Integrating 3D seismic curvature and curvature gradient attributes for fracture characterization: Methodologies and interpretational implications

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ABSTRACT

In 3D seismic interpretation, curvature is a popular attribute that depicts the geometry of seismic reflectors and has been widely used to detect faults in the subsurface; however, it provides only part of the solutions to subsurface structure analysis. This study extends the curvature algorithm to a new curvature gradient algorithm, and integrates both algorithms for fracture detection using a 3D seismic test data set over Teapot Dome (Wyoming). In fractured reservoirs at Teapot Dome known to be formed by tectonic folding and faulting, curvature helps define the crestal portion of the reservoirs that is associated with strong seismic amplitude and high oil productivity. In contrast, curvature gradient helps better define the regional northwest-trending and the cross-regional northeast-trending lineaments that are associated with weak seismic amplitude and low oil productivity. In concert with previous reports from image logs, cores, and outcrops, the current study based on an integrated seismic curvature and curvature gradient analysis suggests that curvature might help define areas of enhanced potential to form tensile fractures, whereas

curvature gradient might help define zones of enhanced potential to develop shear fractures. In certain fractured reservoirs such as at Teapot Dome where faulting and fault-related folding contribute dominantly to the formation and evolution of fractures, curvature and curvature gradient attributes can be potentially applied to differentiate fracture mode, to predict fracture intensity and orientation, to detect fracture volume and connectivity, and to model fracture networks.

INTRODUCTION

Coherence and many other discontinuity attributes, here referred to as discontinuity attributes, have been widely used to detect faults at the seismic scale (Bahorich and Farmer, 1995). Discontinuity attributes have been very helpful in visualizing and highlighting major faults that are discernable from seismic data; however, discontinuity attributes have certain limitations in evaluating fracture intensity, detecting sub-seismic scale fractures, and differentiating fracture mode. These are most important for quantitative reservoir characterization and modeling. To complement the discontinuity attributes for fracture characterization, this study investigates the potential of seismic attributes computed based on reflector geometry. Among these attributes, curvature (Lisle, 1994; Roberts, 2001) is a well-known one and has been widely used in defining faults and fractures in cases where the geometry of reflectors is produced by structural deformation. Recent studies (Gao et al., 2011) indicated that curvature is only part of the solutions to structure characterization. To complement the existing curvature algorithm, Gao et al. (2011) proposed to extend the curvature algorithm to a new derivative by calculating the spatial gradient of curvature in 3D. This paper provides a detailed documentation of the methodologies and their interpretational implications for fracture characterization using Teapot Dome (Wyoming) test data provided by The Rocky Mountain Oilfield Technology Center (RMOTC).

Located at the southwestern edge of the Powder River Basin in the greater Rocky Mountain foreland basin (Cooper et al., 2006), the structure of Teapot Dome (Figure 1) is well documented and known to be dominated by a northwest-trending Laramide-age anticline (Cooper, 2000; Cooper et al., 2006). The hinge zone is populated with bend-induced fractures that have been reportedly observed from image logs, cores, and outcrops (Cooper et al., 2002; Cooper et al., 2006; Schwartz, 2006). The western edge of the structure is bounded by a major west-vergent upthrust fault (Cooper et al., 2001) (Figure 1). In association with the northwest-trending regional folds and thrusts are northeast-trending faults (Lorenz, 1997; Cooper et al., 2001; Cooper et al., 2002) (Figure 1). These different sets of folds and faults form the structural framework, in which a hydrocarbon system is composed of a series of vertically stacked reservoirs and complicated fracture networks of varying scales. Oil and water have been produced from these reservoirs (Smith, 2008) dominated by fracture porosity, and the fracture porosity has been reported to be induced by bending of the reservoir formations (Lorenz, 1997; Cooper et al., 2001; Cooper et al., 2002).

Because of the well-known structural nature of the fractured reservoirs at Teapot Dome, the recently processed pre-stack-depth migrated 3D seismic data provide an ideal test case for workflows of integrating curvature and curvature gradient attributes for fractured reservoirs analysis from a different perspective than previous studies (Stearns and Friedman, 1972; Pinous et al., 2006; Jenkins et al., 2009; Ross et al., 2009; Bejaoui et al., 2010; Ouenes et al., 2010). The purpose of this paper is to demonstrate effective methods and workflows and to explore their potential applications in fractured reservoirs. More specifically, the focus of this paper is to demonstrate the utility of 3D curvature and curvature gradient algorithms as integrated tools for the characterization of fractured reservoirs where fractures are induced by folding and faulting of reservoir formations.

