Gray-level transformation and Canny edge detection for 3D seismic discontinuity enhancement

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In a 3D seismic survey, detecting seismic discontinuities 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 of 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 of 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 helps better define channels, faults, and fractures than the traditional similarity, amplitude gradient, and semblance attributes.

1. Introduction

Recognizing subsurface structural and stratigraphic discontinuities is crucial in subsurface exploration, and an effective workflow for discontinuity detection from seismic data 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 for subsurface exploration (e.g., Bahorich and Farmer, 1995; Haskell et al., 1995; Luo et al., 1996, 2003; Marfurt et al., 1998, 1999; Gersztenkorn and Marfurt, 1996, 1999; Marfurt and Kirlin, 2000; Chopra, 2002; Cohen and Coifman, 2002; Blumentritt et al., 2003; Lu et al., 2003, 2005; Tingdahl and de Rooij, 2005). The coherence algorithm was first proposed by Bahorich and Farmer (1995), which measures local waveform similarity of one seismic trace to its adjacent traces by using a time-lagged cross-correlation operator; however, the first-generation algorithm involves only three neighboring traces, making 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 a large covariance matrix, Cohen and Coifman (2002) defined a smaller correlation matrix \((4 \times 4)\) 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 does not take into account the effect of structural dip. 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 does not consider the amplitude difference between two seismic traces. Tingdahl and de Rooij (2005) then presented a solution by using a similarity operator (Eq. (1)).

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

(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 an analysis window centered at a given sample location, and then perform edge detection in the inline (x-) and crossline (y-) directions on the retrieved seismic amplitude data (Eq. (2)).

\[ c = (f_x \ast u)^2 + (f_y \ast u)^2 \]  

(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 one used in image processing. Specifically, the amplitude-gradient algorithm uses the simplified Sobel operator with 9 traces (Eq. (3)) and the semblance algorithm uses the mean operator with arbitrary traces (Eq. (4)).

\[ f_x(x_j, y_j) = \frac{1}{f} \begin{bmatrix} 0 & 0 & 0 \\ -1 & 0 & +1 \\ 0 & 0 & 0 \end{bmatrix} \quad \text{and} \quad f_y(x_j, y_j) = \frac{1}{f} \begin{bmatrix} 0 & +1 & 0 \\ 0 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} \]  

(3)

\[ f_s(x_j, y_j) = f_s(x_j, y_j) = \frac{1}{f} \]  

(4)

in which \( f \) denotes the analysis window size.

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

\[
\sum_{i=-w}^{w} \sum_{j=-w}^{w} \left\{ \sum_{\tau=1}^{N} \left[ f_s(x_j, y_j) u(t + \tau + px_j + qy_j) \right]^2 + \sum_{\tau=1}^{N} \left[ f_s(x_j, y_j) u(t + \tau + px_j + qy_j) \right]^2 + \sum_{\tau=1}^{N} \left[ f_s(x_j, y_j) u(t + \tau + px_j + qy_j) \right]^2 \right\}
\]  

(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 Eq. (1) or Eq. (5) relies on the assumption that the input seismic amplitude should vary with zero mean. However, when the features of interest fail to be of zero mean, both equations provide an underestimate of 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 Fig. 1 are extracted and displayed in Fig. 3a and b, respectively. Using the regular amplitude scale, it is apparent that amplitude changes more sharply in the west (from \( 1500 \) to \( 1500 \)) than the east (from \( 1500 \) to \( 300 \)). After applying the gray-level transformation with 41 levels (N = 20), both features become of zero mean, and the amplitude changes in the east (Fig. 3d) are enhanced to the same scale as those in the west (Fig. 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 levels (N = 20) or more, without introducing artifacts.

An efficient edge detector is also crucial in robust detection and characterization of seismic discontinuities. Besides the simplified Sobel operator (Eq. (3)) and the mean operator (Eq. (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 (Eq. (8)), the Roberts operator (Eq. (9)) (Roberts, 1963), the Prewitt operator (Eq. (10)) (Prewitt, 1970), and particularly the Canny edge detector (Eq. (11)) (Canny, 1986), which is evaluated as the partial derivatives of the Gaussian filter along x- and y-directions,
Fig. 1. Application of three traditional discontinuity algorithms to a 3D seismic dataset over the Stratton field of Texas. (a) A time slice at 844 ms demonstrating a west–east meandering channel. (b) The discontinuity slice generated from the similarity scheme (Tingdahl and de Rooij, 2005). (c) The discontinuity slice generated from the amplitude-gradient scheme (Luo et al., 1996). (d) The discontinuity slice generated from the semblance scheme (Marfurt et al., 1998). They delineate major boundaries of the channel in the west (denoted by rectangle 1), but not the subtle boundaries in the east (denoted by rectangle 2).

