5.0 degree, thereby significantly improving the computational efficiency. Unfortunately, the enhancement in computational efficiency is achieved at the expense of sacrificing the azimuthal resolution of the generated results.

Conclusions

Most extreme curvature and most extreme flexure are among the most useful seismic attributes for detecting faults and fractures in the subsurface. An integration of most extreme curvature/flexure and the associated azimuth helps define the fracture intensity and fracture orientation. We have developed new methods to compute the magnitude and azimuth of most extreme curvature and most extreme flexure attributes in a computationally most efficient manner. Most extreme curvature and its associated azimuth are calculated using an analytical approach, which is both analytically accurate and computationally efficient. Since the analytical approach cannot be applied to the third-order flexure attribute, we implement an azimuth-scanning algorithm to find the desired magnitude and azimuth of most extreme flexure. We apply our newly-developed algorithms to a 3D seismic survey over Teapot Dome of Wyoming. The results indicate that the most extreme flexure provides a higher resolution on fracture characterization than by most extreme curvature. Moreover, subtle faults/fractures associated with mild bending are better imaged by using most extreme flexure azimuth. Both curvature and flexure are superior to conventional reflector dip and coherence attributes in defining subsurface

faults and fractures, and integrating extreme curvature and extreme flexure along with corresponding azimuth attributes enhances our capability to describe and visualize the complexity of fractured reservoirs.

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Figures

Figure 4-1: Curvature attribute of a curve in two dimensions. Note that curvature k of a curve at a particular point is the inverse of a circular's radius R which is tangent to that curve at that point, and a fault is expressed by the juxtaposition of a positive curvature and a negative curvature (modified from Roberts, 2001; Gao, 2013).

Figure 4-2: Curvature attribute of a quadratic surface in three dimensions, showing maximum curvature k_{max} (red), minimum curvature k_{min} (green), dip curvature k_{dip} , and strike curvature k_{strike} at point P (modified from Roberts, 2001).

In x-y-z coordinate system,

Apparent dips

$$\theta_x = \tan^{-1} \left(\frac{dz}{dx} \right), \quad \theta_y = \tan^{-1} \left(\frac{dz}{dy} \right)$$

Azimuthal dip

$$\theta = \tan^{-1} \left(\frac{dz}{dx} \cdot \cos \varphi + \frac{dz}{dy} \cdot \sin \varphi \right)$$

Figure 4-3: Schematic diagram of defining azimuthal dip θ_φ along any given azimuth φ . Note that θ_x and θ_y are the apparent dips in the inline(x-) and crossline(y-) directions, respectively.

Figure 4-4: Schematic diagrams of finding the principle values and principle directions of curvature using an algebraic approach at point P of the quadratic surface shown in Figure 4-2. (a) The relationship curve of azimuthal curvature k with respect to the measuring azimuth φ , demonstrating the periodic property of 3D curvature attribute. (b) The quadratic curve of azimuthal curvature $\frac{dk}{d\varphi}$ related to the measuring azimuth φ , whose roots indicates the principle directions along which curvature reaches its maximum or minimum.

Figure 4-5: Flowchart of computing 3D most extreme curvature and most extreme curvature azimuth. The input is a regular amplitude volume, and two attribute cubes are computed: one of most extreme curvature and the other of most extreme curvature azimuth.

Figure 4-6: Flexure attribute of a curve in two dimensions. Note that flexure f of a curve at a particular point evaluates the changes in the radius of circles tangent to that curve at that point, and a fault is expressed by a local maximum of flexure (modified from Gao, 2013).

Figure 4-7: Flexure attribute of a cubic surface in three dimensions, showing maximum flexure f_{max} (red), minimum flexure f_{min} (green), dip flexure f_{dip} , and strike curvature gradient f_{strike} at point P .

Figure 4-8: Schematic diagrams of finding the principle values and principle directions of flexure using a scanning approach at point **P** of the cubic surface shown in Figure 4-7. (a) The relationship curve of azimuthal flexure f with respect to the measuring azimuth φ , demonstrating the opposite periodic property of flexure attribute. (b) Schematic diagram in map view of searching for most extreme flexure and the corresponding azimuth (modified from Gao, 2013).

Figure 4-9: Flowchart of computing 3D most extreme flexure and most extreme flexure azimuth. The input is a regular amplitude volume, and two attribute cubes are computed: one of most extreme flexure and the other of most extreme flexure azimuth.

Figure 4-10: Application of our methods to the 3D seismic volume over Teapot Dome in Wyoming. (a) Structure contour of the horizon approximately at 4400 ft, demonstrating a northwest-trending anticline (the fold hinge is denoted by curve) and associated northeast-striking faults (denoted by arrows). (b) The corresponding coherence slice that clearly highlights the major cross-regional faults by zones of low coherence.

Figure 4-11: Geometric attributes of the horizon from Teapot Dome in Wyoming. (a) Dip. (b) Most extreme curvature. (c) Most extreme flexure. Compared to the dip image, more structural details are revealed by curvature and especially flexure.

Figure 4-12: Azimuth of geometric attributes of the horizon from Teapot Dome in Wyoming. (a) Dip azimuth. (b) Most extreme curvature azimuth. (c) Most extreme flexure azimuth. Fractures with different orientations are expressed by varied colors, leading to a better visualization of faults and fractures. Two sets of fractures are clearly demonstrated in the map of flexure azimuth: one is subparallel to the fold hinge, and the other trends perpendicular to the hinge.

Figure 4-13: Fracture interpretation at Teapot Dome. (a) Fifty-one picked faults and fractures. Each red line denotes a compression fracture trending parallel to the fold hinge, and each blue line denotes an extension fracture trending across the fold hinge. (b) The rose diagram of all fractures shown in (a), showing orthogonal trends. (c) The fracture model of Teapot Dome (modified from Cooper et al., 2006).

Chapter 5: Volumetric Extraction of Most Positive/Negative Curvature and Flexure Attributes for Improved Fracture Characterization from 3D Seismic Data

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Abstract

Most positive and negative curvatures are among the most useful attributes for detecting faults and fractures in the subsurface by evaluating second-order variation of the geometry of seismic reflections. When applied to quantitative fracture characterization and modeling of a fractured reservoir, their magnitude and azimuth are greatly expected to help quantify intensity and orientation of faulting and fracturing, respectively. However, previous efforts focus on estimating only the magnitude of both attributes and applying its edge-type visualization to facilitate fault interpretation from three-dimensional (3D) seismic data, whereas their associated azimuth is ignored from computation. This study presents an algorithm for simultaneously evaluating both the magnitude and azimuth of most positive/negative curvature, and moreover, extends it to the third-order flexure attribute for revealing more subtle features that are not recognizable from the conventional discontinuity and curvature attributes. The approach implemented in the new methods is analytical and thereby more accurate and computationally efficient, compared to the existing discrete azimuth-scanning approach used for flexure analysis. The added value of extracting most positive/negative curvature and flexure is demonstrated through applications to a fractured reservoir at Teapot Dome (Wyoming). First, these newly-

extracted attributes make computer-aided fault/fracture decomposition possible. Such technique allows interpreters to focus on one particular direction for fracture characterization at a time, so that a fractured reservoir could be partitioned into different components for further analysis. Second, curvature/flexure azimuth allows interpreters to plot fracture histogram and/or rose diagram in an automatic and quantitative manner. Compared to the conventional workflow of plotting rose diagram based on manual measurements, such automatic plotting is more efficient and offers unbiased insights into fracture characterization by illuminating the most-likely orientations of natural fractures, strain and stress fields in the formations of interest.

Introduction

In fractured reservoirs formed by tectonic deformation, reliable characterization of fault and fracture plays a key role in delineating potential hydrocarbon migration pathways in the reservoir formation and designing horizontal drilling for reservoir development. The conventional discontinuity attributes (e.g., Bahorich and Farmer, 1995; Marfurt et al., 1998; Tingdahl and de Rooij, 2005; Di and Gao, 2014a; Zheng et al., 2014) and curvature attributes (e.g., Lisle, 1994; Roberts, 2001; Sigismondi and Soldo, 2003; Chopra and Marfurt, 2010; Di and Gao, 2014b) have been widely used to detect and visualize faults and fractures from three-dimensional (3D) seismic data. Specifically, by measuring lateral waveform similarity and/or amplitude variation, discontinuity attributes provide a clear detection of the major faults that are already discernable from seismic amplitude. However, such description is only qualitative and has a limited resolution on subtle faults and fractures. Quantitative and more detailed fracture detection could be achieved with the aid of extracting geometric attributes, including reflector dip, curvature, and flexure, which evaluate lateral variation of the geometry of seismic reflections at different scales (Gao and Di, 2015). Particularly, dip evaluates the first-order variation of reflection geometry

and could detect faults with apparent displacement; curvature evaluates the second-order geometry variation and thereby subtle features can be recognized in curvature maps; flexure evaluates the third order geometry variation and has an even higher resolution than the second-order curvature.

Seismic curvature has been the focus of geophysical research since the introduction of Gaussian curvature analysis to structural interpretation by Lisle (1994). Such second-order geometric attribute describes how much a curve deviates from being straight and thereby is capable of clearly highlighting faults and fractures induced by formation bending. Roberts (2001) provided a detailed list of nine curvatures, including maximum/minimum curvatures and most positive/negative curvatures, and demonstrated their values in identifying fault and other subtle features through applications to a dataset from the North Sea; however, his workflow of extracting these attributes is based on a well-prepared horizon and thereby ran the risk of creating artifacts caused by manual horizon mis-interpretation. To avoid interpreter bias, volumetric estimates of seismic curvature were first achieved by Al-Dossary and Marfurt (2006), whose algorithm uses a fractional-order approach but the application is limited to only horizontal or gently-dipping formations. Such limitation is well resolved by applying a computer-aided workflow of fitting a quadratic 9-node grid cell to 3D seismic data (Di and Gao, 2014b). Among these various seismic curvatures, most positive and negative curvatures find the widest applications, due to their capability of providing an edge-type display of faults and fractures for further analysis (e.g., Roberts, 2001; Blumentritt et al., 2006; Chopra and Marfurt, 2007a, 2007b, 2010). When applied to fault interpretation, most positive and negative curvatures highlight the anticlinal up-thrown block and synclinal down-thrown block of a fault, respectively, but provide no definition of the fault plane. Such limits would cause an apparent offset between the actual

fault location and our interpretation, especially for faults with wide damage zones. Moreover, the existing methods for computing both curvatures are limited for computing only their magnitude and applying such property to visualize potential faults and predict the maximum possible intensity of faulting and fracturing in the subsurface. Little work has been focusing on computing their associated azimuth, which is also fundamentally important for robust fracture network modeling by predicting the most-likely orientation of faults and fractures (Gao, 2013).

For better structure analysis and fracture characterization, seismic flexure was proposed to complement the existing curvature attribute (Gao, 2013). Given that curvature is related to the bending of seismic reflections, the new flexure attribute describes lateral changes in the bending moment (Lim and Reddy, 2003) and is capable of highlighting shearing-induced faults and fractures in geologic formations. Physically, flexure evaluates the third-order variation of the geometry of seismic reflections; thus, it is capable of positioning the fault plane and revealing more subtle information about structural deformation that is not detectable by the second-order curvature attribute. Theoretically, an infinite number of flexures can be evaluated from 3D seismic data, due to its dependence on its measuring direction on a surface. Among all possible directions, four important ones for structure analysis are dip direction, strike direction, and two principle directions associated with maximum and minimum flexures, respectively (Di and Gao, 2014c). The first flexure algorithm was developed for evaluating flexure along the direction of true dip, or referred as dip flexure (Di and Gao, 2014d). Then, in order to enhance the resolution on fracture characterization, a discrete azimuth-scanning algorithm is presented for computing extreme (signed maximum) flexure, whose magnitude and azimuth are indicative of the maximum intensity and most-likely orientation of faulting and fracturing (Di and Gao, 2014c). However, scanning is a time-consuming process, and more importantly, extreme flexure contains

information that may be confusing for interpreters when it is used for fracture detection. Fracture interpretation would be more efficient, if flexure attribute extraction can be further improved to provide an edge-type display of faults and fractures, similar to that by most positive and negative curvatures.

This study extends the concept of most positive/negative curvature to seismic flexure and develops two new algorithms for simultaneously computing both the magnitude and azimuth of most positive/negative curvature and flexure attributes. Both algorithms consists of two steps: first to rotate the local seismic reflection to be horizontal by setting the first derivatives of seismic reflections, or apparent dips, to be zero; second to implement attribute analysis on the rotated reflection. For fast and efficient computation in an analytical manner, we start from the newly-developed equations for computing azimuthal curvature and azimuthal flexure, then take a derivative of such equations with respect to azimuth, and finally solve the generated quadratic and cubic equations to compute most positive/negative curvature and flexure. The added value of both algorithms is demonstrated through application to a fractured reservoir at Teapot Dome (Wyoming). The edge-type display of most positive/negative curvature and flexure provides an visualization with more details and less ambiguous information for interpreting subtle fractures, compared to the more commonly used extreme curvature and flexure attributes. More importantly, the orientations of faults and fractures in the subsurface are well quantified by the azimuth property of most positive/negative curvature and flexure. Using the attribute cubes generated from our new algorithms, fracture characterization can be further improved in two ways: (1) computer-aided partitioning of a fractured reservoir into different components that allows interpreters to focus on one particular direction for fracture interpretation at a time, and (2) automatic plotting of fracture histogram and/or rose diagram that allows interpreters to

predict the orientations of natural faulting and fracturing, strain and stress fields in the target formations, without introducing interpreter bias.