ALGORITHMS:

CURVATURE AND CURVATURE GRADIENT

In computing seismic attributes depicting the reflector geometry and morphology (Figure 2), it is important that the vertical positions of reflection events are in true depth rather than in two-way travel time. In the original time domain, well-known velocity pull-up and push-down artifacts due to lateral changes in velocity in the overburden can give rise to structural artifacts. The heterogeneity and lateral changes in velocity can occur at different scales at which geometric attributes are evaluated. To avoid potential pitfalls in geometric attribute analysis, this study chooses to use a Kirchhoff pre-stack depth-migrated data computed by Aktepe (2006). The newly processed 3D depth-migrated seismic data not only provide clear depth imagery (Figure 1b and 1c) of major structural elements but also better preserves amplitude information of seismic signal.

In reflection seismology, curvature as a geometric attribute has been applied to map faults and fractures in seismic data (Lisle, 1994; Roberts, 2001; Hart et al., 2002; Bergbauer et al., 2003; Hart and Sagan, 2005; Hart, 2006; Al-Dossary and Marfurt, 2006; Sullivan et al., 2006; Blumentritt et al., 2006; Chopra and Marfurt, 2011). Geologically, if it can be determined that curvature is related to the bending of beds, then curvature attribute is in turn linked to strain and fracture intensity as commonly reported from lab experiments and outcrops (e.g. Hennings et al., 2000; Stewart and Wynn, 2000; Nelson, 2001; Hart et al., 2002; Wynn and Stewart, 2003; Schwartz, 2006; McLennan et al., 2009; Staples and Marfurt, 2011). The physical link of bend-related curvature to fractures (Stewart and Wynn, 2000; Wynn and Stewart, 2003; Hart, 2006) makes curvature algorithm a useful tool in fractured reservoir analysis at Teapot Dome where bed curvature is indeed bend-related based on previous structural investigations (e.g., Lorenz, 1997; Cooper et al., 2001; Cooper et al., 2002). In this test case, it is unlikely that fractures were due to depositional or other mechanisms (Johnson and Fletcher, 1994; Davis and Reynolds, 1996; Pollard and Fletcher, 2005).

Figure 2 is a two-dimensional (2D) representation of a three-dimensional (3D) reservoir horizon from a depth section of the Teapot Dome seismic survey (Figure 1). A 2D curve (Figure 2) can be thought of being made up of a continuum of arcs of circles with differing radii (Sigismondi and Soldo, 2003). The curvature at a given point on the curve is the reciprocal of the radius of the particular, local arc at the point (Sigismondi and Soldo, 2003; Chopra and Marfurt, 2010). It can also be defined as the derivative of the curve's tangent angle with respect to position on the curve at that point. If $\theta(s)$ denotes the angle which the curve makes with some fixed reference axis as a function of the path length along the curve, then 2D curvature, k_{2D}, is defined as (Sigismondi and Soldo, 2003; Chopra and Marfurt, 2010)

$$k_{2D} = \frac{d\theta}{ds}. \qquad (1)$$

It is convenient to use the Cartesian x-z coordinate system for such a fixed reference axis (Sigismondi and Soldo, 2003). In the system, x and z are Cartesian coordinates and the curve can be easily described using a function *z = z(x)*. Assuming there is no vertical or overturned bedding in the x-z coordinate system, the chain rule gives

$$k_{2D} = \frac{d\theta}{ds} = \frac{d\theta}{dx}\frac{dx}{ds}. \qquad (2)$$

Angle θ can be expressed in the x-z coordinate system by

$$tan(\theta) = \frac{dz}{dx}, \qquad (3)$$

$$\frac{d\theta}{dx} = \frac{d}{dx}\left[\tan^{-1}\left(\frac{dz}{dx}\right)\right] = \frac{\frac{d^2z}{dx^2}}{1+\left(\frac{dz}{dx}\right)^2}. \qquad (4)$$

Also in the x-z coordinate system (Figure 2), a 2D reflector can be represented by

$$z = z(x), \qquad (5)$$

and geometric principle gives

$$(ds)^2 = (dx)^2 + (dz)^2, \qquad (6)$$

which can be rearranged as

$$\frac{dx}{ds} = \left[1+\left(\frac{dz}{dx}\right)^2\right]^{-1/2}. \qquad (7)$$

Substituting equation 2 with equations 4 and 7 leads to

$$k_{2D} = \frac{d\theta}{ds} = \frac{d\theta}{dx}\frac{dx}{ds} = \frac{\frac{d^2z}{dx^2}}{\left[1+\left(\frac{dz}{dx}\right)^2\right]^{3/2}}. \qquad (8)$$