respectively (Fig. 4).

\[
f_x = \frac{1}{8} \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix} \quad \text{and} \quad f_y = \frac{1}{8} \begin{bmatrix} +1 & +2 & +1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}
\]  

\[
f_x = \frac{1}{2} \begin{bmatrix} +1 & 0 & +1 \\ 0 & -1 & 0 \end{bmatrix} \quad \text{and} \quad f_y = \frac{1}{2} \begin{bmatrix} 0 & +1 \\ -1 & 0 \end{bmatrix}
\]

\[
f_x = \frac{1}{6} \begin{bmatrix} -1 & 0 & +1 \\ -1 & 0 & +1 \\ -1 & 0 & +1 \end{bmatrix} \quad \text{and} \quad f_y = \frac{1}{6} \begin{bmatrix} +1 & +1 & +1 \\ 0 & 0 & 0 \\ -1 & -1 & -1 \end{bmatrix}
\]

\[c(t, p, q, 2w) = \frac{\sum_{t=-w}^{t+w} \sum_{p=-w}^{p+w} \sum_{q=-w}^{q+w} [g(x, y)]^2 + \sum_{t=-w}^{t+w} \sum_{p=-w}^{p+w} \sum_{q=-w}^{q+w} [g(x, y)]^2}{\sum_{t=-w}^{t+w} \sum_{p=-w}^{p+w} \sum_{q=-w}^{q+w} [g(x, y)]^2 + \sum_{t=-w}^{t+w} \sum_{p=-w}^{p+w} \sum_{q=-w}^{q+w} [g(x, y)]^2}
\]

\[\theta(t, p, q, 2w) = \arctan\left(\frac{\sum_{t=-w}^{t+w} \sum_{p=-w}^{p+w} \sum_{q=-w}^{q+w} [g(x, y)]^2}{\sum_{t=-w}^{t+w} \sum_{p=-w}^{p+w} \sum_{q=-w}^{q+w} [g(x, y)]^2}ight)
\]

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 reflections (Marfurt et al., 1998). Fig. 5 demonstrates the workflow with four steps: first, to define a set of Canny edge detectors in inline (x-) and crossline (y-) directions (Eq. (11)); second, at a given

\[f_x = \frac{\partial G}{\partial x} = \frac{x}{\sigma^2}G \quad \text{and} \quad f_y = \frac{\partial G}{\partial y} = \frac{y}{\sigma^2}G
\]

Fig. 2. A schematic representation for gray-level transformation with 5 levels (\(N = 2\)).

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\]

where \(G\) denotes the Gaussian filter, in which \(\sigma\) is the standard deviation.

\[G = \exp\left(-\frac{x^2+y^2}{2\sigma^2}\right)
\]

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

Implementing the gray-level transformation (Eq. (7)) coupled with the Canny edge detector (Eq. (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.
sample in a seismic volume, to retrieve local seismic amplitude $u$ and compute its Hilbert transform $u^H$ within an analysis window centered at 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 [Eq. (7)]; finally, to apply the defined Canny detectors to the generated $g$ and $g^H$ for discontinuity computation [Eq. (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.

3. Applications

The 3D seismic dataset over the Stratton field of Texas is reprocessed by the new algorithm, and the resulting discontinuity slice
at 844 ms is displayed in Fig. 6f. Comparisons of Figs. 6f to 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 exaggeration of the channel in the west. Such exaggeration often happens if we simply increase the color contrast in Fig. 1b–d for highlighting the subtle channel boundaries in the east. Additionally, the azimuth slice (Fig. 7) clearly depicts the spatial orientation of both channel boundaries (denoted by dashed curves). Here an analysis window involving 49 traces is used.

In addition to stratigraphic features, two examples with fractured reservoirs are used to demonstrate 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 Fig. 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 Fig. 9a through Fig. 9c, demonstrating the faults parallel and perpendicular to bedding. After processing the amplitude volume using the new algorithm, lateral resolution for seismic discontinuities is enhanced with more structural details. In particular, faults parallel to bedding are better recognized (denoted by arrows in Fig. 9d), and the fault orientation is mapped out by discontinuity azimuth (Fig. 10). Here an analysis window involving 81 traces is used.