Method

A new workflow

The computation of seismic curvature and flexure attributes is strongly dependent on fitting a local surface to 3D seismic data and calculating the spatial derivatives of the surface, which becomes complicated and inaccurate for geologic complexities, such as overturned folds. This study proposes a new workflow of three steps to improve curvature and flexure analysis for complex structures (Figure 5-1). After fitting a local surface to seismic data at a particular sample, the algorithm first rotates the fitted surface to be horizontal at this sample by following its structural dip (Figure 5-2). Then, the derivatives of the rotated surface are calculated, which could accurately represent the variation of the surface geometry even for complexly-deformed formations. Finally, the algorithm searches for the maximum and minimum from all possible curvature/flexure values. The above steps are repeatedly executed from sample to sample, and consequently a regular amplitude volume is transformed into an attribute volume of seismic curvature/flexure. Considering the computational efficiency of the new derivatives after surface rotation, in this paper, we simplify the workflow by approximating them by the surface derivatives before rotation. Even though such simplification decreases the accuracy of curvature/flexure estimates, the associated output, often known as the most positive and negative attributes, is not only close to the true ones in most cases but also most popular and useful for fracture characterization.

Most positive/negative curvature

Most positive and negative curvatures, k_+ and k_- , are defined as maximum and minimum curvature analysis without considering local structural dip, respectively. Compared to the existing methods (Roberts, 2001; Al-Dossary and Marfurt, 2006), the new method presented in the paper has the strength of providing interpreters with two fundamental properties of most positive/negative curvature, k_+ and k_- , with one being the magnitude and the other being the associated azimuth. The former is popular and has been widely used to predict the intensity of maximum faulting and fracturing in the target reservoir formations, whereas the latter is new and could be useful for indicating the most-likely orientations of faults and fractures.

Our method starts from the equation for computing azimuthal curvature k_φ on a surface (Di and Gao, 2014b; Gao and Di, 2015).

$$k_\varphi = \frac{1}{[1+A_1^2+A_2^2]^{1/2}} \frac{(B_1+B_2 \tan^2 \varphi + 2B_3 \tan \varphi)}{[(1+A_1^2)+(1+A_2^2)\tan^2 \varphi + 2A_1 A_2 \tan \varphi]}, \quad (1)$$

where φ denotes the azimuthal direction. $A_1 = \frac{\partial z}{\partial x}$ and $A_2 = \frac{\partial z}{\partial y}$ denote the first derivatives of a seismic reflection along inline (x -) and crossline (y -) directions, also known as apparent dips, respectively. $B_1 = \frac{\partial^2 z}{\partial x^2}$, $B_2 = \frac{\partial^2 z}{\partial y^2}$ and $B_3 = \frac{\partial^2 z}{\partial x \partial y}$ denote the second derivatives. To avoid interpreter bias, all the derivatives are calculated using a computer-aided workflow for fitting a quadratic surface to local seismic data, based on a rectangle grid cell with 9 nodes (Di and Gao, 2014d). Then the following steps are conducted at each sample:

Step 1: perform surface rotation. In this study, surface rotation is achieved by setting the apparent dips, A_1 and A_2 , to be zero (Young, 1978), and then Equation 1 is simplified to be related to only the second derivatives.

$$k_\varphi = (B_1 \cos^2 \varphi + B_2 \sin^2 \varphi + 2B_3 \cos \varphi \sin \varphi), \quad (2)$$

Using this equation, we can plot a curve of curvature attribute with respect to azimuth (Figure 3a), and k_+ and k_- can be derived by searching the maximum and minimum of all possible normal curvatures on the rotated surface (Equation 3).

$$k_+ = \max(k_\varphi) , \quad k_- = \min(k_\varphi) , \quad (3)$$

Step 2: calculate curvature azimuth. We implement an analytical approach to avoid time-consuming searching. By taking a derivative of Equation 2 with respect to azimuth , we obtain a quadratic equation

$$\frac{dk_\varphi}{d\varphi} = 2\cos^2\varphi \cdot [-B_3\tan^2\varphi - (B_1 - B_2)\tan\varphi + B_3] , \quad (4)$$

Based on mathematics, equation $\frac{dk_\varphi}{d\varphi} = 0$ always has two real roots (Equation 5), since its discriminant $\Delta = (B_1 - B_2)^2 + 4B_3^2$ is always positive in all possible cases.

$$\varphi_{1,2} = \text{atan}\left(\frac{-(B_1 - B_2) \pm \sqrt{(B_1 - B_2)^2 + 4B_3^2}}{2B_3}\right) , \quad (5)$$

As shown in Figure 5-3b, one root represents the azimuth associated with most positive curvature k_+ (red), while the other represents the azimuth associated with most negative curvature k_- (blue). Also we notice that the two roots are nearly orthogonal, separated with an interval of about 90°.

Step 3: calculate curvature magnitude. Substituting Equation 2 with Equation 5 leads to the magnitude of most positive and negative curvatures, k_+ and k_- (Appendix A)

$$k_+ = \frac{1}{2} \left[(B_1 + B_2) + \sqrt{(B_1 - B_2)^2 + 4B_3^2} \right] , \quad (6a)$$

$$k_- = \frac{1}{2} \left[(B_1 + B_2) - \sqrt{(B_1 - B_2)^2 + 4B_3^2} \right] , \quad (6b)$$

The same equations can be found in Roberts (2001), and this helps verify the correctness of the analytical method presented in this study.

Most positive/negative flexure

Flexure at a point on a curve is defined as the rate of changes in curvature with respect to the curve length at this point (Gao, 2013), thereby a fault can be highlighted and easily recognized by this attribute (Figure 5-4). As a third-order geometric attribute, flexure is capable of revealing more subtle structural features than the second-order curvature. In order to provide an edge-type visualization of flexure attribute for improved fracture characterization, in this study we extend the definition of most positive/negative curvature to flexure and propose the first method for volumetrically computing most positive and negative flexure, f_+ and f_- .

Similar to curvature analysis, the computation of most positive/negative flexure, f_+ and f_- , starts with the equation for computing azimuthal flexure f_φ on a surface (Di and Gao, 2014c; Gao and Di, 2015).

$$f_\varphi = \frac{\cos\varphi}{[1+A_1^2+A_2^2]} \frac{(C_1+3C_3\tan\varphi+3C_4\tan^2\varphi+C_2\tan^3\varphi)}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]} - \frac{\cos\varphi}{[1+A_1^2+A_2^2]^2} \frac{[B_1+B_2\tan^2\varphi+2B_3\tan\varphi]}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]^2} [(3A_1^3B_1 + A_1^2A_2B_3 + 2A_1A_2^2B_1 + 3A_1B_1 + A_2B_3) + (5A_1^3B_3 + 4A_1^2A_2B_1 + A_1^2A_2B_2 + 6A_1A_2^2B_3 + 5A_1B_3 + A_2B_2 + 2A_2B_1 + 2A_2^3B_1)\tan\varphi + (2A_1^3B_2 + 6A_1^2A_2B_3 + A_1A_2^2B_1 + 4A_1A_2^2B_2 + A_1B_1 + 2A_1B_2 + 5A_2B_3 + 5A_2^3B_3)\tan^2\varphi + (2A_1^2A_2B_2 + A_1A_2^2B_3 + A_1B_3 + 3A_2B_2 + 3A_2^3B_2)\tan^3\varphi] \quad (7)$$

where $C_1 = \frac{\partial^3 z}{\partial x^3}$, $C_2 = \frac{\partial^3 z}{\partial y^3}$, $C_3 = \frac{\partial^3 z}{\partial x^2 \partial y}$ and $C_4 = \frac{\partial^3 z}{\partial x \partial y^2}$ denote the third derivatives of the geometry of seismic reflections, and a diamond grid cell with 13 nodes is used for fitting a cubic surface to local seismic data and calculating these third derivatives (Di and Gao, 2014d). Then the following steps are conducted at each sample:

Step 1: perform surface rotation. In this study, we rotate the surface to be horizontal by setting the apparent dips to be zero ($A_1 = A_2 = 0$). By applying the surface rotation, Equation 7 is significantly simplified to be related to only the third derivatives and more applicable for find an analytical solution (Equation 8).

$$f_{\varphi} = C_1 \cos^3 \varphi + 3C_3 \cos^2 \varphi \sin \varphi + 3C_4 \cos \varphi \sin^2 \varphi + C_2 \sin^3 \varphi , \quad (8)$$

Using this simplified equation, we also can plot a curve of flexure attribute with respect to azimuth (Figure 5-5a), and f_+ and f_- can be derived by searching the maximum and minimum of all possible normal flexures on the rotated surface (Equation 9).

$$f_+ = \max(f_{\varphi}) , \quad f_- = \min(f_{\varphi}) , \quad (9)$$

Step 2: calculate flexure azimuth. The analytical approach takes a derivative of Equation 8 with respect to azimuth φ , which generates a cubic equation

$$\frac{df_{\varphi}}{d\varphi} = \cos^3 \varphi \cdot [-C_4 \tan^3 \varphi - (2C_3 - C_2) \tan^2 \varphi + (2C_4 - C_1) \tan \varphi + C_3] , \quad (10)$$

The real roots of solving $\frac{df_{\varphi}}{d\varphi} = 0$ represent three potential azimuths, each of which is related to most positive flexure f_+ (red), most negative flexure f_- (blue), and a medium peak (black), and three roots are separated with an interval of about 60° (Figure 5-5b). Solving the cubic equation $\frac{df_{\varphi}}{d\varphi} = 0$ is mathematically complicated, and Appendix B provides effective calculation of real roots of a cubic equation in three different cases.

Step 3: calculate flexure magnitude. Substituting Equation 8 with these roots provides us with the magnitude of most positive and negative flexures.

Results

We generate most positive/negative curvature and flexure from a prestack depth-migration seismic volume of a fractured reservoir at Teapot Dome in Wyoming (USA), where the subsurface structure is dominated by a northwest-trending anticline, and the hinge zone is populated with bend-induced faults and fractures (Cooper et al., 2002; Cooper et al., 2006). The volume is approximately 4 mile $\times$ 7 mile (188 inlines $\times$ 345 crosslines) with 266 samples in each trace, and the horizon used for result demonstration in this study is created by 3D auto-tracking an easily recognizable peak within the whole volume and then manually correcting the picks. To facilitate result comparison and demonstrate the added value of the new geometric attributes, we first generate these attributes for the whole volume and then display them along a well-interpreted horizon approximately at 1400 m (Figure 5-6a), in which the western edge of the anticline is bounded by a major west-convergent up-thrust fault. The discontinuity attribute (Figure 5-6b) clearly highlights the major northeast-trending faults that are already visible from the structure map (denoted by arrows).

In Figure 5-7, we display the magnitude of most positive curvature and most negative curvature, each of which represents the upthrown and downthrown blocks of a fault, respectively, with the fault plane between them. Besides the major northeast-trending faults, curvature helps reveal more detailed information about delineating the structural deformation over the fold hinge. Specifically, most positive curvature highlights the anticlinal block of subsurface lineaments, especially those with a northwest-trending orientation, while the synclinal block of the northeast-trending lineaments are highlighted better using most negative curvature (denoted by circles). By generating most positive and negative flexures (Figure 5-8), we notice an enhancement in the resolution with more lineaments detected as potential faults and fractures (denoted by circles), compared to most positive and negative curvatures (Figure 5-7).

Then we display the azimuth of most positive/negative curvature and flexure in Figure 5-9 and 5-10, respectively. Both images reveal more structural details of the fractured reservoir than the magnitude property (Figure 5-7 and 5-8). For example, subtle fractures with weak curvature/flexure magnitude across the reservoir crest are clearly defined as lineaments with one particular orientation in the azimuth maps (denoted by circles). Also we notice curvature azimuth shows potential fractures perpendicular to the fold hinge with a dominant orientation of N60°E, but has a limited resolution on the northwest-trending fractures that have been observed from outcrop and image logs (Cooper et al., 2006; Schwartz, 2006). However, flexure azimuth (Figure 10) not only clearly illuminates these fractures, but also defines their orientations in a quantitative manner. Such azimuth could be helpful for quantifying the most-likely orientation of faulting and fracturing in the fractured reservoir.

Finally, to demonstrate the advantages of the new analytical methods over previous ones, we compute extreme curvature and extreme flexure, and the attribute images are displayed in Figure 5-11 and Figure 5-12, respectively. Comparisons demonstrate that most positive/negative curvature and flexure are superior to extreme curvature and flexure by providing an edge-type display of lineaments and improved clarity for fracture interpretation. Also a comparison between Figure 5-11 and Figure 5-12 demonstrates the improved and direct definition of fault plane by flexure attribute, instead of fault blocks by curvature attribute (denoted by arrows). In addition to the result comparisons, we also measure the computational time of these attributes. The computation of most positive/negative curvature is comparable to that of extreme curvature, since the latter can also be calculated using an analytical approach (Di and Gao, 2014b; Gao and Di, 2015). For flexure computation, however, we notice a significant improvement from extreme flexure to most positive/negative flexure, since the former can only be evaluated using a discrete

azimuth-scanning approach (Di and Gao, 2014c). Table 1 lists the time of flexure computation using two different approaches, and for the Teapot Dome dataset, the new analytical approach is about 8 times faster than the scanning one.

Interpretational Applications

In fractured reservoir analysis, fracture intensity and orientation are two fundamentally important properties for robust reservoir network modeling and reliable fluid flow prediction. In practice, however, they are very difficult and expensive to define due to the complexity of fracture systems and the lack of sufficient and reliable data in the subsurface. With the aid of the generated curvature and flexure attributes, their magnitude could be used for predicting the intensity of maximum faulting and fracturing, whereas their associated azimuth could serve the purpose of predicting the fracture orientations required for robust fracture characterization and modeling. In particular, we could apply the newly generated curvature/flexure cubes to (1) computer-aided decomposition of faults and fractures which allows interpreters to focus on one particular direction for fracture characterization at a time, especially in a structurally complicating fractured reservoir, and (2) automatic prediction of fracture orientations which allows interpreters to predict the trends of natural fractures, design the direction of horizontal drilling, and thereby reduce economical cost and environmental risk.