2D curvature gradient (Figure 2) is evaluated by taking a new derivative of the curve's curvature with respect to position on the curve (Gao et al., 2011). If $\frac{d\theta}{ds}$ denotes the curvature as a function of the path length along the curve, then 2D curvature gradient, k'_{2D}, is expressed as

$$k'_{2D} = \frac{d}{ds}\left(\frac{d\theta}{ds}\right) = \frac{d^2\theta}{ds^2} \qquad (9)$$

In the x-z coordinate system, the chain rule gives

$$k'_{2D} = \frac{d}{ds}\left(\frac{d\theta}{ds}\right) = \frac{d}{dx}\left(\frac{d\theta}{ds}\right)\frac{dx}{ds}. \qquad (10)$$

$$k'_{2D} = \frac{d}{dx}\left[\frac{\frac{d^2z}{dx^2}}{\left(1+\left(\frac{dz}{dx}\right)^2\right)^{3/2}}\right]\frac{dx}{ds} = \frac{\frac{d^3z}{dx^3}}{\left(1+\left(\frac{dz}{dx}\right)^2\right)^{5/2}} - \frac{3\left(\frac{d^2z}{dx^2}\right)^2\frac{dz}{dx}}{\left(1+\left(\frac{dz}{dx}\right)^2\right)^{7/2}} \qquad (11)$$

Given that curvature is related to the bending of the reservoir formations at Teapot Dome (Figure 1), curvature gradient is indicative of changes in bending moment (Lim and Reddy, 2003) of the reservoir formations (Figure 2). Even more specifically in the case of the Tensleep reservoir at Teapot Dome, high curvature is associated with the crest of the reservoir where extensional fractures typically occur, whereas high curvature gradient is at the edge of the reservoir compartments where shear fractures and faults dominate. In this case, the sign (positive and negative) of curvature is indicative of the polarity of opening (upward and downward) of extensional fractures related to the bending of the reservoir formation, whereas the sign (positive and negative) of curvature gradient is indicative of the sense of shearing (normal and reverse) related to the displacement of bounding faults.

In 3D space, both curvature and curvature gradient are non-unique because they depend on the evaluation direction (Lisle, 1994; Roberts, 2001). The apparent (or Euler) curvature (Chopra and Marfurt, 2011) and curvature gradient in an arbitrary azimuthal direction do not necessarily give the most likely intensity and orientation of fractures. The goal of this study is to let the seismic data, based on an appropriate and relevant conceptual model, map out the highest possible intensity and the most likely orientation of fractures at any location in 3D space. To achieve that objective, this study chooses to evaluate the signed maximum (most extreme) curvature and curvature gradient that is considered to be useful to infer the most likely azimuthal direction in which there is the highest potential for fractures to develop. It is important to note that the extremity of curvature and curvature gradient is scale dependent and is computed based on the lateral analysis window size (scale) defined by the number of voxels/data points centered at the analysis location. Different window sizes can be used to evaluate curvature and curvature gradient at varying scale, thereby facilitating the evaluation of the structural complexity and scale dependency of fracturing.

There are two different approaches to evaluate the most extreme curvature and curvature gradient and the associated azimuthal direction. One is to search among all the azimuthal directions to find the signed maximum at a specific azimuthal direction (Figure 3a), which is computationally expensive. The other is to use the two apparent curvature and curvature gradient attributes along two orthogonal (inline and crossline) directions to derive the most extreme curvature and curvature gradient and the corresponding azimuth direction (Figure 3b). This study takes the latter approach considering its computational efficiency. Given the x-direction gradient $\frac{dz}{dx}$ and the y-direction gradient $\frac{dz}{dy}$, and assuming the local linearity of attributes at an analysis point, there is a relationship between the signed maximum gradient $\frac{dz}{dt}$ and the x-direction and the y-direction apparent gradients $\frac{dz}{dx}$ and $\frac{dz}{dy}$. Based on Figure 3b, the principle of trigonometry gives

$$\frac{dx}{dt} = \frac{\left[(dx)^2 + (dy)^2\right]^{1/2}}{dy}, \qquad (12)$$

and by multiplying dz it becomes

$$\frac{dz}{dt} = dz\frac{\left[(dx)^2 + (dy)^2\right]^{1/2}}{dxdy}, \qquad (13)$$

which can in turn be re-arranged as:

