Introduction

Natural fractures in carbonates are of great importance for exploration of the oil and gas reservoir plays. Geophysical interpreters pay a significant attention to indicate the fracture properties and then estimate the reservoir performance. There exists some methods and algorithms to delineate the discontinuities such as fracture zones from post-stack 3D seismic data by measuring lateral variations in waveform, dip and amplitude. Dip and azimuth maps can interpret anomalies in seismic reflector dip and azimuth amplitude across discontinuities (Barnes, 2003; Marfurt, 2006). Coherence attributes highlight adjacent waveform changes using crosscorrelation (Bahorich and Farmer, 1995), semblance (Marfurt et al., 1998) and eigenstructure (Gersztenkorn and Marfurt, 1999) measured along dips and azimuths of seismic reflector. Gradient-based edge detections to measure reflection magnitude variations nearby discontinuities by using seismic amplitude gradient operator (Luo et al., 1996). Curvatures are able to indicate fracture distributions by measuring bending stratal deformation (Lisle, 1994; Roberts, 2001) and even to depict features at different scales (Al-Dossary and Marfurt, 2006; Chen et al., 2012). To enhance the faults and fractures in seismic data, Hale (2012; 2013) first used the likelihood algorithm to automatically obtain faults, strikes and dips images from 3D seismic data. To implement automatic fault extraction, the ant tracking was achieved by the cooperative behavior of thousands of “artificial ants” (Randen et al., 2001; Pedersen et al., 2002). This work is favorable to accurately depict the detailed fracture networks and improve their visual appearances with satisfactory efficiency.

In this paper, since our target reservoirs are deep karsted carbonates at depth of more than 6500m, located at Northwestern China, we propose a novel spatially windowed 2D Hilbert transform (SWHT)-based operator to perform volumetric edge detection on 3D seismic field data. Then the volumetric edge results are co-rendered with other seismic geometric attributes for excellent delineation of the geologic anomalies at different scales in the deep carbonates.

Method and Workflow

For a 2D signal with $N_1 \times N_2$, the 2D Hilbert operator in spatial domain can be given by the cotangent form (Bose and Prabhu, 1979)

$$ h(x, y) = \left( \cot \frac{\pi}{N_1} x + \cot \frac{\pi}{N_2} y \right) \frac{2}{N_1 N_2} $$

(1)

where $x \in [0, N_1 - 1]$ and $y \in [0, N_2 - 1]$ with $N_1$ and $N_2$ taken to be integers. Then the corresponding discrete 2D Hilbert transform of a seismic data slice denoted as $s(x, y)$ can be implemented by the 2D convolution operation expressed in the following form

$$ e(x, y) = \sum_{k_1=0}^{N_1-1} \sum_{k_2=0}^{N_2-1} s(k_1, k_2) h(x-k_1, y-k_2) $$

(2)

The edition of the above equation in wavenumber domain can be expressed as

$$ E \left( k_x, k_y \right) = S \left( k_x, k_y \right) H \left( k_x, k_y \right) $$

(3)

where $E(\cdot)$, $S(\cdot)$ and $H(\cdot)$ are the discrete 2D Fourier transform results of $e(\cdot)$, $s(\cdot)$ and $h(\cdot)$ in Eq. (2) with respect to $x$ and $y$, respectively. Here, $H(k_x, k_y)$ is denoted as

$$ H \left( k_x, k_y \right) = -\left[ \text{sgn} \left( k_x, k_y \right) + bdy \left( k_x, k_y \right) \right] $$

(4)

where

$$ \text{sgn} \left( k_x, k_y \right) = \begin{cases} 1 & k_x \in (0, N_1/2), k_y \in (0, N_2/2) \\ -1 & k_x \in (N_1/2, N_1), k_y \in (N_2/2, N_2), \\ 0 & \text{elsewhere} \end{cases} $$

(5)

$$ bdy \left( k_x, k_y \right) = \begin{cases} 1 & k_x = 0, k_y \in (0, N_1/2) \text{ or } k_x = 0, k_y \in (0, N_2/2) \\ -1 & k_y = 0, k_x \in (N_1/2, N_1) \text{ or } k_y = 0, k_x \in (N_2/2, N_2) \\ 0 & \text{elsewhere} \end{cases} $$

A routine idea of denoising filters is to produce the output filtered signal by Gaussian kernel convolution.
with the original signal. Here, we introduce a 2D elliptic Gaussian filter with axes aligned along
the coordinate system to produce the spatially windowed 2D Hilbert transform operator. The 2D elliptic
Gaussian filter in spatial domain is expressed as
\[
g(x, y; \sigma_x, \sigma_y) = \frac{1}{2\pi \sigma_x \sigma_y} \exp \left[ -\frac{1}{2} \left( \frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2} \right) \right]
\] (6)
where \(x\) and \(y\) represent the two directions of the 2D Gaussian function. \(\sigma_x\) and \(\sigma_y\) denote standard
deviations in \(x\) and \(y\), respectively, which control both the area scale and shape of the Gaussian filters.

In the equation above, the anisotropic Gaussian filter in two dimensional space can be obtained by
choosing different scaling factors in the \(x\)- and \(y\)-directions, respectively.