Computer-aided decomposition of faults and fractures

There are two ways that fracture detection along one particular direction can be achieved. One is to compute azimuthal curvature and azimuthal flexure along the desired direction using Equation 2 and Equation 8, respectively. Such results are generated along azimuth (a) 0° (North), (b) 30°, (c) 60°, (d) 90° (East), (e) 120°, and (f) 150°, and displayed in Figure 5-13 and 5-14. The northwest-trending lineaments are better detected when curvature and flexure are measured

along an azimuth of 30° to 60°, while the azimuth of 120° to 150° helps highlight the northeast-trending lineaments. The other way is to use flexure azimuth as fracture orientation and then decompose a well-defined fracture cube (e.g., coherence, ant-tracking, and flexure) into different orientations representing different components. In the case of Teapot Dome, as shown in Figure 5-15, we could separate the (a) northwest- and (b) northeast-trending fractures by partitioning the extreme flexure attribute (Figure 5-12a), and such decomposition offers new insight into understanding the regional and cross-regional faulting and fracturing of the fractured reservoir at Teapot Dome.

Automatic prediction of fracture orientations

One major goal of fracture interpretation is to measure the orientations of faults and fractures, which directly affect the anisotropy in mechanical properties of fractured reservoirs and the prevailing direction for fluid flow. Therefore, predicting fracture orientation from 3D seismic data can avoid wasteful drilling in the wrong direction, and a popular and useful tool is to plot fracture histogram and/or rose diagram that indicates the trends of natural fractures, strain and even stress fields in the intervals of interest. Using the generated curvature azimuth and flexure azimuth, histogram/rose diagram can be produced in an automatic manner, which avoids the traditional manual measurements of fracture orientation by seismic interpreters (Blumentritt et al., 2006). Figure 5-16 and 5-17, respectively, show the (a) histogram and (b) rose diagram for the picked horizon at Teapot Dome using the generated azimuth property of curvature and flexure attributes. Particularly, as illuminated by flexure azimuth, three sets of faulting and fracturing are depicted: (1) a hinge-perpendicular set with a strike of about N60°E (T1), (2) a hinge-oblique set with a strike of about N65°W (T2), and (3) a hinge-parallel set with a strike of about N25°W (T3). Such results are consistent with previous observations reported from

outcrops, image logs, and oil production data (Hennings et al., 2000; Nelson, 2001; Cooper et al., 2002, 2006; Gilbertson, 2006; Schwartz, 2006; Smith, 2008).

Discussions

Seismic curvature and flexure represent the second- and third-order measures of reflection geometry, respectively. The analysis presented here shows that flexure is able to highlight more subtle faults and fractures that might not be easily discernible from the popular discontinuity and curvature attributes, and such attribute could be implemented for improving fracture characterization and network modeling. Particularly, flexure magnitude provides quantitative estimates of changes in the intensity of bending, thus it could be used for quantitative strain/stress analysis in the reservoir formations. Flexure azimuth provides a better prediction of fracture trends than curvature azimuth, for example the T3 trend (Figure 5-17) confirmed by outcrop and well log analysis (Cooper et al., 2006). Besides the most important magnitude and azimuth properties, recent research indicate that flexure sign could also be helpful for differentiating fracture mode (shear vs. tensile), which is of significant importance for modeling shear fractures and improving the efficiency of fluid flow from reservoir formations.

Estimates of seismic curvature and flexure should follow the geometry of seismic reflections, which includes accurate estimates of the first-, second-, and third-derivatives of the reflection geometry. However, most positive/negative curvature and flexure simplifies the computation process by assuming the first derivatives to be zero without adjusting the second- and/or third-derivatives in correspondence with the surface rotation; therefore, the simplified analysis is close to accurate curvature/flexure estimates for horizontal or gently-dipping horizons. For horizons dipping at a large angle and suffering from complicated deformation, these measures will undesirably overestimate the magnitude of curvature and flexure attributes

that is linked to the predictions of fracture intensity, and inaccurately evaluate the associated azimuth that is linked to the predictions of fracture orientation. In such cases, therefore, seismic curvature and flexure should be estimated using the proposed workflow with the spatial derivatives of the rotated surface, instead of those of the surface before rotation.

In practice, seismic geometric attributes (dip, curvature, flexure) could be extracted in either depth or time domain. However, best detection could be achieved from depth data, in which lateral variation well represents structural deformation occurred in the target formations. In time domain, instead, interpretation should take into account abnormalities of velocity distribution, such as low velocity zones associated with hydrocarbon migration, such as gas chimney. Therefore, reliable time-depth conversion is greatly recommended before generating curvature and flexure attributes, especially in the areas with complicated velocity distribution.

Conclusions

Most positive and negative curvatures are among the most useful seismic attributes for fault interpretation from 3D seismic, and such concept could extend to the third-order flexure attribute for an improved resolution on fracture characterization and modeling. We have presented new analytical methods for evaluating these attributes, which simultaneously extract both the magnitude and azimuth properties of most positive/negative curvature and flexure. Compared to the conventional extreme curvature and flexure, most positive/negative curvature and flexure is capable of providing a more detailed edge-type display of faults and fractures to facilitate fault interpretation. Application to 3D seismic data demonstrates not only an enhanced clarity and resolution of interpreting each lineament, but also a significant improvement of the accuracy and computational efficiency by implementing the analytical approaches.

Our new method of computing most positive/negative curvature and flexure as well as their associated azimuth provides a powerful tool for better fracture characterization, and these attribute could be used for (1) computer-aided decomposition of faults and fractures which partitions a fractured reservoir into different components and allows interpreters to focus on one particular direction for fracture characterization, and (2) automatic plotting of fracture histogram and rose diagram which allows interpreters to predict the orientations of natural fractures, strain and stress fields in the subsurface.

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Appendix A

Derivation of equation for most positive/negative curvature

Solving the quadratic equation $\frac{dk_\varphi}{d\varphi} = 0$ leads to two real roots $\varphi_{1,2}$ (Equation 5). From this solution, we can further calculate

$$\tan\varphi_{1,2} = -\frac{1}{2B_3} [(B_1 - B_2) \mp \sqrt{\Delta}] , \quad (\text{A-1a})$$

$$\tan^2\varphi_{1,2} = \frac{1}{2B_3^2} [(B_1 - B_2)^2 + 2B_3^2 \mp (B_1 - B_2)\sqrt{\Delta}] , \quad (\text{A-1b})$$

where $\Delta = (B_1 - B_2)^2 + 4B_3^2$, and $\Delta \geq 0$

Then we have

$$\begin{aligned}
B_1 + B_2 \tan^2 \varphi + 2B_3 \tan \varphi &= B_2 \pm \sqrt{\Delta} + B_2 \tan^2 \varphi = B_2(1 + \tan^2 \varphi) \pm \sqrt{\Delta} = (1 + \\
\tan^2 \varphi) \left[B_2 \pm \frac{\sqrt{\Delta}}{1 + \tan^2 \varphi} \right] &= (1 + \tan^2 \varphi) \left[B_2 \pm \frac{2B_3^2}{\sqrt{\Delta} \mp (B_1 - B_2)} \right] = (1 + \tan^2 \varphi) \left[B_2 \pm \right. \\
\left. \frac{1}{2} \left(\sqrt{\Delta} \pm (B_1 - B_2) \right) \right] &= \frac{1}{2} (1 + \tan^2 \varphi) \left((B_1 + B_2) \pm \sqrt{\Delta} \right). \tag{A-2}
\end{aligned}$$

Equation 2 can be represented as

$$k_\varphi = \frac{1}{1 + \tan^2 \varphi} (B_1 + B_2 \tan^2 \varphi + 2B_3 \tan \varphi), \tag{A-3}$$

and substituting equation A-3 with equation A-2 leads to

$$k_{1,2} = \frac{1}{2} \left[(B_1 + B_2) \mp \sqrt{(B_1 - B_2)^2 + 4B_3^2} \right]. \tag{A-4}$$

Finally, most positive curvature is the maximum of $k_{1,2}$

$$k_+ = \frac{1}{2} \left[(B_1 + B_2) + \sqrt{(B_1 - B_2)^2 + 4B_3^2} \right], \tag{A-5a}$$

and most negative curvature is the minimum of $k_{1,2}$

$$k_- = \frac{1}{2} \left[(B_1 + B_2) - \sqrt{(B_1 - B_2)^2 + 4B_3^2} \right]. \tag{A-5b}$$

Appendix B

Calculation of real roots of a cubic equation

Let a cubic equation be

$$ax^3 + bx^2 + cx + d = 0, \tag{B-1}$$

with $a \neq 0$. It has three roots, and the general expressions are

$$x_1 = -\frac{b}{3a} - \frac{1}{3a} \sqrt[3]{\frac{\Delta_1 + \sqrt{\Delta_1^2 - 4\Delta_0^3}}{2}} - \frac{1}{3a} \sqrt[3]{\frac{\Delta_1 - \sqrt{\Delta_1^2 - 4\Delta_0^3}}{2}}, \tag{B-2a}$$

$$x_2 = -\frac{b}{3a} + \frac{1+i\sqrt{3}}{6a} \sqrt[3]{\frac{\Delta_1 + \sqrt{\Delta_1^2 - 4\Delta_0^3}}{2}} + \frac{1-i\sqrt{3}}{6a} \sqrt[3]{\frac{\Delta_1 - \sqrt{\Delta_1^2 - 4\Delta_0^3}}{2}}, \quad (\text{B-2b})$$

$$x_3 = -\frac{b}{3a} + \frac{1-i\sqrt{3}}{6a} \sqrt[3]{\frac{\Delta_1 + \sqrt{\Delta_1^2 - 4\Delta_0^3}}{2}} + \frac{1+i\sqrt{3}}{6a} \sqrt[3]{\frac{\Delta_1 - \sqrt{\Delta_1^2 - 4\Delta_0^3}}{2}}. \quad (\text{B-2c})$$

where $\Delta = \sqrt{-1}$; $\Delta_1 = 2b^3 - 9abc + 27a^2d$; $\Delta_0 = b^2 - 3ac$;

and $\Delta = -\frac{1}{27a^2} (\Delta_1^2 - 4\Delta_0^3) = 18abcd - 4b^3d + b^2c^2 - 4ac^3 - 27a^2d^2$ is the discriminant that distinguishes three cases of the roots. In each case, equation B-2 can be simplified for effective solution of Equation B-1.

Case 1: if $\Delta > 0$, then there are three distinct real roots. In the case, $\Delta_0 > 0$, and $\Delta_1^2 - 4\Delta_0^3 < 0$ when $\Delta > 0$. In complex domain,

$$\frac{1}{2} \left(\Delta_1 + \sqrt{\Delta_1^2 - 4\Delta_0^3} \right) = \sqrt{\Delta_0^3} e^{i\alpha}, \quad (\text{B-3a})$$

and

$$\frac{1}{2} \left(\Delta_1 - \sqrt{\Delta_1^2 - 4\Delta_0^3} \right) = \sqrt{\Delta_0^3} e^{-i\alpha}, \quad (\text{B-3b})$$

where $\alpha = \tan^{-1} \frac{\sqrt{\Delta_1^2 - 4\Delta_0^3}}{\Delta_1}$.

Substituting equation B-2 with equation B-3 leads to three real roots.

$$x_1 = -\frac{b}{3a} - \frac{2}{3a} \sqrt{\Delta_0} \cos \frac{\alpha}{3}, \quad (\text{B-4a})$$

$$x_2 = -\frac{b}{3a} + \frac{1}{3a} \sqrt{\Delta_0} \left(\cos \frac{\alpha}{3} - \sqrt{3} \sin \frac{\alpha}{3} \right), \quad (\text{B-4b})$$

$$x_3 = -\frac{b}{3a} + \frac{1}{3a} \sqrt{\Delta_0} \left(\cos \frac{\alpha}{3} + \sqrt{3} \sin \frac{\alpha}{3} \right). \quad (\text{B-4c})$$

Case 2: if $\Delta = 0$, then the cubic equation has a multiple root and all three roots are real. By substituting $\Delta_1^2 = 4\Delta_0^3$ into equation B-2, the roots are

$$x_1 = -\frac{b}{3a} - \frac{2}{3a}\sqrt{|\Delta_0|}, \quad (\text{B-5a})$$

$$x_2 = x_3 = -\frac{b}{3a} + \frac{1}{3a}\sqrt{|\Delta_0|}. \quad (\text{B-5b})$$

Case 3: if $\Delta < 0$, then there is one real root and two non-real complex conjugate roots. In the

case, $\sqrt{\Delta_1^2 - 4\Delta_0^3}$ is real. Let $C = \sqrt[3]{\frac{\Delta_1 + \sqrt{\Delta_1^2 - 4\Delta_0^3}}{2}}$ is real, then

$$x_1 = -\frac{b}{3a} - \frac{C}{3a} - \frac{\Delta_0}{3aC}, \quad (\text{B-6a})$$

$$x_2 = -\frac{b}{3a} + \frac{1}{6a}\left(C + \frac{\Delta_0}{C}\right) + \frac{i}{6a}\left(C - \frac{\Delta_0}{C}\right), \quad (\text{B-6b})$$

$$x_3 = -\frac{b}{3a} + \frac{1}{6a}\left(C + \frac{\Delta_0}{C}\right) - \frac{i}{6a}\left(C - \frac{\Delta_0}{C}\right), \quad (\text{B-6c})$$

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Figures & Tables

Figure 5-1: A new workflow for computing seismic curvature and flexure attributes for complex seismic structures. The input is a regular amplitude volume, and the output volume is seismic curvature and flexure.

Figure 5-2: Schematic diagram of surface rotation to be horizontal. It could be readily obtained by setting the structural dip p to be zero (Young, 1978).