$$\frac{dz}{dt} = \left(\frac{dz}{dx}\right)\left(\frac{dz}{dy}\right)\left[\left(\frac{dx}{dz}\right)^2 + \left(\frac{dy}{dz}\right)^2\right]^{1/2} \qquad (14)$$

where $\frac{dz}{dt}$ is the most extreme gradient at a specific azimuthal direction, $\frac{dz}{dx}$ and $\frac{dz}{dy}$ are the apparent gradient in the two orthogonal (x and y) directions, respectively. There are two simple cases where either x-direction or y-direction coincides with the most extreme gradient direction (Figure 3b): 1) if $\frac{dz}{dx}$=0, then $\frac{dz}{dt} = \frac{dz}{dy}$; or 2) if $\frac{dz}{dy}$=0, then $\frac{dz}{dt} = \frac{dz}{dx}$. As a result, this method generates two independent attributes, one is the magnitude of the most extreme curvature and curvature gradient and the other is the corresponding azimuth direction of the most extreme curvature and curvature gradient.

VISULIZATION AND COMPARISON

The most extreme curvature and curvature gradient are computed at each sample location in 3D on a running-window basis using 15 feet, 30 feet, and 45 feet characteristic lateral lengths (sampling steps), respectively. Processing using these three parameters generates a suite of curvature and curvature gradient attribute volumes at three different scales from the same seismic volume. One of the most effective methods for visualizing curvature and curvature gradient is simply to use depth slicing because faults and fractures are typically cross-stratal, particularly for steep-dipping upthrusts and strike-slip faults at Teapot Dome. Depth slicing through curvature and curvature gradient volumes can interactively reveal structural features. Figure 4 shows curvature and curvature gradient volumes at a depth slice above the Tensleep reservoir. Advantageous over the regular seismic amplitude depth slice (Figure 1b), positive and negative curvature and curvature gradient directly isolate distinct fracture domains not easily discernible from the amplitude depth slice (compare Figure 4 with Figure 1b). More specifically, the curvature high defines the most intensively bended portion of the reservoir (Figure 4a); whereas the gradient high defines the major northwest-trending thrust faults and particularly the northeast-trending cross-regional lineaments (Figure 4b). In compliment to depth slicing (box probing), horizon slicing (horizon probing) through curvature and curvature gradient volumes from the top to the base of the reservoir of interest can be instrumental in subsequent reservoir fracture analysis.

To demonstrate their spatial relations among different data sets, this study presents curvature and curvature gradient attributes in the context of regular seismic amplitude or discontinuity by using volume visualization techniques (Figures 5 through 8). To avoid confusing curvature or curvature gradient with regular amplitude or discontinuity, curvature and curvature gradient are intentionally shown in red-and-blue color whereas regular seismic amplitude and discontinuity in black-and-white. One of the most effective techniques is co-rendering curvature or curvature gradient attributes with the regular seismic amplitude or discontinuity with a transparency filter to overlay curvature or curvature gradient highs with regular amplitude or discontinuity. To correlate curvature and curvature gradient to regular amplitude and discontinuity, the former are overlaid in blue-and-red color as layer 2 in the foreground, whereas the latter are shown in black-and-white as layer 1 in the background. To better represent the 3D relationships, the results are visualized in the cross section, map, and perspective views. The cross sections are generally perpendicular to the trend of structural lineaments of interest. The maps are either a depth slice or a horizon slice at a stratigraphic level of interest, or an optically stacked thin-slab of the reservoir interval using either a formation probe or a box probe in which anomalies are visible through the entire reservoir interval of interest. The perspective view combines maps and cross sections in a chair display to optimally visualize the spatial correlation of folds and faults in 3D space.

These integrated volume visualization results indicate that curvature and curvature gradient define two complimentary components of fractured reservoirs. The crestal portion of the reservoirs is associated with the curvature high (red) (Figure 5a), whereas the northwest-trending faults (Figure 5b) and the northeast-trending faults (Figure 5c) are located at the edge or at the boundary between the positive and the negative curvature. In other words, curvature is not really highlighting major discontinuities but the coherent portion of folds where no major faults are visible from seismic data; whereas curvature gradient do define those major faults easily visible from seismic data (Figures 6 and 7). These two distinctive structural elements are otherwise very difficult to differentiate and visualize in 3D space in a quantitative and interactive manner.