The second is a Kirchhoff prestack depth-migrated dataset at 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, 2006). The western edge of the structure is bounded by a major west-vergent 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, 2002). Fig. 11 displays a 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 Fig. 12a–d. Comparison demonstrates that the new method helps reveal more structural details over the anticline hinge.
(denoted by circles). The discontinuity azimuth image from the new algorithm is shown in Fig. 13, which defines two sets of faults and fractures: one for the northeast-trending set (green to blue) and the other for the northwest-trending set (red to yellow). Furthermore, we perform an ant-tracking processing (Pedersen et al., 2002) on the four discontinuity cubes (Fig. 14a–d). Apparently, more structural details (denoted by arrows) are identified from 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.

Fig. 8. A time slice at 1728 ms from the 3D seismic dataset over the offshore Netherlands North Sea, demonstrating faults parallel and perpendicular to bedding.

Fig. 9. Application of four discontinuity algorithms to the 3D seismic dataset over the offshore Netherlands North Sea. (a) The similarity scheme (Tingdahl and de Rooij, 2005). (b) The amplitude-gradient scheme (Luo et al., 1996). (c) The semblance scheme (Marfurt et al., 1998). (d) The new scheme that better depicts faults. (Data courtesy: TNO and dGB Earth Sciences).

Fig. 10. A discontinuity azimuth slice at 1728 ms generated from the new algorithm to map the orientation of faults.
Fig. 11. A depth slice at 4800 ft from the 3D seismic dataset over Teapot Dome in Wyoming.

Fig. 12. Discontinuity slices at 4800 ft generated from four discontinuity schemes. (a) The similarity scheme (Tingdahl and de Rooij, 2005). (b) The amplitude-gradient scheme (Luo et al., 1996). (c) The semblance scheme (Marfurt et al., 1998). (d) The new scheme that helps depict structural details over the anticline hinge (denoted by circles).

Fig. 13. A discontinuity azimuth slice at 4800 ft generated from the new algorithm to map the orientation of faults.
4. Discussion

The quality of input seismic data has a significant impact on discontinuity detection. Integrating current methods with other ones 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 noise on discontinuity extraction. Combining texture model regression (TMR) method (Gao, 2004, 2011) with discontinuity detection could help enhance structural resolution and signal/noise ratio.

Robust discontinuity detection relies on detecting subtle lateral amplitude changes. First, gray-level transformation is one of the most 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 to the characterization of seismic discontinuities by the using a 3D edge detector.

Applying the gray-level transformation helps enhance subtle amplitude changes, but might also magnify non-seismic random noises. The amplified artifacts in the resulting discontinuity cube could lead to interpretational bias or even misinterpretation of 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 the 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. Physically, structural deformation of reservoir formations is related to lateral changes in reflection geometry rather than reflection coherency. A more quantitative characterization for fractured reservoirs can be achieved by using geometric attributes, such as curvature and curvature gradient (Gao, 2013; Di and Gao, 2014).

5. Conclusions

In 3D seismic interpretation, lateral amplitude changes are often evaluated to delineate structural or stratigraphic discontinuities in the subsurface. The traditional discontinuity-detection techniques are based on the assumption of amplitude variation being of zero mean, and thus limited for detecting faults and fractures from seismic amplitude data of non-zero mean. This study proposes implementing a gray-level transformation and the Canny edge detector into the workflow for discontinuity characterization. The gray-level transformation generates new zero-mean data for re-characterizing seismic features with non-zero mean amplitude variation, and the Canny edge detector helps more effectively capture 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 fractured reservoirs at Teapot Dome (Wyoming) and offshore Netherlands (North Sea). Compared to the traditional similarity, amplitude-gradient, and semblance schemes, the new algorithm produces better images of channels, faults, and fractures along with their orientation in the subsurface.

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Fig. 14. Ant-track (Pedersen et al., 2002) slices at 4800 ft based on discontinuity cubes generated from four discontinuity schemes. (a) The similarity scheme (Tingdahl and de Rooij, 2005). (b) The amplitude-gradient scheme (Luo et al., 1996). (c) The semblance-based coherence scheme (Marfurt et al., 1998). (d) The new scheme that reveals subtle faults and fractures (denoted by arrows).
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References