Figure 5-3: Schematic diagram of the analytical approach to compute both the magnitude and azimuth of most positive and negative curvatures, k_+ and k_- . (a) A curve of azimuthal curvature k_φ showing the curvature values evaluated along all possible azimuths. (b) The quadratic curve of $\frac{dk}{d\varphi}$ showing the derivative of azimuthal curvature with respect to azimuth. Equation $\frac{dk}{d\varphi} = 0$ has two real roots, with one associated with most positive curvature k_+ (red) and the other with most negative curvature k_- (blue). Two roots are orthogonal, and separated with an interval of about 90° .

Figure 5-4: Schematic diagram demonstrating depth, curvature, and flexure of a horizon folded and cut by a fault (Modified from Gao, 2013). R denotes the radius of the osculating circle tangent to the horizon. Note that curvature highlights the anticlinal upthrown and synclinal downthrown blocks of the fault, whereas flexure helps locate the fault plane.

Figure 5-5: schematic diagram of the analytical approach to compute both the magnitude and azimuth of most positive and negative flexures, f_+ and f_- . (a) A curve of azimuthal flexure f_ϕ showing the flexure values evaluated along all possible azimuths. (b) The cubic curve of $\frac{df}{d\phi}$ showing the derivative of azimuthal flexure with respect to azimuth. Equation $\frac{df}{d\phi} = 0$ has three real roots, with one associated with most positive flexure f_+ (red), one with most negative flexure f_- (blue). Three roots are separated with an interval of about 60° .

Figure 5-6: Seismic-scale structures of a reservoir horizon at approximately 1400 m below the surface at Teapot Dome in Wyoming. (a) Depth structure showing a northwest-trending anticline. (b) Discontinuity attribute defining three major northeast-trending faults (denoted by arrows) (Di and Gao, 2014a).

Figure 5-7: The magnitude of (a) most positive curvature and (b) most negative curvature of the horizon shown in Figure 5-6. An edge-type display is provided for highlighting faults and fractures, especially those over the fold hinge (denoted by circles).

Figure 5-8: The magnitude of (a) most positive flexure and (b) most negative flexure of the horizon shown in Figure 5-6. An edge-type display is provided for locating the plane of faults and fractures and revealing more subtle lineaments than curvature (denoted by circles).

Figure 5-9: The azimuth of (a) most positive curvature and (b) most negative curvature of the horizon shown in Figure 5-6.

Figure 5-10: The azimuth of (a) most positive flexure and (b) most negative flexure of the horizon shown in Figure 6. The orientations of faults and fractures are better quantified by flexure azimuth than curvature azimuth.

Figure 5-11: The (a) magnitude and (b) azimuth of the commonly-used extreme curvature of the horizon shown in Figure 5-6 (Di and Gao, 2014b; Gao and Di, 2015).

Figure 5-12: The (a) magnitude and (b) azimuth of the commonly-used extreme flexure of the horizon shown in Figure 5-6 (Di and Gao, 2014c). Note the direct definition of fault plane compared to curvature attribute (denoted by arrows).

Figure 5-13: Computer-aided decomposition of faults and fractures for the horizon shown in Figure 5-6, by computing azimuthal curvature along (a) 0° (North), (b) 30°, (c) 60°, (d) 90° (East), (e) 120°, and (f) 150°. Note that the northwest-trending lineaments are best defined by the azimuth between 30° and 60°, whereas the northeast-trending lineaments by the azimuth between 120° and 150°.

Figure 5-14: Computer-aided decomposition of faults and fractures for the horizon shown in Figure 5-6, by computing azimuthal flexure along (a) 0° (North), (b) 30°, (c) 60°, (d) 90° (East), (e) 120°, and (f) 150°. Note that the northwest-trending lineaments are best defined by the azimuth between 30° and 60°, whereas the northeast-trending lineaments by the azimuth between 120° and 150°.

Figure 5-15: Computer-aided decomposition of faults and fractures for the horizon shown in Figure 5-6, by partitioning the flexure magnitude to (a) northwest-trending (N10°W to N80°W) and (b) northeast-trending (N10°E to N80°E) orientations representing the regional and cross-regional components of the reservoir.

Figure 5-16: Automatic prediction of fracture orientations for the horizon shown in Figure 5-6, based on the newly-generated curvature azimuth attribute. The histogram (a) and rose diagram (b) demonstrates two sets of fractures that are perpendicular (T1), oblique (T2) to the fold hinge.

Figure 5-17: Automatic prediction of fracture orientations for the horizon shown in Figure 5-6, based on the newly-generated flexure azimuth attribute. The histogram (a) and rose diagram (b) demonstrates three sets of fractures that are perpendicular (T1), oblique (T2), and parallel (T3) to the fold hinge. Such observation is consistent with previous fracture interpretation at Teapot Dome (Cooper et al., 2006; Schwartz, 2006).

Approach	Extreme (Signed Maximum) flexure	Most positive/negative flexure
Scanning	16 min 12 sec	12 min 8 sec
Analytical	Not Applicable	2 min 2 sec

Table 5-1: Comparison of computational time of seismic flexures using two different approaches, the existing scanning approach and the new analytical approach.

Chapter 6: Improved Estimates of Seismic Curvature and Flexure Based on 3D Surface Rotation in the Presence of Structure Dip

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Abstract

Fracture characterization is critical to the reliable exploration of many reservoirs. Faults and fractures often develop in reservoir formations with strong bending and/or shearing, which can be well described by seismic curvature and flexure analysis. However, previous analysis methods have limitations of overestimating both attributes and decreasing the reliability of applying them to quantitative fracture characterization in steeply-dipping formations. This study presents new algorithms for volumetric curvature and flexure analysis based on three-dimensional (3D) surface rotation that corrects for local reflector dip at each sample within a seismic volume and thereby could avoid such attribute overestimates. Among the infinite number of curvatures and flexures in 3D space, this study focuses on signed maximum curvature and signed maximum flexure that are evaluated as the largest absolute value of all curvatures/flexures and physically considered to be the most effective for predicting intensity and orientation of faulting and fracturing of reservoir formations. New analytical approaches are implemented for finding their magnitude and corresponding azimuth in a more accurate and efficient manner compared to the existing approach of discrete azimuth scanning. Applications to a 3D seismic survey from Teapot Dome (Wyoming) demonstrate the added value of the new methods by resolving more subtle

structural details that are otherwise not easily discernible from regular amplitude and conventional attributes and enhancing our capability to visualize and understand the structural complexity of fractured reservoirs.

Introduction

Seismic discontinuity, such as coherence, semblance, and other edge detection attributes, only provide a qualitative description of major faults by evaluating lateral changes in seismic waveform and/or amplitude across a discontinuity (e.g., Bahorich and Farmer, 1995; Marfurt et al., 1998; Gerstzenkorn and Marfurt, 1999; Marfurt, 2006; Di and Gao, 2014a). In contrast, characterizing reflection geometry quantitatively measures strain, which can then be used to delineate faults and fractures. Various seismic geometric attributes, including reflector dip, curvature, and flexure, have been developed by measuring lateral changes in the geometry of seismic reflections at different scales. Specifically, by evaluating the first-order variation of reflection depth, the dip attribute is capable of highlighting major faults with apparent offsets (e.g., Dalley et al., 1989; Marfurt and Kirlin, 2000; Marfurt, 2006; Barnes, 2007); however, subtle faults and fractures are often not detected from maps of dip magnitude and dip azimuth.

Starting from Lisle (1994), geophysicists have made considerable progress in introducing curvature to three-dimensional (3D) seismic structure interpretation and generating various curvatures for fault and fracture delineation (e.g., Roberts, 2001; Sigismondi and Soldo, 2003;; Blumentritt et al., 2006; Chopra and Marfurt, 2007a, 2007b). Among all curvatures in 3D space, the most popular and useful include signed maximum curvature, dip/strike curvatures, and most positive/negative curvatures. These attributes can be computed by fitting a quadratic surface to either 3D interpreted horizons (Roberts, 2001) or 3D seismic volumes (Di and Gao, 2014b). In particular, the signed maximum curvature coupled with its azimuth is considered indicative of

the maximum possible fracture intensity and most-likely fracture orientation, respectively (Lisle, 1994; Hansen and deRidder, 2006; Gao, 2013). Dip/strike curvature best describes the local surface morphology. Most positive/negative curvature provides an edge-type display of faults and fractures that is most convenient for visualizing and interpreting each lineament from 3D seismic data. Each of the individual curvature attributes gives similar measures of a particular surface with subtle differences. For example, most positive/negative curvature provides estimates approximate signed maximum curvature for a gently-dipping formation. However, for steeply-dipping or overturned formations, the former would cause an overestimate of curvature magnitude and inaccurate evaluation of its associated azimuth. Such overestimate can negatively affect quantitative description of either curvature interpretation or curvature-based strain analysis (Starr, 2014).

For improved fracture characterization and modeling from 3D seismic data, flexure was proposed by evaluating lateral changes in seismic curvature (Gao, 2013). Therefore, flexure describes the third-order variation of reflector geometry, and its computation requires fitting a cubic surface to seismic data (Di and Gao, 2014b). Similar to curvature analysis, an infinite number of flexures can be estimated from the localized reflection at every sample, and a set of algorithms have been developed for computing the most useful flexures. Di and Gao presented the first applicable equation for dip flexure (2014b), and then developed a discrete azimuth-scanning approach for computing signed maximum flexure (2014c). To enhance the visualization of flexure images, Di and Gao (2015) extended the concept of most positive/negative curvature to flexure and implemented an analytical approach to speed up its computation. In particular, dip flexure is evaluated along the direction of maximum dipping, and its sign is helpful for indicating the sense of displacement of faulting and fracturing. Signed maximum flexure is considered most

indicative of fundamental fracture properties, including intensity, orientation, and scale; however, discrete scanning is a time-consuming process. Most positive/negative flexure has an enhanced computational efficiency and more importantly, is capable of providing an edge-type visualization of each lineament to facilitate fracture interpretation. However, similar to most positive/negative curvature, most positive/negative flexure fails to take into account the structural dip, and limits its application to horizontal or gently-dipping formation. For steeply-dipping formations, intensity of structural deformation predicted by such an attribute is often larger than the actual one. The stronger a formation dips, the more significant the overestimate would be.

To improve both the accuracy and computational efficiency of seismic curvature/flexure analysis in the presence of steep dip, this study presents new analytical algorithms for computing seismic curvature and flexure attributes based on 3D surface rotation. At each sample within a seismic volume, a quadratic/cubic surface is fit to seismic data by following local reflector dip; therefore, the fit surface can best represent local reflection geometry centered about the target sample. Then, 3D rotation is performed to correct the effect of structural dip, so that the surface is horizontal (first-derivatives being zero) in the rotated coordinate system. The benefit of performing such rotation is to offer us an analytical solution for generating signed maximum curvature and signed maximum flexure as well as their associated azimuths. Finally, we apply them to a 3D data set from Teapot Dome in Wyoming. The results demonstrate not only enhanced accuracy of curvature/flexure estimates but also improved computational efficiency compared to the existing flexure algorithms.

Methods

This study proposes a new workflow of four steps to improve the computation of volumetric seismic curvature and flexure attributes in the presence of strong structure dip. First, at each sample within a seismic volume, the algorithm fits a local surface to represent the geometry of local reflection centered about the sample. Second, dip magnitude and dip azimuth are computed and used to build a new coordinate system, in which the surface is rotated to be horizontal. Third, the first-, second-, and third-derivatives are calculated from the rotated surface, and signed maximum curvature/flexure is computed using an analytical approach. Finally, the azimuth is calibrated back to the original coordinate system. The above steps are repeatedly executed from sample to sample, and consequently a regular amplitude volume is transformed into magnitude and azimuth volumes of seismic curvature/flexure.

3D surface rotation

Conventionally, a 3D seismic volume is collected and described using the common x_0 - y_0 - z_0 coordinate system, in which x_0 and y_0 denote inline and crossline directions, respectively; z_0 denotes the direction of depth/time (Figure 1). Using such a system, the dip magnitude θ_{dip} and dip azimuth φ_{dip} are often represented as

$$\theta_{dip} = \tan^{-1} \left(\sqrt{A_1^2 + A_2^2} \right) \quad , \text{ and } \quad \varphi_{dip} = \tan^{-1} \left(\frac{A_2}{A_1} \right) \quad , \quad (1)$$

where $A_1 = \frac{\partial z_0}{\partial x_0}$ and $A_2 = \frac{\partial z_0}{\partial y_0}$ denote the first derivatives along x_0 and y_0 axis, respectively, also known as apparent dips. Note that $\varphi_{dip} = 0$ is aligned with the x_0 axis, and its sign convention follows the right-hand rule, as denoted by arrows in Figure 1. Various approaches have been developed for volumetric dip estimates (e.g., Dalley et al., 1989; Marfurt and Kirlin, 2000; Marfurt, 2006; Barnes, 2007). This study implements the method of complex-seismic-trace

analysis to compute dip as well as the second- and third-derivatives at every sample (Di and Gao, 2014b).

In this study, we define a new x_1 - y_1 - z_1 system, with x_1 along the direction of dipping azimuth and z_1 perpendicular to the surface at the origin. There are various ways for rotating the original x_0 - y_0 - z_0 system to the new x_1 - y_1 - z_1 system. Figure 2 illustrates the procedure used in this study: first perform a counterclockwise (right-hand) rotation of the x_0 - y_0 - z_0 system (blue) with z_0 as the rotation axis and φ_{dip} as the rotation angle, obtaining a x_1 - y_1 - z_0 system (Figure 2b); then perform a counterclockwise (right-hand) rotation of the x_1 - y_1 - z_0 system with y_1 as the rotation axis and θ_{dip} as the rotation angle, obtaining the desired x_1 - y_1 - z_1 system (red) (Figure 2c). Mathematically, the two-step rotation is represented as the product of two rotation matrix

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \mathbf{R}_{y_1}(\theta_{dip}) \cdot \mathbf{R}_{z_0}(\varphi_{dip}) \cdot \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix}, \quad (2)$$

where $\mathbf{R}_{z_0}$ and $\mathbf{R}_{y_1}$ denotes the rotation matrix with z_0 and y_1 as the rotation axis, respectively (Appendix A).