Curvature attribute analysis in this study is consistent with previous observations reported from outcrops, image logs, and oil production data (Hennings et al., 2000; Nelson, 2001; Cooper et al., 2002; Cooper et al., 2006; Schwartz, 2006; Smith, 2008). Based on outcrop observations, Cooper et al. (2006) reported that the crestal portion of the structure is typically populated by local and small fractures parallel to the hinge of the anticline in the Teapot Dome area. Based on image log analysis, Schwartz (2006) reported that fractures in the subsurface occur in various directions including those hinge-parallel fractures at the crest of the anticline. These fractures are vertical and open and some appear to be induced ones (Schwartz, 2006) that could be an expression of the existing natural fractures broken during the well operation. Although these fractures are too small to be directly recognizable from the seismic data, significant correlation between curvature and amplitude, as shown in several fracture-dominated reservoirs that were known to be structurally deformed (Figure 9), suggest possible seismic amplitude expression of enhanced fracture porosity associated with enhanced curvature. Furthermore, production data previously reported from 18 wells penetrating the Tensleep reservoir (Smith, 2008) show that peak production occurs where high positive curvature occurs, with the highest oil production trend being parallel to the local curvature trend.

Unlike curvature, curvature gradient appears to be more linear and shows a stronger preferred orientation than curvature (compare Figures 4a and 4b). Here curvature gradient highlights two primary sets of lineaments. One set trends to the northwest and is subparallel to the regional folds and thrusts that have been well documented in previous studies (Cooper et al., 2006). The other set trends to the northeast, runs across the hinge of the Dome, and shows a strong preferred orientation (Figure 4b). Obviously, the cross-regional, northeast-trending lineaments are much better imaged by curvature gradient than the curvature itself. Seismic data show that the major discontinuities associated with high curvature gradient have weak amplitude response (Figure 9), and production data (Smith, 2008) indicate that they do not seem to be spatially correlated to oil productivity. Although these cross-regional lineaments have not been well documented in previous seismic studies, several authors reported the existence of faults and fractures oblique to the hinge of the fold at Teapot Dome from outcrop studies and image log analysis (Stearns and Friedman, 1972; Cooper et al., 2006; Schwartz, 2006). Stearns and Friedman (1972) reported that some of the cross-regional conjugate shear fractures resulted from the local bending of the reservoir formations but not to the regional contractional stress across the basin. These local hinge-oblique fractures induced by bending of reservoir formations should not be confused with the cross-regional lineaments depicted in the seismic curvature gradient attribute.

POTENTIAL INTERPRETATIONAL IMPLICATIONS

Differentiating fracture mode

Observations from seismic data at Teapot Dome in this study, coupled with observations previously reported from image logs, cores, and outcrops suggest that it is possible to differentiate fracture mode based on curvature and curvature gradient analysis. In the structurally controlled, fracture-dominated reservoirs at Teapot Dome, curvature attribute could delineate areas with enhanced potential to develop tensile fractures, whereas curvature gradient attribute could delineate zones with enhanced potential to develop shear fractures. Although this argument is intentionally simple in terms of mechanisms and the implication might not apply to other cases of fractured reservoirs, it could be a powerful tool within the limit of the analysis type. Teapot Dome is part of a northwest-trending, regional thrust-and-fold belt that is primarily associated with regional horizontal contraction coupled with lateral shearing along northeast-trending, cross-regional lineaments. By virtue of isolating different fracture modes in such a tectonic setting, curvature and curvature gradient attributes could provide a seismic analog for interpreting potential indicators of tensile and shear fracture zones if the attributes can be integrated with other fracture characterization methods such as physical and numerical modeling. Furthermore, the interpretation of curvature and curvature gradient attributes as potential indicators for fracture mode makes it possible to delineate "geobodies" of tensile fracture mode and of shear fracture mode (Figure 10) using seismic data. This information can be useful at least qualitatively to identify sweet spots from a 3D seismic perspective in fractured reservoirs.

Predicting fracture intensity and orientation

Both fracture intensity and fracture orientation have been difficult to define in the subsurface but are crucial in well bore planning targeting the fracture sweet spots in exploration for and production of oil and gas. Basically, the most extreme curvature magnitude coupled with its azimuth could be used to predict the maximum possible tensile fracture intensity and most-likely tensile fracture orientation, respectively (Lisle, 1994; Hansen and deRidder, 2006); whereas the most extreme curvature gradient magnitude coupled with its azimuth could be used to predict the maximum possible shear fracture intensity and most-likely shear fracture orientation, respectively. Here, curvature and curvature gradient attributes provide the basis to infer important fracture parameters that are critical in well bore planning for hydrocarbon exploration and CO_2 sequestration in fractured reservoirs.

