A new analytical method for azimuthal curvature analysis from 3D seismic data
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Summary

Seismic curvature is a useful second-order geometric attribute and has demonstrated its value for structure analysis, especially for fracture characterization in fractured reservoirs. Our recent efforts have been primarily focused on computing most extreme (signed maximum) curvature, whose magnitude and direction are usually associated with and indicative of the most-likely intensity and orientation of fractures in 3D space, respectively. This study presents an applicable equation for computing curvature attribute along any direction in 3D space, and an analytical algorithm that can simultaneously calculate the magnitude and azimuthal direction of the most extreme curvature at any location in the reservoir. We apply the algorithm to one of the major fractured reservoirs at Teapot Dome (Wyoming). We found that the critical fracture components of the reservoir such as those associated with the regional folding and cross-regional faulting are better defined by the new method. The example demonstrates the potential of the technology for more robust characterization of fractured reservoirs.

Introduction

Detecting faults and fractures from three-dimensional (3D) seismic data is one of the most significant tasks in subsurface exploration. 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) provides the potential to delimit faults and fractures in a more quantitative manner. In 3D space, curvature attribute is dependent on the measuring azimuthal direction on a surface, and 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 curvature values, respectively (Figure 1). Among the twelve different types of curvature (Roberts, 2001), most extreme curvature is most effective for characterizing faults and fractures in the subsurface (Gao, 2013).

Evaluation of most extreme curvature is computationally intensive. The first generation of curvature algorithm is based on a horizon picked by an interpreter (Roberts, 2001). Al-Dossary and Marfurt (2006) present a fractional approach for volumetrically computing 3D curvature at every sample in an uninterpreted cube, which helps avoid interpreter bias. However, little efforts have been focused on methods for evaluating most extreme curvature that can help define the intensity and orientation of the principle stress and strain (Roberts, 2001).

Figure 1: Curvature on a 3D surface. Note the intersection of two orthogonal planes with the surface, which describes the maximum curvature $k_{\text{max}}$ (red), and the minimum curvature $k_{\text{min}}$ (green). Two other important curvatures, dip curvature $k_{\text{dip}}$ and strike curvature $k_{\text{strike}}$, are also drawn on the surface. $P$ denotes the point whose curvature is evaluated. (Modified from Roberts, 2001)

This paper presents a new efficient method for computing both the magnitude and azimuth of most extreme curvature attribute. First, we present an applicable equation that can be used for curvature estimate along any specified azimuth in 3D space. Then an analytical approach is implemented to find most extreme curvature and its associated azimuth. We apply our proposed method to the seismic survey from Teapot Dome in Wyoming, and find that the method offers an opportunity for interpreters to separately define azimuthal variation of curvature, whereas most extreme curvature and its associated azimuth best define both regional and cross-regional faults and fractures over Teapot Dome.
Azimuth curvature analysis

Algorithm description

We begin with developing an applicable equation for computing azimuth curvature $k_\psi$, which represents the curvature evaluated along any azimuthal direction in 3D space.

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

(1)

where $A_1 = \frac{dx}{dy}$ and $A_2 = \frac{dy}{dx}$ denote the first derivatives of the reflector along x- and y-directions, also known as apparent dips, respectively. $B_1 = \frac{d^2x}{dx^2}$, $B_2 = \frac{d^2x}{dy^2}$ and $B_3 = \frac{d^2z}{dxdy}$ denote the second reflector derivatives. At every point on a surface, we can compute azimuthal curvature along any direction between 0° (North) and 360° (South) by equation 1, and then pick the principle directions by which curvature reaches its maximum and minimum (Figure 2a). However, this approach is time-consuming, especially for attribute generation from 3D seismic dataset.

In order to automatically search for most extreme curvature and its associated azimuth, we propose an analytical approach that is computationally efficient and accurate. By taking a derivative of the equation for azimuthal curvature with respect to azimuth $\psi$, we obtain a quadratic equation

$$\frac{dk_\psi}{d\psi} = d \cdot [a \cdot \tan^2 \psi + b \cdot \tan \psi + c] = 0$$  

(2)

where $a = (A_1 A_2 B_2 - A_2^2 B_3 - B_3)$ is a quadratic coefficient; $b = (A_1^2 B_2 - A_1^2 B_1 - B_1 + B_2)$ is a linear coefficient; $c = (A_1^2 B_3 - A_1 A_2 B_1 + B_3)$ is a constant term; and $d$ is a scaling term. Principle directions of curvature attribute can be accurately evaluated by solving equation 2, which has two roots, one is associated with the maximum and the other with the minimum (Figure 2b).