Starting from the rotation matrix, we can then calculate the derivatives of the new surface after rotation, including the first derivatives (Appendix B), the second derivatives (Appendix C), and the third derivatives (Appendix D). For example, at the target sample, the first derivatives

$\frac{\partial z_1}{\partial x_1}$ and $\frac{\partial z_1}{\partial y_1}$ can be evaluated as

$$\frac{\partial z_1}{\partial x_1} = \mathbf{n} \cdot \mathbf{M}_{A1}, \quad \text{and} \quad \frac{\partial z_1}{\partial y_1} = \mathbf{n} \cdot \mathbf{M}_{A2}. \quad (3)$$

where $\mathbf{n} = [\cos \varphi_{dip} \sin \theta_{dip} \quad \sin \varphi_{dip} \sin \theta_{dip} \quad \cos \theta_{dip}]$ denotes the unit vector normal to the local surface in the original coordinate system. $\mathbf{M}_{A1}$ and $\mathbf{M}_{A2}$ are vectors of the first derivatives in the new coordinate system. By substituting Equation 3 into Equation 1 and

simplifying the generated expressions, we obtain $\frac{\partial z_1}{\partial x_1} = 0$ and $\frac{\partial z_1}{\partial y_1} = 0$, which demonstrate that the surface is now horizontal at the origin in the new x_1 - y_1 - z_1 system.

Signed maximum curvature

Curvature is defined as lateral changes in the dipping angle of a two-dimensional (2D) curve and describes how much the curve deviates from being a straight line (Roberts, 2001). Using the second-order geometric attribute, a fault anomaly is highlighted as the juxtaposition of a positive curvature and a negative curvature, representing its anticlinal and synclinal blocks, respectively. When applied to 3D seismic interpretation, curvature is dependent on the direction of attribute extraction, and an infinite number of curvatures could be extracted at each sample. The new method for computing signed maximum curvature starts from the applicable equation for computing azimuthal curvature k_{φ_0} in a generalized form in the original x_0 - y_0 - z_0 system (Equation 4),

$$k_{\varphi_0} = \frac{1}{[1+A_1^2+A_2^2]^{1/2}} \cdot \frac{(B_1+B_2 \tan^2 \varphi_0 + 2B_3 \tan \varphi_0)}{[(1+A_1^2)+(1+A_2^2)\tan^2 \varphi_0 + 2A_1A_2 \tan \varphi_0]} , \quad (4)$$

where φ_0 denotes the azimuthal direction in the x_0 - y_0 - z_0 system. $B_1 = \frac{\partial^2 z_0}{\partial x_0^2}$, $B_2 = \frac{\partial^2 z_0}{\partial y_0^2}$ and

$B_3 = \frac{\partial^2 z_0}{\partial x_0 \partial y_0}$ denote the second derivatives (Gao and Di, 2015), which are calculated using a 9-

node cell (Di and Gao, 2014b). After surface rotation to the new x_1 - y_1 - z_1 system, with $\frac{\partial z_1}{\partial x_1}$ and

$\frac{\partial z_1}{\partial y_1}$ being zero, Equation 4 is simplified, indicating that curvature is related to only the second

derivatives of the rotated surface.

$$k_{\varphi_1} = \frac{\partial^2 z_1}{\partial x_1^2} \cos^2 \varphi_1 + 2 \frac{\partial^2 z_1}{\partial x_1 \partial y_1} \cos \varphi_1 \sin \varphi_1 + \frac{\partial^2 z_1}{\partial y_1^2} \sin^2 \varphi_1 , \quad (5)$$

where φ_1 denotes the azimuthal direction in the new x_1 - y_1 - z_1 system. $\frac{\partial^2 z_1}{\partial x_1^2}$, $\frac{\partial^2 z_1}{\partial x_1 \partial y_1}$, and $\frac{\partial^2 z_1}{\partial y_1^2}$

denote the second derivative of the rotated surface, and can be calculated as

$$\frac{\partial^2 z_1}{\partial x_1^2} = \mathbf{n} \cdot \mathbf{M}_{B1} \quad , \quad \frac{\partial^2 z_1}{\partial y_1^2} = \mathbf{n} \cdot \mathbf{M}_{B2} \quad , \text{ and } \quad \frac{\partial^2 z_1}{\partial x_1 \partial y_1} = \mathbf{n} \cdot \mathbf{M}_{B3} \quad , \quad (6)$$

where $\mathbf{M}_{B1}$, $\mathbf{M}_{B2}$ and $\mathbf{M}_{B3}$ are vectors of the second derivatives in the new coordinate system (Appendix C).

Using the simplified equation for computing k_{φ_1} (Equation 5), at every sample within a seismic volume, we can then evaluate an infinite number of curvature values associated with various azimuths (Figure 3a). In order to find the signed maximum from all possible curvatures, this study implements an analytical approach. First, we take a derivative of azimuthal curvature k_{φ_1} (Equation 5) with respect to azimuth φ_1 and obtain a quadratic equation

$$\frac{dk_{\varphi_1}}{d\varphi_1} = 2\cos^2\varphi_1 \cdot \left[-\frac{\partial^2 z_1}{\partial x_1 \partial y_1} \tan^2\varphi_1 - \left(\frac{\partial^2 z_1}{\partial x_1^2} - \frac{\partial^2 z_1}{\partial y_1^2} \right) \tan\varphi_1 + \frac{\partial^2 z_1}{\partial x_1 \partial y_1} \right] . \quad (7)$$

Second, setting $\frac{dk_{\varphi_1}}{d\varphi_1} = 0$ provides us with two roots (Equation 8), which represent the azimuth associated with maximum curvature k_{max} (red) and minimum curvature k_{min} (blue), respectively (Figure 4b).

$$\varphi_{max} = \text{atan} \left(\frac{1}{2 \left(\frac{\partial^2 z_1}{\partial x_1 \partial y_1} \right)} \cdot \left[- \left(\frac{\partial^2 z_1}{\partial x_1^2} - \frac{\partial^2 z_1}{\partial y_1^2} \right) + \sqrt{\left(\frac{\partial^2 z_1}{\partial x_1^2} - \frac{\partial^2 z_1}{\partial y_1^2} \right)^2 + 4 \left(\frac{\partial^2 z_1}{\partial x_1 \partial y_1} \right)^2} \right] \right) , \text{ and } \quad (8a)$$

$$\varphi_{min} = \text{atan} \left(\frac{1}{2 \left(\frac{\partial^2 z_1}{\partial x_1 \partial y_1} \right)} \cdot \left[- \left(\frac{\partial^2 z_1}{\partial x_1^2} - \frac{\partial^2 z_1}{\partial y_1^2} \right) - \sqrt{\left(\frac{\partial^2 z_1}{\partial x_1^2} - \frac{\partial^2 z_1}{\partial y_1^2} \right)^2 + 4 \left(\frac{\partial^2 z_1}{\partial x_1 \partial y_1} \right)^2} \right] \right) . \quad (8b)$$

Third, we substitute azimuth curvature k_{φ_1} (Equation 5) with both roots and evaluate the magnitude of maximum curvature k_{max} (red) and minimum curvature k_{min} (blue).

$$k_{max} = \frac{1}{2} \left[\left(\frac{\partial^2 z_1}{\partial x_1^2} + \frac{\partial^2 z_1}{\partial y_1^2} \right) + \sqrt{\left(\frac{\partial^2 z_1}{\partial x_1^2} - \frac{\partial^2 z_1}{\partial y_1^2} \right)^2 + 4 \left(\frac{\partial^2 z_1}{\partial x_1 \partial y_1} \right)^2} \right] , \text{ and } \quad (9a)$$

$$k_{min} = \frac{1}{2} \left[\left(\frac{\partial^2 z_1}{\partial x_1^2} + \frac{\partial^2 z_1}{\partial y_1^2} \right) - \sqrt{\left(\frac{\partial^2 z_1}{\partial x_1^2} - \frac{\partial^2 z_1}{\partial y_1^2} \right)^2 + 4 \left(\frac{\partial^2 z_1}{\partial x_1 \partial y_1} \right)^2} \right] . \quad (9b)$$

The final step is to compare the two principle curvatures and generate the signed maximum one and its associated azimuth.

For a specific surface, curvature magnitude is independent of the coordinate system; however, curvature azimuth is dependent on the coordinate system in which it is described. Therefore, the curvature azimuth estimated in the new x_1 - y_1 - z_1 system (Equation 5) is different from that estimated in the original x_0 - y_0 - z_0 system (Equation 4) and should be calibrated for meaningful interpretation. Figure 4 displays the azimuthal curvature for a surface dipping at 30° along various azimuths. The curve demonstrates that the curvature in the new system (red) has the same trend as the actual values in the original system (blue), but with a shift. Such a shift is due to the surface rotation and theoretically equals to the dipping azimuth. Therefore, after evaluating curvature attribute in the new x_1 - y_1 - z_1 system, we calibrate its azimuth back to the original x_0 - y_0 - z_0 system by subtracting dip azimuth φ_{dip} from curvature azimuth estimated in the new system.

$$\varphi_0 = \varphi_1 - \varphi_{\text{dip}} . \quad (10)$$

Signed maximum flexure

Flexure is defined as the lateral changes in the curvature of a 2D curve (Gao, 2013) and describes how much the curve deviates from being a circle. Using the third-order geometric attribute in 2D vertical slice, a fault anomaly is highlighted as a peak indicating the fault plane, instead of the juxtaposition of a positive value and a negative value by curvature. Moreover, the sign of the peak depends on whether flexure is measuring along or opposite to the direction of fault displacement, and thereby it could be used for differentiating faults with different

orientations. Examine the graben structure with two normal faults shown in Figure 5. If the measuring azimuth is defined to be west to east, Figure 6b shows the associated flexure with a negative peak and a positive peak for two faults developed at the western part and eastern part of the graben, respectively.

Similar to curvature, when turning to 3D seismic interpretation, flexure is dependent on the measuring direction, and an infinite number of flexures can be extracted at every sample within a seismic volume. In order to compute the signed maximum flexure, our new method starts from the applicable equation for computing azimuthal flexure f_φ in a generalized form in the original x_0 - y_0 - z_0 system.

$$f_{\varphi_0} = \frac{\cos \varphi_0}{[1+A_1^2+A_2^2]} \cdot \frac{(C_1+3C_3 \tan \varphi_0+3C_4 \tan^2 \varphi_0+C_2 \tan^3 \varphi_0)}{[(1+A_1^2)+(1+A_2^2) \tan^2 \varphi_0+2A_1A_2 \tan \varphi_0]} - \frac{\cos \varphi_0}{[1+A_1^2+A_2^2]^2} \cdot \frac{[B_1+B_2 \tan^2 \varphi_0+2B_3 \tan \varphi_0]}{[(1+A_1^2)+(1+A_2^2) \tan^2 \varphi_0+2A_1A_2 \tan \varphi_0]^2} \cdot$$

$$[(3A_1^3B_1 + A_1^2A_2B_3 + 2A_1A_2^2B_1 + 3A_1B_1 + A_2B_3) + (5A_1^3B_3 + 4A_1^2A_2B_1 + A_1^2A_2B_2 + 6A_1A_2^2B_3 +$$

$$5A_1B_3 + A_2B_2 + 2A_2B_1 + 2A_2^3B_1) \tan \varphi_0 + (2A_1^3B_2 + 6A_1^2A_2B_3 + A_1A_2^2B_1 + 4A_1A_2^2B_2 + A_1B_1 +$$

$$2A_1B_2 + 5A_2B_3 + 5A_2^3B_3) \tan^2 \varphi_0 + (2A_1^2A_2B_2 + A_1A_2^2B_3 + A_1B_3 + 3A_2B_2 + 3A_2^3B_2) \tan^3 \varphi_0] \quad , \quad (11)$$

where $C_1 = \frac{\partial^3 z_0}{\partial x_0^3}$, $C_2 = \frac{\partial^3 z_0}{\partial y_0^3}$, $C_3 = \frac{\partial^3 z_0}{\partial x_0^2 \partial y_0}$ and $C_4 = \frac{\partial^3 z_0}{\partial x_0 \partial y_0^2}$ denote the third derivatives (Gao and

Di, 2015), which are calculated using a 13-node cell (Di and Gao, 2014b). After surface rotation

to the new x_1 - y_1 - z_1 system, with $\frac{\partial z_1}{\partial x_1}$ and $\frac{\partial z_1}{\partial y_1}$ being zero, Equation 11 is significantly simplified,

indicating that flexure is related to only the third derivatives of the rotated surface.

$$f_{\varphi_1} = \frac{\partial^3 z_1}{\partial x_1^3} \cos^3 \varphi_1 + 3 \frac{\partial^3 z_1}{\partial x_1^2 \partial y_1} \cos^2 \varphi_1 \sin \varphi_1 + 3 \frac{\partial^3 z_1}{\partial x_1 \partial y_1^2} \cos \varphi_1 \sin^2 \varphi_1 + \frac{\partial^3 z_1}{\partial y_1^3} \sin^3 \varphi_1 \quad , \quad (12)$$

where $\frac{\partial^3 z_1}{\partial x_1^3}$, $\frac{\partial^3 z_1}{\partial x_1^2 \partial y_1}$, $\frac{\partial^3 z_1}{\partial x_1 \partial y_1^2}$, and $\frac{\partial^3 z_1}{\partial y_1^3}$ denote the third derivative of the rotated surface, and can

be calculated as

$$\frac{\partial^3 z_1}{\partial x_1^3} = \mathbf{n} \cdot \mathbf{M}_{C1} \quad , \quad \frac{\partial^3 z_1}{\partial y_1^3} = \mathbf{n} \cdot \mathbf{M}_{C2} \quad , \quad \frac{\partial^3 z_1}{\partial x_1^2 \partial y_1} = \mathbf{n} \cdot \mathbf{M}_{C3} \quad , \quad \text{and} \quad \frac{\partial^3 z_1}{\partial x_1 \partial y_1^2} = \mathbf{n} \cdot \mathbf{M}_{C4} \quad , \quad (13)$$

where $\mathbf{M}_{C1}$, $\mathbf{M}_{C2}$, $\mathbf{M}_{C3}$, and $\mathbf{M}_{C4}$ are vectors of the third derivatives in the new coordinate system (Appendix D).