Detecting fracture volume and connectivity

Volume curvature and curvature gradient attributes make it possible to evaluate fracture volume and fracture connectivity in 3D space by highlighting domains (geobodies) with enhanced potential for shear or tensile fractures. This can be achieved by using volume visualization techniques such as opacity filtering and connectivity detection. First, by rendering geobodies with high curvature and curvature gradient opaque and the remaining volume transparent, interpreters can interactively highlight the potential tensile fracture geobodies (Figure 11) and the potential shear fracture geobodies (Figure 12). These provide the basis to visualize the spatial distribution of fractured reservoir geobodies, and to speculate the gross storage capacity (Figures 11 and 12). Second, interpreters can also detect and isolate geobodies of fractures if and only if they are laterally and vertically connected (Figure 13) by using a seed-based 3D propagation technique. The seed can be a production or injection well bore, and the 3D propagation could help investigate the potential pressure plumes and spatial connectivity of fractures communicating with the well bore. This connectivity detection can be useful to investigate and predict the potential communications among well bores. This information is instructive in well bore planning to minimize the number of wells to be drilled, thereby reducing the economic cost and mitigating the environmental risk in energy exploration and CO_2 sequestration. In practice, both opacity filter and seed-based propagation methods must be calibrated with well logs, production, and pressure data to better estimate the gross fracture volume (storage capacity) and fracture connectivity.

Modeling fracture networks

Unlike modeling conventional matrix-dominated reservoirs, modeling fracture-dominated reservoirs requires reliance on attributes that are most relevant to the fracture aperture, intensity, and orientation (Cooper, 2000; Hennings et al., 2000; Schwartz, 2006; Smith, 2008; Bejaoui et al., 2010; Ouenes et al., 2010). Curvature and curvature gradient attributes could serve the purpose by providing relevant input as constraint for modeling fracture networks (Boerner et al., 2003; Chopra and Marfurt, 2005; Christensen et al., 2006; Ouenes et al., 2008; Wilson et al., 2012). Furthermore, combining curvature with curvature gradient attributes could even make it possible to model both shear and tensile fracture networks. To model tensile fracture networks, the most extreme curvature attribute can serve as the open fracture intensity driver whereas the corresponding azimuth can serve as the open fracture orientation driver. To model shear fracture networks, the most extreme curvature gradient attribute can serve as the shear fracture intensity driver whereas the corresponding azimuth can serve as the shear fracture orientation driver.

One of the most important properties of curvature and curvature gradient is their spectral nature and scale dependency (Bergbauer et al., 2003; Al-Dossary and Marfurt, 2006; Chopra and Marfurt, 2010). For example, Figure 14 and Figure 15 show curvature and curvature gradient evaluated using 15 feet, 30 feet, and 45 feet sampling lengths, respectively. These can be used to define faults and fractures at the three specific scales. In the subsequent fracture modeling effort, curvature and curvature gradient evaluated at these three different scales can be used to represent three component models of fractured reservoir. In practice, a spectrum of curvature and curvature gradients might be evaluated and selected from depending on the scale of faults and fractures in the reservoir of interest in the subsurface.

LIMITATIONS AND PITFALLS

Although bed curvature (Lisle, 1994) and curvature gradient could be caused by finite linear and finite shear strain of the reservoir formations in response to local or regional stress (tensile or shear), in some other cases curvature and curvature gradient might not be related to structures in general and with fractures in particular. For example, the current fracture characterization workflow is not applicable where bed curvature and curvature gradient are caused by depositional or syn-tectonic depositional processes. Curvature and curvature gradient may still be applicable not only in sheet-flow type reservoirs but also in reservoirs with channels, levees, slumps, dunes, reefs, sink holes, differential compaction features; However, interpreters must differentiate depositional from deformational curvature and curvature gradient, for example by evaluating curvature at varying scales.

Evaluating the relationships among curvature and curvature gradient and fracture intensity, fracture orientation, and fracture mode can become increasingly challenging with the increasing complexity in deformation history and mechanical properties of reservoirs (Johnson and Fletcher, 1994; McLennan et al., 2009; Pearce et al., 2011). In many other cases where fractured reservoirs are structurally more complicated by multiple episodes of tectonic deformation with different deformational mechanism (such as passive folding instead of flexural-slip bending), the present-day state of the fractured reservoir could involve changes in direction deformation. In such cases, more detailed structural history analysis is needed and a dynamic curvature analysis is required based on geometrical restoration of folding and faulting coupled with geomechanical forward modeling (Johnson and Fletcher, 1994; Davis and Reynolds, 1996; Alsop, 1996; Pollard and Fletcher, 2005; Staples and Marfurt, 2011).