An analytical solution of equation 2 provides us with two principle directions of curvature attribute

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

(3)

and two principle magnitudes of curvature attribute

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

(4)

Finally, comparison of two principle curvatures leads to most extreme curvature

$$k_{\text{max}} = \begin{cases} k_1 & \text{if } |k_1| \geq |k_2| \\ k_2 & \text{if } |k_1| < |k_2| \end{cases}$$  

(5a)

and most extreme curvature azimuth

$$\varphi_{\text{max}} = \begin{cases} \varphi_1 & \text{if } |k_1| \geq |k_2| \\ \varphi_2 & \text{if } |k_1| < |k_2| \end{cases}$$  

(5b)

Application

To illustrate the value of azimuthal curvature, most extreme curvature and its associated azimuth on fracture characterization, we apply our method to the 3D seismic dataset from Teapot Dome of Wyoming, and generate a suite of attributes in the fractured reservoir. In Figure 3, we show the structure contour map of an interpreted horizon at

![Figure 2: Schematic diagram of computing most extreme (signed maximum) curvature using an analytical approach at point P on the surface shown in Figure 1. (a) Azimuthal curvatures by equation 1. (b) $\frac{dk_\psi}{d\psi}$ curve of azimuth curvature $k_\psi$ with respect to azimuth $\psi$ (equation 2). The two roots are corresponding to the maximum curvature $k_{\text{max}}$ (red) and the minimum curvature $k_{\text{min}}$ (green), respectively.](image)

![Figure 3: Application to the 3D seismic dataset from Teapot Dome in Wyoming. (a) Structure contour map of the horizon approximately at 4600 ft, demonstrating the northwest-trending anticline (the fold hinge is denoted by curve) and the northeast-striking faults (denoted by arrows). (b) The corresponding coherence slice.](image)
Azimuthal curvature analysis

First, curvature is evaluated along six different orientations, and the generated azimuthal curvature slices are displayed in Figure 4a through 4f. Then we generate volumes of most extreme curvature and its associated azimuth using the proposed analytical method, and Figure 5 displays the attributes along the picked horizon. Besides the major structural lineaments, more detailed information is revealed by most extreme curvature attribute (Figure 5a). Furthermore, most extreme curvature azimuth provides an image of most-likely structural orientation over Teapot Dome. A combination of most extreme curvature and its associated azimuth might help better describe and characterize the fractured reservoir that is complicated by intensive folding and faulting at Teapot Dome (Wyoming) (Cooper et al., 2006).

Conclusions

This study develops an applicable equation that can evaluate curvature along any given azimuth on seismic reflectors and provide the interpreter with azimuthal curvature cubes for structure interpretation. For most extreme curvature analysis, an analytical approach is implemented to calculate both principle magnitudes and principle directions of curvature. The added value of our algorithm is shown through applications to a fractured reservoir from Teapot Dome in Wyoming. While providing an estimate of fracture intensity, the new algorithm also

Figure 4: Azimuthal curvature slices computed along six different orientations. (a) 0°; (b) 30°; (c) 60°; (d) 90°; (e) 120°; and (f) 150°.

Figure 5: Images of most extreme curvature (a) and most extreme curvature azimuth (b).

Conclusions

This study develops an applicable equation that can evaluate curvature along any given azimuth on seismic reflectors and provide the interpreter with azimuthal curvature cubes for structure interpretation. For most extreme curvature analysis, an analytical approach is implemented to calculate both principle magnitudes and principle directions of curvature. The added value of our algorithm is shown through applications to a fractured reservoir from Teapot Dome in Wyoming. While providing an estimate of fracture intensity, the new algorithm also
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produces an image of the most-likely fracture orientation in the fractured reservoir.

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REFERENCES