Using the simplified equation for computing f_{φ_1} (Equation 12), at every sample within a seismic volume, we can then evaluate an infinite number of flexure values associate with various azimuths (Figure 6a). In order to find the signed maximum of all possible flexures, an analytical approach is implemented similar to that used for curvature analysis. First, we take a derivative of azimuth flexure f_{φ_1} (Equation 12) with respect to azimuth φ_1 and obtain a cubic equation,

$$\frac{df_{\varphi_1}}{d\varphi_1} = \cos^3 \varphi_1 \cdot \left[-\frac{\partial^3 z_0}{\partial x_0 \partial y_0^2} \tan^3 \varphi_1 - \left(2 \frac{\partial^3 z_0}{\partial x_0^2 \partial y_0} - \frac{\partial^3 z_0}{\partial y_0^3} \right) \tan^2 \varphi_1 + \left(2 \frac{\partial^3 z_0}{\partial x_0 \partial y_0^2} - \frac{\partial^3 z_0}{\partial x_0^3} \right) \tan \varphi_1 + \frac{\partial^3 z_0}{\partial x_0^2 \partial y_0} \right] \quad . \quad (12)$$

Second, setting $\frac{df_{\varphi_1}}{d\varphi_1} = 0$ results in three roots, corresponding to the azimuth associated with maximum flexure f_{max} (red), minimum flexure f_{min} (blue), and another local peak (green) (Figure 6b). Third, we substitute azimuth flexure f_{φ_1} (Equation 12) with the three roots and evaluate the magnitude of maximum flexure f_{max} (red), median flexure f_{med} (green), and minimum flexure f_{min} (blue). The final step is to compare the three principle flexures and generate the signed maximum one and its associated azimuth. Different from the second-order curvature attribute but similar to the first-order dip attribute, flexure changes its sign when estimated from an opposite direction (Figure 6a); therefore, for a better visualization of flexure azimuth, it is modulated so that flexure could be evaluated as positive along that direction

$$\hat{o} = \begin{cases} o & \text{if } f \geq 0 \\ 180 + o & \text{if } f < 0 \end{cases} \quad , \quad (13)$$

where f and ϕ denote the magnitude and azimuth of three principle flexures by solving $\frac{df_{\phi_1}}{d\phi_1} = 0$.

Therefore, flexure azimuth is estimated in the range of $[0^\circ, 360^\circ)$, while curvature azimuth is in $[0^\circ, 180^\circ)$.

Similar to the curvature attribute, for a specific surface, flexure magnitude is independent on the coordinate system; however, flexure azimuth is dependent on the coordinate system in which it is evaluated, and thereby flexure azimuth estimated in the new $x_1-y_1-z_1$ system (Equation 12) is different from that estimated in the original $x_0-y_0-z_0$ system (Equation 11). Figure 7 displays the azimuth flexure for a surface dipping at 30° along various azimuths using two coordinate systems. The estimated flexure in the new system (red) demonstrates the same trend as the actual value in the original one (blue), but with a shift equal to the dip azimuth. Such a shift is due to the surface rotation. Therefore, after evaluating the azimuth of signed maximum flexure, it also is calibrated back to the original $x_0-y_0-z_0$ system based on the dip azimuth at the target sample (Equation 10).

Results

After illustrating the proposed algorithms based on 3D surface rotation, we demonstrate their enhanced accuracy and added value on structure interpretation as well as fracture characterization in the subsurface. First, various approaches are used to generate curvature and flexure from a surface dipping at 30° with N45°E as its azimuth (Figure 8). The most positive curvature and flexure is highlighted in green, whereas the signed maximum curvature and flexure estimated by the proposed new algorithms is highlighted in red. For comparison, the blue curve denotes the dependence of the actual curvature and flexure on azimuth, and the blue arrow indicates the signed maximum curvature/flexure that we expect. Note that both curvature and

flexure are overestimated by the most positive attributes, being about 10% and 40% larger than the actual values, respectively. Also, a subtle difference occurs between their associated azimuths, indicating that most positive/negative curvature and flexure do not accurately follow the direction of maximum bending or shearing of a formation in the presence of structural dip. The red curve demonstrates that the new approach is capable of generating a more accurate estimate of signed maximum curvature and flexure, with the estimated magnitude being equal to the actual one and the azimuth shifting by 45° . After applying Equation 10 to calibrate the estimate azimuth, the estimated curve (red) would overlap with the actual one (blue).

Next, the new method is applied to a 3D seismic dataset over Teapot Dome in Wyoming, where the subsurface structure is dominated by a northwest-trending anticline, and the hinge zone is populated with bend-induced faults and fractures (Cooper et al., 2002; Cooper et al., 2006). The volume is approximately 4 mile $\times$ 7 mile (188 inlines $\times$ 345 crosslines) with 266 samples in each trace, and the horizon used for result demonstration in this study is approximately at 4600 ft (Figure 9a), which is created by 3D auto-tracking an easily recognizable peak within the whole volume and then manually correcting the picks. All attributes displayed below are first generated from the whole volume and then extracted along the interpreted horizon. The black line denotes a vertical slice through the three major faults shown in Figure 10 and Figure 13. The conventional discontinuity map is provided for result comparison (Figure 9b), which clearly highlights the northeast-trending major faults. In order to illustrate the effect of formation dip on curvature and flexure estimates, dip magnitude is also displayed (Figure 9c), from which we notice gentle formation dipping (less than 10°) over the fold hinge and increasing dipping (less than 30°) towards the fold edge. Strong dipping (more than 30°) occurs in the faulting zones (denoted by circles), where apparent overestimates of

seismic curvature and flexure are expected if most positive/negative curvature and flexure are used. First, signed maximum curvature is computed. Figure 10 shows such attribute by a vertical slice with the black curve representing the interpreted horizon. Along the horizon, we then compare signed maximum curvature (Figure 11) to the signed largest absolute of most positive curvature and most negative curvature (Figure 12). For the magnitude, even shown in the same scale and colormap, the latter has a stronger color contrast through the horizon, demonstrating the overestimates by most positive/negative curvature; especially at the faulting zones featured with large structural dip, such overestimate becomes more apparent (denoted as circles). For the azimuth, no overestimates occur, but the differences could affect the interpretation of the most-likely orientations of faults and fractures in the formation based on curvature azimuth. Then, signed maximum flexure is computed. Figure 13 shows such attribute by a vertical slice with the black curve representing the interpreted horizon. Note the difference in fault delineation by curvature and flexure. Along the horizon, we then compare signed maximum flexure (Figure 14) to the signed largest absolute of most positive flexure and most negative flexure (Figure 15), and more apparent overestimates of flexure magnitude is noticed in the zone of steep structural dipping (denoted as circles). In addition, a comparison between curvature azimuth and flexure azimuth demonstrates that the latter offers a clearer image for interpreting subtle lineaments that are not detectable by even curvature/flexure magnitude and quantifying their orientations.

Finally, the efficiency of extracting signed maximum flexure by the proposed new approach is compared with the existing ones. Our comparison excludes seismic curvature, because signed maximum curvature analysis is less complicated and various analytical methods have been developed to compute it with similar computational efficiency (Al-Dossary and Marfurt, 2006; Gao and Di, 2015). By contrast, no such analytical method has been proposed for signed

maximum flexure, and discrete azimuth scanning is the only applicable approach for computing such flexure (Di and Gao, 2014c), whose efficiency is greatly dependent on the scanning interval. Table 1 lists the time for computing signed maximum flexure using both approaches. Our tests show that the scanning approach generates accurate results when using an interval of 1° or less, but the computational time is seven times longer than the analytical approach. A larger interval, for example 20° , helps reduce the computational time, but significantly decreases the resolution of the generated signed maximum flexure maps, especially its azimuth (Figure 16). All computations are performed on a workstation with a i5-2520M CUP @ 2.50GHz and 8.00 GB memory.

Conclusions

Most positive/negative curvature and flexure are most useful for detecting faults and fractures from 3D seismic data by evaluating lateral changes in reflection geometry; however, in the presence of structure dip, such analysis often overestimates the maximum magnitude of seismic curvature and flexure and thereby fails to generate accurate geometric-attribute-based prediction of bending and shearing of a fractured reservoir. This paper presents an analytical algorithm for computing signed maximum curvature and signed maximum flexure, whose magnitude and azimuth are considered most indicative of the maximum possible intensity and the most-likely orientation of faulting and fracturing, respectively. The new approach starts from 3D rotation of local reflections to be horizontal in a new coordinate system, and such rotation helps improve both the accuracy and computational efficiency of attribute extraction compared to the existing azimuth-scanning algorithms. The application of this new methodology to a 3D data set from the Teapot Dome in Wyoming demonstrates the added values of the improved curvature and flexure analysis in the presence of structural dip, especially in the faulting zones

where formation dips steeply ($>30^\circ$) and apparent overestimates of curvature and flexure would occur.

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Appendix A

3D surface rotation

In 3D space, a rotation from a x_0 - y_0 - z_0 coordinate system to a new x_1 - y_1 - z_1 system could be represented by the product of three basic rotations, including

$$\mathbf{R}_{x0}(\theta_x) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_x & -\sin \theta_x \\ 0 & \sin \theta_x & \cos \theta_x \end{bmatrix}, \quad (\text{A-1a})$$

$$\mathbf{R}_{y0}(\theta_y) = \begin{bmatrix} \cos \theta_y & 0 & -\sin \theta_y \\ 0 & 1 & 0 \\ \sin \theta_y & 0 & \cos \theta_y \end{bmatrix}, \text{ and} \quad (\text{A-1b})$$

$$\mathbf{R}_{z0}(\theta_z) = \begin{bmatrix} \cos \theta_z & \sin \theta_z & 0 \\ -\sin \theta_z & \cos \theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (\text{A-1c})$$

where θ_x , θ_y , and θ_z denote the rotation angle along x_0 -, y_0 -, and z_0 -axis, respectively, in a counterclockwise direction when looking towards the origin (Goldstein, 1980; Arfken, 1985). For example, assume the x_0 - y_0 - z_0 system is first rotated along z_0 axis with φ as the rotation angle and then rotated along y_0 axis with θ as the rotation angle, the new x_1 - y_1 - z_1 system is

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \mathbf{R}_{y_0}(\theta) \cdot \mathbf{R}_{z_0}(\varphi) \cdot \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} = \begin{bmatrix} \cos \varphi \cos \theta & \sin \varphi \cos \theta & -\sin \theta \\ -\sin \varphi & \cos \varphi & 0 \\ \cos \varphi \sin \theta & \sin \varphi \sin \theta & \cos \theta \end{bmatrix} \cdot \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix}, \quad (\text{A-2a})$$

and the new x_1 - y_1 - z_1 system can also be rotated back to the original x_0 - y_0 - z_0 one by taking an inverse of the basic rotations (Equation A-2b)

$$\begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} = \mathbf{R}_{z_0}^{-1}(\varphi) \cdot \mathbf{R}_{y_0}^{-1}(\theta) \cdot \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \begin{bmatrix} \cos \varphi \cos \theta & -\sin \varphi & \cos \varphi \sin \theta \\ \sin \varphi \cos \theta & \cos \varphi & \sin \varphi \sin \theta \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix}. \quad (\text{A-2b})$$

Appendix B

Computation of the first derivatives after rotation

Starting from the rotation matrix (Equation A-2) from the x_0 - y_0 - z_0 coordinate system to the new x_1 - y_1 - z_1 system, we can evaluate ∂z_1 and ∂x_1 as

$$\partial z_1 = [\cos \varphi \sin \theta \quad \sin \varphi \sin \theta \quad \cos \theta] \cdot \begin{bmatrix} \partial x_0 \\ \partial y_0 \\ \partial z_0 \end{bmatrix}, \text{ and} \quad (\text{B-1a})$$

$$\partial x_1 = [\cos \varphi \cos \theta \quad \sin \varphi \cos \theta \quad -\sin \theta] \cdot \begin{bmatrix} \partial x_0 \\ \partial y_0 \\ \partial z_0 \end{bmatrix}. \quad (\text{B-1b})$$

Then a series of matrix operations lead to the equation for computing $\frac{\partial z_1}{\partial x_1}$

$$\frac{\partial z_1}{\partial x_1} = \mathbf{n} \cdot \mathbf{M}_{A1}, \quad (\text{B-2})$$

where $\mathbf{n} = [\cos \varphi \sin \theta \quad \sin \varphi \sin \theta \quad \cos \theta]$ denotes the unit vector normal to the plane defined by dip angle θ and dip azimuth φ . and

$$\mathbf{M}_{A1} = \begin{bmatrix} \cos \varphi \cos \theta + \sin \varphi \cos \theta \frac{\partial x_0}{\partial y_0} - \sin \theta \frac{\partial x_0}{\partial z_0} \\ \cos \varphi \cos \theta \frac{\partial y_0}{\partial x_0} + \sin \varphi \cos \theta - \sin \theta \frac{\partial y_0}{\partial z_0} \\ \cos \varphi \cos \theta \frac{\partial z_0}{\partial x_0} + \sin \varphi \cos \theta \frac{\partial z_0}{\partial y_0} - \sin \theta \end{bmatrix}.$$