CONCLUSIONS

In seismic fracture characterization, curvature gradient as a new derivative attribute complements the existing curvature in the description and characterization of bed geometry and morphology. Although their structural implications can be complicated by depositional processes, deformational mechanisms, and tectonic history, integrated curvature and curvature gradient algorithms are useful tools for characterizing reservoir geometry and structural complexity. In certain cases where bed curvature is caused by structural bending and shearing, integrating curvature and curvature gradient attributes helps better describe the geometry of folds and the relationship between folds and faults.

Using pre-stack depth-migrated 3D seismic data at Teapot Dome (Wyoming) as a test case, this study demonstrates how to integrate curvature and curvature gradient to better characterize fractured reservoirs. The test case study shows that positive curvature anomalies define the folded, but un-faulted, crestal portion of the reservoirs, which are spatially associated with strong amplitude and high oil productivity. In complement to curvature, curvature gradient anomalies delineate the northwest-trending thrust faults and northeast-trending lineaments, which are spatially associated with weak amplitude and low oil productivity. In concert with previous direct observations from surface outcrops, cores, and image logs, the result from seismic attributes in this study suggests that curvature might help define areas with enhanced potential to form tensile fractures, whereas curvature gradient might help define zones with enhanced potential to form shear fractures. The integrated curvature and curvature gradient algorithms should have potential interpretational implications for discriminating fracture mode, defining fracture intensity and orientation, evaluating fracture storage capacity, and modeling fracture networks.

Acknowledgments

This study has been funded by the US Department of Energy/NETL under the contract RES1000023/144U (Project Activity ID Number: 4000.4.641.251.002.541), and partially funded by the US Department of Energy/NETL carbon storage project (NT42804). Thanks go to Kurt Marfurt for his kind help and offering newly-processed pre-stack depth-migrated seismic data over Teapot Dome. The Kirchhoff pre-stack depth migration was computed by Suat Aktepe at the University of Houston. Lierong Zhu helped with testing a preliminary algorithm. Thanks go to Tom Wilson, Tim Carr, and Jaime Toro for their comments. Data over Teapot Dome from the Rocky Mountain Oilfield Technology Center (RMOTC) provided the basis for many of the discussions in this paper. Paradigm Geophysical Inc. granted 3D seismic visualization software for research. Peer reviews by Debapriya Paul, Jamie Rich, and an anonymous reviewer helped improve the quality of the paper. This study is a contribution to the West Virginia University Advanced Energy Initiative program.

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Figure captions

Figure 1 (a) False-color Landsat image at Teapot Dome (Wyoming) showing the surface expression of the regional northwest-trending folds and the cross-regional northeast-trending lineaments. Green color denotes rivers that run along the regional northwest-trending and the cross-regional northeast-trending lineaments. (b) Depth slice above the Tensleep reservoir through the pre-stack depth migrated seismic volume, showing the subsurface seismic expression of the regional northwest-trending and the cross-regional northeast-trending lineaments. (c) Cross section of the seismic volume, showing structurally bended Tensleep and other reservoirs. Location index maps are shown above the images.

Figure 2 Schematic diagrams in the cross-sectional view demonstrating depth, curvature, and curvature gradient of the bended and faulted Tensleep reservoir horizon. Note that the maximum curvature highlights the crest of the fold, whereas the maximum curvature gradient highlights the fault (shear zone) at the edge of the fold. See Figure 1 for position of the reservoir horizon.

Figure 3 Schematic diagrams in the map view demonstrating the 3D algorithms in different approaches. (a) Search of the signed maximum (most extreme) curvature and curvature gradient and the corresponding azimuthal direction at a target location in the center of the analysis window. (b) Calculation of the signed maximum (most extreme) curvature and curvature gradient and the corresponding azimuthal direction at the target location using the inline and crossline curvature and curvature gradient and assuming local linearity. See text for equations.

Figure 4 Depth slice through curvature volume (a) and curvature gradient volume (b) at the same structure level above the Tensleep reservoir. Both curvature and curvature gradient highlight the regional and cross-regional structural features that are not directly visible from the regular seismic data at the same structural level as shown in Figure 1b.

Figure 5 (a) A seismic line in black-and-white (left) compared with the corresponding curvature attribute in red-and-blue color (right). (b) Perspective chair display of the curvature attribute (depth slice) in red-and-blue color along with a seismic line in black-and-white, showing the northwest-trending regional fold and thrust fault. (c) Perspective chair display of the curvature attribute (depth slice) in red-and-blue color along with a seismic line in black-and-white, showing the northeast-trending cross-regional lineaments.