The corresponding edition in wavenumber domain after 2D Fourier transform of Eq. (4) with respect to
\(x\) and \(y\) is given by
\[
G(k_x, k_y; \sigma_x, \sigma_y) = e^{-2\pi^2(\sigma_x^2k_x^2 + \sigma_y^2k_y^2)}
\] (7)

To highlight the local directional anomalous discontinuities such as karst caves and fracture networks
while suppress the noise, we define the novel SWHT below by incorporating Eq. (7) into Eq. (3)
\[
\hat{E}(k_x, k_y) = S(k_x, k_y)H(k_x, k_y)G(k_x, k_y; \sigma_x, \sigma_y)
\] (8)

Then, we define the SWHT-based volumetric edge detection operator on 3D seismic field data to obtain
the geologic discontinuities at vertical location of \(\tau\), which is given by
\[
Z(\tau, x, y) = \sum_{t=-\infty}^{\infty} \sum_{x, y = 0}^{N_x-1} \frac{|\hat{e}(\tau-t, x, y)|^2}{\sqrt{\sum_{x, y = 0}^{N_x-1} |\hat{s}(\tau-t, x, y)|^2}}
\] (9)
where \(\hat{e}(x, y)\) denotes the SWHT in spatial domain after performing 2D inverse Fourier transform of
\(\hat{E}(k_x, k_y)\) with respect to \(k_x\) and \(k_y\).

The more excellent performance of our SWHT-based volumetric edge detection operator by comparing
with conventional 2D Hilbert transform on a noisy image is not exhibited here due to space limitation
in this paper.

In our study areas, there are distributions of deep karsted carbonates in the target interval at depth of
more than 6500m. The strata have undergone long-term geologic evolution and tectonic process. The
natural fracture networks and karst caves at different scales widely distribute in the carbonate. Thus, the
seismic reflections suffer from notable lateral discontinuities and anisotropy, chaotic events, attenuated
energy with relative lower resolution. This challenge and difficulties lead to present a particular new
workflow by integrating the seismic geometric attributes for reliable delineation of fractures and karst
caves as well as their characteristics. Accordingly, the first mandatory step of the workflow is to
suppress noise in seismic data while highlight discontinuities associated with geologic anomalies of
interest by our SWHT-based volumetric edge detection. The other geometric attributes involve the 3D
multi-scale volumetric curvature (MSVC) proposed by Chen et al. (2012). To sharply highlight the
detailed fractures at different scales, we subsequently employ the ant tracking algorithm performed on
the MSVC-based attributes and then the fault likelihood (Hale, 2013) after running the ant tracking.
Next, we co-render the SWHT-based volumetric edge detection with the fault likelihood data.

**Examples and Applications**

The seismic data sets are acquired from the XT oil field located in Northwestern China. In Figure 1, we
obtain the horizontal slices by using several seismic geometric attributes and the integrated workflow.
We perform the SWHT-based volumetric edge detection by choosing the anisotropic spatial window in
different directions. It can be observed that numerous gray-circle-look-like karst caves widely distribute
on the horizontal slice in Figure 1b. Following some karst caves trajectory, we can track two NW-SE
trending faults (indicated by cyan arrows) and one NE-SW trending fault (indicated by a red arrow).
Their spatial pattern looks like an inverse capital “N”. In addition, we can track another subtle NE-SW
trending fault (indicated by a green arrow). Since the stiff and brittle carbonate strata in our target area underwent deformation and then broken after the long-term tectonic process, in Figure 1c, the MSVC-based most positive curvature slice shows numerous distinct fractured anomalies besides the same karst caves and faults shown in Figure 1b. Figure 1d is the final output obtained by the integrated workflow of orderly performing the MSVC, ant tracking algorithm and fault likelihood measurement. There are quite detailed fracture zones and faults at various scales (indicated by colour arrows) can be observed on the slice (Figure 1d).

To simultaneously and more clearly exhibit all the faults, fracture zones and karst caves on one map, in Figure 2a, we co-render the SWHT-based slice in Figure 1b with the final output in Figure 1d. Thus, all the discontinuities of interest such as faults in various directions, fracture zones as well as the karst caves can be easily identified and well interpreted. The co-rendering outcome in Figure 2a fully accommodates the geologic anomalies of interest contained in the seismic data. Figure 2b and Figure 2c illustrate the different discontinuities and their characteristics that the SWHT-based and integrated workflow-based final output can exhibit nearby the zone at one of the NE-SW trending faults, respectively.

We then comparatively analyse the sections (Figure 3) extracted from the data sets corresponding to the seismic raw data, the SWHT-based volumetric edge detection and integrated workflow-based output data volumes, respectively. The sections’ location is indicated by red solid lines in Figure 2b and Figure 2c. The anomalous discontinuities in the target interval such as faults and concomitant fractures (outlined by red dash contours) are clearly

Figure 1 Horizontal slices of (a) raw seismic data, (b) SWHT-based volumetric edge detection, (c) MSVC-based most positive curvature and (d) fault likelihood measurement after performing the ant tracking algorithm on the MSVC-based most positive curvature data volume.

Figure 2 (a) co-rendering map of the SWHT-based volumetric edge detection in Figure 1b and fault likelihood in Figure 1d, the divided plots of the fractured fault zone in NE-SE direction (indicated by a red arrow) of (b) volumetric edge detection map extracted from Figure 1b and (c) fault likelihood map extracted from Figure 1d, respectively.
exhibited in Figure 3b and Figure 3c, which are difficult to be identified and exactly interpreted on the seismic section in Figure 3a.

Conclusions

We propose the novel SWHT-based volumetric edge detection method and describe case study of reservoir characterization in deep karsted carbonates by a new target-oriented workflow on post-stack 3D seismic data. The workflow can make full use of the advantages and integrate the distinctions of the candidate seismic geometric attributes. It is able to fully extract detailed geologic discontinuities of interest at different scales for excellent delineation of fracture zones and karst caves.

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