Similarly, $\frac{\partial z_1}{\partial y_1}$ is evaluated as

$$\frac{\partial z_1}{\partial y_1} = \mathbf{n} \cdot \mathbf{M}_{A2} , \quad (\text{B-3})$$

$$\text{where } \mathbf{M}_{A2} = \begin{bmatrix} -\sin \varphi + \cos \varphi \frac{\partial x_0}{\partial y_0} \\ -\sin \varphi \frac{\partial y_0}{\partial x_0} + \cos \varphi \\ -\sin \varphi \frac{\partial z_0}{\partial x_0} + \cos \varphi \frac{\partial z_0}{\partial y_0} \end{bmatrix} .$$

Appendix C

Computation of the second derivatives after rotation

Take $\frac{\partial^2 z_1}{\partial x_1^2}$ for example. Based on the computation of $\frac{\partial z_1}{\partial x_1}$ (Equation B-2), $\frac{\partial^2 z_1}{\partial x_1^2}$ can be evaluate as a derivative of $\frac{\partial z_1}{\partial x_1}$ with respect to x_1

$$\frac{\partial^2 z_1}{\partial x_1^2} = \frac{\partial}{\partial x_1} \left(\frac{\partial z_1}{\partial x_1} \right) . \quad (\text{C-1})$$

After a series of matrix operations, Equation C-1 can be simplified to

$$\frac{\partial^2 z_1}{\partial x_1^2} = \mathbf{n} \cdot \mathbf{M}_{B1} , \quad (\text{C-2})$$

where

$$\mathbf{M}_{B1} = \begin{bmatrix} \sin^2 \varphi \cos^2 \theta \frac{\partial^2 x_0}{\partial y_0^2} - 2 \sin \varphi \cos \theta \sin \theta \frac{\partial^2 x_0}{\partial y_0 \partial z_0} + \sin^2 \theta \frac{\partial^2 x_0}{\partial z_0^2} \\ \cos^2 \varphi \cos^2 \theta \frac{\partial^2 y_0}{\partial x_0^2} - 2 \cos \varphi \cos \theta \sin \theta \frac{\partial^2 y_0}{\partial x_0 \partial z_0} + \sin^2 \theta \frac{\partial^2 y_0}{\partial z_0^2} \\ \cos^2 \varphi \cos^2 \theta \frac{\partial^2 z_0}{\partial x_0^2} + 2 \cos \varphi \sin \varphi \cos^2 \theta \frac{\partial^2 z_0}{\partial x_0 \partial y_0} + \sin^2 \varphi \cos^2 \theta \frac{\partial^2 z_0}{\partial y_0^2} \end{bmatrix} .$$

Similarly, $\frac{\partial^2 z_1}{\partial y_1^2}$ and $\frac{\partial^2 z_1}{\partial x_1 \partial y_1}$ are evaluated as

$$\frac{\partial^2 z_1}{\partial y_1^2} = \frac{\partial}{\partial y_1} \left(\frac{\partial z_1}{\partial y_1} \right) = \mathbf{n} \cdot \mathbf{M}_{B2} , \quad (\text{C-3})$$

where

$$\mathbf{M}_{B2} = \begin{bmatrix} \cos^2 \varphi \frac{\partial^2 x_0}{\partial y_0^2} \\ \sin^2 \varphi \frac{\partial^2 y_0}{\partial x_0^2} \\ \sin^2 \varphi \frac{\partial^2 z_0}{\partial x_0^2} - 2 \cos \varphi \sin \varphi \frac{\partial^2 z_0}{\partial x_0 \partial y_0} + \cos^2 \varphi \frac{\partial^2 z_0}{\partial y_0^2} \end{bmatrix} .$$

$$\frac{\partial^2 z_1}{\partial x_1 \partial y_1} = \frac{\partial}{\partial y_1} \left(\frac{\partial z_1}{\partial x_1} \right) = \frac{\partial}{\partial x_1} \left(\frac{\partial z_1}{\partial y_1} \right) = \mathbf{n} \cdot \mathbf{M}_{B3} \quad , \quad (\text{C-4})$$

where

$$\mathbf{M}_{B3} = \begin{bmatrix} \cos \varphi \sin \varphi \cos \theta \frac{\partial^2 x_0}{\partial y_0^2} + \cos \varphi \sin \theta \frac{\partial^2 x_0}{\partial y_0 \partial z_0} \\ - \cos \varphi \sin \varphi \cos \theta \frac{\partial^2 y_0}{\partial x_0^2} + \sin \varphi \sin \theta \frac{\partial^2 y_0}{\partial x_0 \partial z_0} \\ - \cos \varphi \sin \varphi \cos \theta \frac{\partial^2 z_0}{\partial x_0^2} + (\cos^2 \varphi - \sin^2 \varphi) \cos \theta \frac{\partial^2 z_0}{\partial x_0 \partial y_0} + \cos \varphi \sin \varphi \cos \theta \frac{\partial^2 z_0}{\partial y_0^2} \end{bmatrix} .$$

Appendix D

Computation of the third derivatives after rotation

Take $\frac{\partial^3 z_1}{\partial x_1^3}$ for example. Based on the computation of $\frac{\partial^2 z_1}{\partial x_1^2}$ (Equation C-2), $\frac{\partial^3 z_1}{\partial x_1^3}$ can be

evaluate as a derivative of $\frac{\partial^2 z_1}{\partial x_1^2}$ with respect to x_1

$$\frac{\partial^3 z_1}{\partial x_1^3} = \frac{\partial}{\partial x_1} \left(\frac{\partial^2 z_1}{\partial x_1^2} \right) . \quad (\text{D-1})$$

After a series of matrix operations, Equation D-1 can be simplified to

$$\frac{\partial^3 z_1}{\partial x_1^3} = \mathbf{n} \cdot \mathbf{M}_{C1} \quad , \quad (\text{D-2})$$

where

$$\mathbf{M}_{C1} =$$

$$\begin{bmatrix} \sin^3 \varphi \cos^3 \theta \frac{\partial^3 x_0}{\partial y_0^3} - 3 \sin^2 \varphi \cos^2 \theta \sin \theta \frac{\partial^3 x_0}{\partial y_0^2 \partial z_0} + 3 \sin \varphi \cos \theta \sin^2 \theta \frac{\partial^3 x_0}{\partial y_0 \partial z_0^2} - \sin^3 \theta \frac{\partial^3 x_0}{\partial z_0^3} \\ \cos^3 \varphi \cos^3 \theta \frac{\partial^3 y_0}{\partial x_0^3} - 3 \cos^2 \varphi \cos^2 \theta \sin \theta \frac{\partial^3 y_0}{\partial x_0^2 \partial z_0} + 3 \cos \varphi \cos \theta \sin^2 \theta \frac{\partial^3 y_0}{\partial x_0 \partial z_0^2} - \sin^3 \theta \frac{\partial^3 y_0}{\partial z_0^3} \\ \cos^3 \varphi \cos^3 \theta \frac{\partial^3 z_0}{\partial x_0^3} + 3 \cos^2 \varphi \sin \varphi \cos^3 \theta \frac{\partial^3 z_0}{\partial x_0^2 \partial y_0} + 3 \cos \varphi \sin^2 \varphi \cos^3 \theta \frac{\partial^3 z_0}{\partial x_0 \partial y_0^2} + \sin^3 \varphi \cos^3 \theta \frac{\partial^3 z_0}{\partial y_0^3} \end{bmatrix}$$

Similarly, $\frac{\partial^3 z_1}{\partial y_1^3}$, $\frac{\partial^3 z_1}{\partial x_1^2 \partial y_1}$, and $\frac{\partial^3 z_1}{\partial x_1 \partial y_1^2}$ are evaluated as

$$\frac{\partial^3 z_1}{\partial y_1^3} = \frac{\partial}{\partial y_1} \left(\frac{\partial^2 z_1}{\partial y_1^2} \right) = \mathbf{n} \cdot \mathbf{M}_{C2} \quad , \quad (\text{D-3})$$

where

$$\mathbf{M}_{C2} = \begin{bmatrix} \cos^3 \varphi \frac{\partial^3 x_0}{\partial y_0^3} \\ - \sin^3 \varphi \frac{\partial^3 y_0}{\partial x_0^3} \\ - \sin^3 \varphi \frac{\partial^3 z_0}{\partial x_0^3} + 3 \cos \varphi \sin^2 \varphi \frac{\partial^3 z_0}{\partial x_0^2 \partial y_0} - 3 \cos^2 \varphi \sin \varphi \frac{\partial^3 z_0}{\partial x_0 \partial y_0^2} + \cos^3 \varphi \frac{\partial^3 z_0}{\partial y_0^3} \end{bmatrix} .$$

$$\frac{\partial^3 z_1}{\partial x_1^2 \partial y_1} = \frac{\partial}{\partial y_1} \left(\frac{\partial^2 z_1}{\partial x_1^2} \right) = \frac{\partial}{\partial x_1} \left(\frac{\partial^2 z_1}{\partial x_1 \partial y_1} \right) = \mathbf{n} \cdot \mathbf{M}_{C3} \quad , \quad (\text{D-4})$$

where

$$\mathbf{M}_{C3} = \begin{bmatrix} \cos \varphi \sin^2 \varphi \cos^2 \theta \frac{\partial^3 x_0}{\partial y_0^3} - 2 \cos \varphi \sin \varphi \cos \theta \sin \theta \frac{\partial^3 x_0}{\partial y_0^2 \partial z_0} + \cos \varphi \sin^2 \theta \frac{\partial^3 x_0}{\partial y_0 \partial z_0^2} \\ - \cos^2 \varphi \sin \varphi \cos^2 \theta \frac{\partial^3 y_0}{\partial x_0^3} + 2 \cos \varphi \sin \varphi \cos \theta \sin \theta \frac{\partial^3 y_0}{\partial x_0^2 \partial z_0} - \sin \varphi \sin^2 \theta \frac{\partial^3 y_0}{\partial x_0 \partial z_0^2} \\ - \cos^2 \varphi \sin \varphi \cos^2 \theta \frac{\partial^3 z_0}{\partial x_0^3} + (\cos^2 \varphi - 2 \sin^2 \varphi) \cos \varphi \cos^2 \theta \frac{\partial^3 z_0}{\partial x_0^2 \partial y_0} + (2 \cos^2 \varphi - \sin^2 \varphi) \sin \varphi \cos^2 \theta \frac{\partial^3 z_0}{\partial x_0 \partial y_0^2} + \cos \varphi \sin^2 \varphi \cos^2 \theta \frac{\partial^3 z_0}{\partial y_0^3} \end{bmatrix}$$

$$\frac{\partial^3 z_1}{\partial x_1 \partial y_1^2} = \frac{\partial}{\partial x_1} \left(\frac{\partial^2 z_1}{\partial y_1^2} \right) = \frac{\partial}{\partial y_1} \left(\frac{\partial^2 z_1}{\partial x_1 \partial y_1} \right) = \mathbf{n} \cdot \mathbf{M}_{C4} \quad , \quad (\text{D-5})$$

where

$$\mathbf{M}_{C4} = \begin{bmatrix} \cos^2 \varphi \sin \varphi \cos \theta \frac{\partial^3 x_0}{\partial y_0^3} - \cos^2 \varphi \sin \theta \frac{\partial^3 x_0}{\partial y_0^2 \partial z_0} \\ \cos \varphi \sin^2 \varphi \cos \theta \frac{\partial^3 y_0}{\partial x_0^3} - \sin^2 \varphi \sin \theta \frac{\partial^3 y_0}{\partial x_0^2 \partial z_0} \\ \cos \varphi \sin^2 \varphi \cos \theta \frac{\partial^3 z_0}{\partial x_0^3} - (2 \cos^2 \varphi - \sin^2 \varphi) \sin \varphi \cos \theta \frac{\partial^3 z_0}{\partial x_0^2 \partial y_0} + (\cos^2 \varphi - 2 \sin^2 \varphi) \cos \varphi \cos \theta \frac{\partial^3 z_0}{\partial x_0 \partial y_0^2} + \cos^2 \varphi \sin \varphi \cos \theta \frac{\partial^3 z_0}{\partial y_0^3} \end{bmatrix}$$

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Figures & Tables

Figure 6-1: Definition of dip angle θ and dip azimuth φ in the conventional x_0 - y_0 - z_0 coordinate system. Note that the sign convention of dip azimuth follows the right-hand rule.

Figure 6-2: Two-step rotation of a surface from the original x_0 - y_0 - z_0 system (blue) to the new x_1 - y_1 - z_1 system (red), which makes the x_1 axis along the direction of dipping azimuth and the z_1 axis perpendicular to the dipping surface.

Figure 6-3: The analytical approach for computing maximum curvature (red) and minimum curvature (blue). (a) The curve of azimuthal curvature demonstrating the dependency of curvature on azimuth. (b) The curve of the derivative of azimuthal curvature with respect to azimuth, which has two zero points that are associated with maximum curvature and minimum curvature, respectively.

Figure 6-4: Curvature estimates of surfaces dipping along various azimuths, (a) N0°E, (b) N45°E, (c) N90°E, and (d) N135°E, by the proposed curvature algorithm. Compared to the actual curvature (blue), the new method (red) is capable of measuring curvature magnitude accurately at a shifted azimuth, and the shift equal to the dipping azimuth.

Figure 6-5: Flexure attribute for a graben structure, demonstrating the potential of using flexure sign to differentiate faults and fractures with different orientations.

Figure 6-6: The analytical approach for computing maximum flexure (red), median flexure (green), and minimum flexure (blue). (a) The curve of azimuthal flexure demonstrating the dependency of flexure on azimuth. (b) The curve of the derivative of azimuthal flexure with respect to azimuth, which has three zero points that are associated with maximum flexure, median flexure, and minimum curvature, respectively.

Figure 6-7: Flexure estimates of surfaces dipping along various azimuths, (a) N0°E, (b) N45°E, (c) N90°E, and (d) N135°E, by the proposed flexure algorithm. Compared to the actual flexure (blue), the new method (red) is capable of measuring flexure magnitude accurately at a shifted azimuth, and the shift equal to the dipping azimuth.