Figure 6 (a) Co-rendering (overlay) of positive curvature in red (layer 1 in the foreground) with amplitude in black-and-white (layer 2 in the background). Note the crestal portion of folds is highlighted by the curvature highs, and as the intensity of folding increases, the intensity of curvature increases. (b) Co-rendering (overlay) of the curvature gradient highs in red-and-blue (layer 1 in the foreground) with amplitude in black-and-white (layer 2 in the background). Note the faults at the edge of folds are highlighted by the curvature gradient highs, and as the intensity of faults increases, the intensity of curvature gradient increases. Also, both curvature and curvature gradient generally increase with depth, indicating that both folding and faulting intensify with depth, which is typical of a basement-involved structure (Mitra and Mount, 1998) at Teapot Dome. The yellow lines associated with the color bars are the transparency filters applied to highlight the curvature and curvature gradient anomalies, respectively.

Figure 7 (a) Co-rendering (overlay) of positive curvature in red (layer 1 in the foreground) with discontinuity attribute in black-and-white (layer 2 in the background). Note the positive curvature (red) is bounded by the regional northwest-trending and the cross-regional northeast-trending faults (black). (b) Co-rendering (overlay) of the positive and negative curvature gradient in red-and-blue (layer 1 in the foreground) with discontinuity attribute in black-and-white (layer 2 in the background). Note the positive and negative curvature gradient highlights regional northwest-trending and cross-regional northeast-trending faults. The yellow lines associated with the color bars are the transparency filters applied to highlight the curvature and curvature gradient anomalies, respectively.

Figure 8 (a) Perspective view of the Tensleep reservoir structure. Note the reservoir is bounded at the western edge by the northwest-trending regional upthrust and segmented by the northeast-trending cross-regional lineaments. (b) Map view of the curvature attribute of the reservoir interval with a transparency filter applied to visualize the curvature distribution (optical stacking) within the reservoir interval. White dashed lines are the major northeast-trending faults at the edges or boundaries of the positive and negative curvature. The yellow line associated with the color bar is the transparency filter applied to highlight the curvature anomalies.

Figure 9 Amplitude horizon slice with structure contour overlay at the Tensleep reservoir (T) on the left and three other reservoirs (R1, R2, and R3) on the right, showing seismic amplitude variations across the reservoirs. Note that amplitude increases from the flank towards the crest of the structure with the high curvature, indicating positive correlation of reflection amplitude with reflector curvature. The inset seismic amplitude section and the cross plot also show the correlation between reflection amplitude and reflector curvature. Colored lines are 18 well bores drilled in the reservoir. Production data from these wells reported in previous studies (Smith, 2008) demonstrate significant positive correlation to the curvature and amplitude trend shown in these maps.

Figure 10 (a) Perspective view of positive curvature in red, along with a depth slice of discontinuity in black-and-white in the background. (b) Perspective view of positive curvature gradient in red, along with a depth slice of discontinuity in black-and-white in the background. Here curvature and curvature gradient make it possible to map out volumetric extent of zones and domains with enhanced potential to develop tensile and shear fractures, by using transparency filters defined by the yellow lines associated with the color bars.

Figure 11 Box probe of positive curvature in red color, co-rendered with a depth slice of discontinuity in black-and-white, highlighting volumetric extent of domains of potential tensile fractures using two different transparency filters defined by the yellow lines associated with the color bars. (a) Conservative filter. (b) Aggressive filter.

Figure 12 Box probe of positive and negative curvature gradient in red-and-blue color, co-rendered with a depth slice of discontinuity in black-and-white, highlighting volumetric extent of domains of potential shear fractures using two different transparency filters defined by the yellow lines associated with the color bars. (a) Conservative filter. (b) Aggressive filter.

Figure 13 Geobodies of fracture domains with positive curvature intensity (threshold >=0.213 as shown by the yellow line associated with the color bar), each of which is detected by using a 3D propagation algorithm based on spatial connectivity from a seed. The seed can be a production or injection well bore. (a) 3D perspective view. (b) 2D map view.

Figure 14 Curvature attributes evaluated at three different scales using a lateral sampling lengths of 15 feet (a), 30 feet (b), and 45 feet (c), respectively. These are shown at the same structural level above the Tensleep reservoir.

Figure 15 Curvature gradient attributes derived from curvature at three different scales corresponding to those of the curvature, respectively. These are shown at the same structural level above the Tensleep reservoir.