Figure 6-8: (a) Curvature and (b) flexure computation of a built surface dipping at 30° with $N45^\circ E$ as its azimuth using various methods, with the actual estimate in blue, most positive estimate in green, and the proposed method in red. Note the overestimated magnitude by most positive curvature and flexure.

Figure 6-9: Application of the proposed method to a fractured reservoir at Teapot Dome (Wyoming). (a) The contour map of the structure of the horizon approximately at 4600 ft. The black line denotes a vertical slice through the three major faults shown in Figure 6-10 and Figure 6-13. (b) The associated discontinuity map with the northeast-trending faults highlighted in black. (c) The associated dip angle map demonstrating gentle dipping over the fold hinge and steep dipping in the faulting zone (more than 30°).

Figure 6-10: The vertical slice of signed maximum curvature with the black curve representing the interpreted horizon.

Figure 6-11: The (a) magnitude and (b) azimuth of signed maximum curvature estimated by the new method based on 3D surface rotation.

Figure 6-12: The (a) magnitude and (b) azimuth of signed largest absolute of most positive curvature and most negative curvature. Note the stronger color contrast than Figure 6-11, indicating the overestimated magnitude due to the presence of structural dip, especially in the faulting zones (denoted by circles).

Figure 6-13: The vertical slice of signed maximum flexure with the black curve representing the interpreted horizon. Comparison with Figure 6-10 demonstrates the different delineations of a fault anomaly by curvature and flexure attributes.

Figure 6-14: The (a) magnitude and (b) azimuth of signed maximum flexure estimated by the new method based on 3D surface rotation.

Figure 6-15: The (a) magnitude and (b) azimuth of signed largest absolute of most positive flexure and most negative flexure. Note the stronger color contrast than Figure 6-14, indicating the overestimated magnitude due to the presence of structural dip, especially in the faulting zones (denoted by circles).

Figure 6-16: The (a) magnitude and (b) azimuth of signed maximum flexure estimated by the conventional discrete azimuth-scanning approach. A 20° scanning interval is used to improve the computational efficiency, but apparently decreases the resolution of flexure maps.

Approach	Flexure
Analytical with 3D surface rotation (this study)	2 min 32 sec
Discrete scanning (1° as interval)	14 min 54 sec
Discrete scanning (20° as interval)	2 min 27 sec

Table 6-1: Computational time of signed maximum flexure by various approaches.

Chapter 7: Future Work

Reflection Geometry-based Strain Analysis from 3D Seismic Data

Quantifying localized deformation in the target reservoir formations is of importance for the drilling and production of hydrocarbons. Our recent efforts have been primarily focused on generating seismic geometric attributes (discontinuity, curvature, and flexure) and applying them for qualitative description of fractured reservoirs (e.g., Lisle, 1994;; Roberts, 2001; Al-Dossary and Marfurt, 2006; Gao, 2013; Di and Gao, 2014b, 2014c, 2014d; Gao and Di, 2015); however, no quantitative relationship has been developed between geometric attributes and finite strain. Starr (2014) proposed using a modified curvature analysis for quantifying deformation intensity with the Marcellus shale; however, the method is a two-dimensional averaging method that provides little information for instantaneous strain (Figure 7-1).

$$e = \lambda - 1 = \frac{\Delta L}{L_0} \quad (1)$$

where e and λ denote Cauchy strain and stretch ratio, respectively. L_0 denotes the original length before deformation. ΔL denotes the amount of change in length after deformation.

When turning to 3D space, particle could move along any direction, from being parallel to a defined plane to being perpendicular to the plane, which cannot be described using the one-dimensional Cauchy strain or stretch ratio (Equation 1). Then a 3x3 tensor $\bar{\epsilon}$ (Equation 2) becomes popular for 3D strain analysis, which consists of components along three principle directions. Specifically, as shown in Figure 7-2, the 3 orthogonal components represent the normal strain, which is perpendicular to the plane and evaluates the amount of change in bulk after deformation. The other 6 components represent the shear strain, which is parallel to the plane and evaluates the amount of change in shape after deformation. Here, we follow the sign

convention used in engineering mechanism, with positive normal strain representing extensional deformation and positive shear strain clockwise rotation.

$$\bar{\epsilon} = \begin{bmatrix} \epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{yx} & \epsilon_{yy} & \epsilon_{yz} \\ \epsilon_{zx} & \epsilon_{zy} & \epsilon_{zz} \end{bmatrix} \quad (2)$$

For strain analysis from 3D seismic data, we presents a new method for quantitative strain analysis based on reflection geometry from 3D seismic data. Our method is based on an infinitesimal octahedron with the target sample (red dot) in the center and 6 surrounding samples (black dots) along inline (x-), crossline (y-), and depth (z-) directions (Figure 7-3). The advantage of using an octahedron over the traditional hexahedron is that, the intersection by cutting the octahedron through the target sample **O** along the three principle directions is a diamond, which is most convenient for strain analysis.

Take the x-z plane as an example (Figure 7-4). Before being loaded with stress, we assume that the 5 samples within the diamond are equally spaced, and the shape should not vary if all of them move along the same direction at the same rate. In most cases, however, relative displacement often occurs due to inconsistent moving direction and/or rate, which leads to the changes in bulk and shape, often evaluated as normal strain and shear strain. Here we evaluate such inconsistence by tracking the first-order variation of reflection geometry associated with reflector dip (Equation 3)

$$\tan \theta_A = \frac{u_z - \frac{\partial u_z}{\partial x} dx}{u_x - \frac{\partial u_x}{\partial x} dx}, \quad \tan \theta_O = \frac{u_z}{u_x}, \quad \tan \theta_B = \frac{u_z + \frac{\partial u_z}{\partial x} dx}{u_x + \frac{\partial u_x}{\partial x} dx} \quad (3)$$

where u_x and u_z denote the displacement along x- and z-direction, respectively, and dx is the x-spacing. Physically, great difference in the dip at sample **A-O-B** indicates large relative sample

displacement as well as strong strain, and Equation 4 is then developed for computing the associated normal strain ε_{xx} and shear strain ε_{xz} .

$$\varepsilon_{xx} = \frac{\partial u_x}{\partial x} = \frac{1}{dx} \frac{2 \tan \theta_O - (\tan \theta_B + \tan \theta_A)}{\tan \theta_B - \tan \theta_A} \quad (4a)$$

$$\varepsilon_{xz} = \frac{\partial u_z}{\partial x} = \frac{1}{dx} \frac{\tan \theta_O (\tan \theta_B + \tan \theta_A) - 2 \tan \theta_B \tan \theta_A}{\tan \theta_B - \tan \theta_A} \quad (4b)$$

Similarly, tracking the dip at sample **C-O-D** provides us with normal strain ε_{zz} and shear strain ε_{zx} (Equation 5).

$$\varepsilon_{zz} = \frac{\partial u_z}{\partial z} = \frac{1}{dz} \frac{\tan \theta_O (\tan \theta_D + \tan \theta_C) - 2 \tan \theta_D \tan \theta_C}{\tan \theta_D - \tan \theta_C} \quad (5a)$$

$$\varepsilon_{zx} = \frac{\partial u_x}{\partial z} = \frac{1}{dz} \frac{2 \tan \theta_O - (\tan \theta_D + \tan \theta_C)}{\tan \theta_D - \tan \theta_C} \quad (5b)$$

By repeating the analysis for the x-y and y-z planes, the 3x3 strain tensor is readily evaluated to compute volume dilatation ε_V (Equation 6) and vertical shearing ε_S (Equation 7).

$$\varepsilon_V = (1 + \varepsilon_{xx})(1 + \varepsilon_{yy})(1 + \varepsilon_{zz}) - 1 \quad (6)$$

$$\varepsilon_S = \frac{1}{4} (\varepsilon_{xz} + \varepsilon_{yz} + \varepsilon_{zx} + \varepsilon_{zy}) \quad (7)$$

Then, we apply our new method to the 3D seismic dataset from Teapot Dome in Wyoming, which is a fractured tight-sand reservoir created by west-vergent thrusting and folding. Figure 7-5 shows the horizon at the top of Tensleep formation (a) and its corresponding discontinuity (b), which demonstrate the regional northwest-trending anticline and the cross-regional northeast-trending faults. Then the regular amplitude volume is processed for strain analysis and the results are displayed along the same horizon.

Volume dilatation (Figure 7-6a) demonstrates contraction and extension. Specifically, contractional deformation is associated with the northwest-trending upthrust to the west of the anticline, whereas extensional deformation is over the regions of fold hinge loaded with tensile stress induced by anticlinal bending. The former could help develop closed fractures as effective traps for hydrocarbons, while the latter could help develop open fractures as hydrocarbon reservoirs (Gao, 2013; Gao and Di, 2015). Vertical shearing (Figure 6b) demonstrates enhanced shearing particularly along the northeast-trending transfer faults (Gao, 2013; Gao and Di, 2015). These are consistent with previous interpretations based on curvature and flexure analysis.

Finally, we collect the wells drilled in this area, and Figure 7-7 shows the 28 producing wells on the strain images. In general, there is a good correlation between the strongly-strained zones in the reservoir and the productive wells. More detailed cross correlation and validation remain to be performed between finite strain attributes and porosity of the fractured reservoir in which the dip change are known to be caused by bending and shearing of reservoir formation rather than rigid body rotation.

To be clear, strain analysis from 3D seismic is a challenging topic, and the method presented here is only a preliminary version and more work is expected on testing and improving our algorithm.

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Figures

Figure 7-1: 1D strain as the amount of change in length after deformation.

Figure 7-2: 3D strain analysis of an infinitesimal solid.

Figure 7-3: An octahedron with 7 grids used for constructing the 3x3 strain tensor.

Figure 7-4: Evaluation of normal strain and shear strain in the x - z plane.

Figure 7-5: Structure contour (a) and discontinuity (b) on the horizon at the top of Tensleep formation, demonstrating a northwest-trending anticline and northeast-trending faults.

Figure 7-6: Volume dilatation (a) and vertical shearing (b) on the same horizon. Notice contraction associated with the west-vergent upthrust to the west of the anticline and extension over the fold hinge.

Figure 7-7: Volume dilatation (a) and vertical shearing (b) overlaid with 28 producing wells (red dots). Notice the good correlation between these wells and high-strain zones.

Chapter 8: Conclusions

Effective fracture characterization from three-dimensional (3D) seismic data is of significant importance in subsurface exploration by delineating the major boundaries of fault blocks, stratigraphic units, and hydrocarbon reservoirs. Various seismic geometric attributes (e.g. coherence, semblance, curvature) have been the focus of geophysical research and gained wide applications in the industry through the past few decades; however, detection resolution by such attributes is limited especially when subtle faults and fractures are the target of seismic interpretation and reservoir characterization, which undesirably decreases the accuracy and reliability of applying seismic attributes in fracture detection. To address such limitation, the dissertation presents new methodologies for generating the traditional geometric attributes (discontinuity and curvature) and more importantly the new flexure attribute and verifies their applications through various 3D seismic datasets.

For the traditional discontinuity attribute, lateral amplitude changes are often evaluated for delineating structural or stratigraphic discontinuities in the subsurface. Enhanced resolution is achieved by implementing a gray-level transformation and the Canny edge detection into the workflow for enhanced discontinuity characterization. The gray-level transformation generates new zero-mean data for re-characterizing localized seismic features with non-zero mean amplitude variation, and the Canny edge detection helps more effectively capture the amplitude changes associated with discontinuities. Compared to the traditional similarity scheme, amplitude-gradient scheme, and semblance scheme, the new algorithm produces better images of channels, faults, and fractures along with their orientation in the subsurface.

Curvature and flexure estimate is the major topic of the dissertation. First, new and efficient algorithms are developed for robust estimate of 3D volumetric curvature and flexure attributes along the direction of true reflector dip, denoted as dip curvature and dip flexure, respectively. Both algorithms consist of two steps: 1) to automatically construct a local surface representing the geometry of a seismic reflector, and 2) to compute attributes using the coefficients of the built surface equation. The new dip curvature algorithm constructs a quadratic surface using a 9-node grid cell, whereas the new dip flexure algorithm constructs a cubic surface using a more complicated 13-node grid cell. The major advantages of our algorithms over the existing ones are the enhanced accuracy and efficiency for delineating faults and fractures in 3D space.

Then, an integration of most extreme curvature and most extreme flexure are recommended for optimal fracture characterization from 3D seismic. Specifically, most extreme curvature and its associated azimuth are calculated using an analytical approach, which is both analytically accurate and computationally efficient. Since the analytical approach cannot be applied to the third-order flexure attribute, an azimuth-scanning approach is implemented as the first-generation algorithm for computing the desired magnitude and azimuth of most extreme flexure.

Then most positive and negative curvature/flexure attributes are proposed for providing an edge-type visualization of faults and fractures to facilitate fault interpretation, both of which can be evaluated using an analytical approach with significantly improved computational efficiency. The generated most positive/negative curvature and flexure as well as their associated azimuth provides a powerful tool for better fracture characterization, and these attribute could be used for (1) computer-aided decomposition of faults and fractures which partitions a fractured reservoir into different components and allows interpreters to focus on one particular direction for fracture characterization, and (2) automatic plotting of fracture histogram and rose diagram which allows

interpreters to predict the orientations of natural fractures, strain and stress fields in the subsurface.

Finally, in order to resolve the major limitation of magnitude overestimates by most positive and negative attribute, a new analytical algorithm is developed so that it is capable of computing signed maximum curvature and signed maximum flexure, whose magnitude and azimuth are considered most indicative of the maximum possible intensity and the most-likely orientation of faulting and fracturing, respectively. The new approach starts from 3D rotation of local reflections to be horizontal in a new coordinate system, and such rotation helps improve both the accuracy and computational efficiency of attribute extraction compared to the existing azimuth-scanning algorithms. The improved algorithm generates more reliable curvature and flexure analysis in the presence of structural dip, especially in the faulting zones where formation dips steeply ($>30^\circ$) and apparent overestimates of curvature and flexure would occur.