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Directional complex-valued coherence attributes for discontinuous edge detection

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ABSTRACT

We propose directional complex-valued coherence attributes through a simple calculation of the cross-correlation between neighboring complex seismic traces normalized by their corresponding envelope within a local time window along a certain spatial direction. For 3D seismic data with varying directional geological edges, the complex-valued coherence attributes along different spatial directions are distinct, and the coherence along a certain direction can highlight discontinuities at (or near) the perpendicular direction. These separate directional coherence attributes can assist in interpreting the dominant direction(s) of fault development, which is vital in determining sweet spots and locating hydrocarbon wells, and can facilitate the detection of weak or hidden geological edges. In addition, we obtain the minimum complex-valued coherence attribute by comparing all directional coherence volumes to describe the entire lineament and spatial extension direction of geological abnormalities (e.g., channels). In essence, the minimum coherence attribute can be regarded as the result of implementing multi-trace complex-valued coherence calculation along the direction perpendicular to the structural trend. An example of 3D synthetic data with a fault system and channel complex is employed to demonstrate the effectiveness of the directional and minimum complex-valued coherence attributes. The application on a real 3D seismic data of tight sandstone reservoir with faults, flexures and fractures, illustrates that the directional and minimum complex-valued coherence attributes can highlight subtle structures and the directional details of geological abnormalities, which are favorably consistent with the manually interpreted results.

1. Introduction

Detecting subsurface anomalous structures is one of the key objectives in seismic exploration. The sharp discontinuities in seismic data caused by faults, channels, waveform distortion and lithological changes can result in low values of similarity or coherence in the coherence volume. Therefore, the coherence technique (Bahorich and Farmer, 1995) can be utilized to identify such features as faults, channels, mud volcanoes, deltas, beaches, unconformity, reefs, canyons, fan and sand bodies, as well as to detect subtle traps and favorable structural reservoirs. In recent years, this technique has evolved as an important analytic tool for determining migration velocity and migration algorithm, attenuating noise, eliminating acquisition footprint, evaluating the rationality of seismic processing work flow and assessing the efficiency of 3D continuous coverage processing (e.g., Chopra and Marfurt, 2007).

The three classical coherency calculation algorithms are consist of the cross-correlation based C1 algorithm coherence (Bahorich and Farmer, 1995), multi-trace semblance C2 algorithm coherence (Marfurt et al., 1998) and eigen-structure based C3 coherence algorithm (Gersztenkorn and Marfurt, 1999). These widely used coherence algorithms have their own advantages, as well as drawbacks. The three-trace cross-correlation based C1 algorithm calculates efficiently and works well in high-quality seismic data, but is very sensitive to noise. Multi-trace semblance C2 algorithm can accurately estimate coherency, dip and azimuth using a few time samples to detect thin, subtle, stratigraphic features in noisy data environments, but with lower lateral resolution and higher computational expenses if more seismic traces are used. Eigen-structure based C3 algorithm, which successfully solves the spatial averaging effect issue, can suppress noise more effectively and can identify more geological details with higher lateral resolution compared with C1 and C2 algorithms. However, the computation of C3 algorithm, involved constructing covariance matrix with a small sub-volume of traces, is more complex. Furthermore, the original C3 algorithm does not implement dip scanning, so it cannot provide accurate coherence estimation in areas with strong structural dips. Later soon, Marfurt et al. (1999) developed C3.5 and C3.6 algorithms with structural dip scanning to remove low coherence anomalies caused by steep dipping structure, which have advantages of higher lateral resolution and resisting noise effectively. Several modified coherence algorithms (e.g., Cohen and Coifman, 2002; Lu et al., 2005; Browaeys,

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2009; Wang et al., 2012; Wang et al., 2015) have also been introduced to improve computational efficiency and achieve high-quality coherence attributes from 3D seismic data. Both the original and improved coherence techniques can be adopted to assist in fast automatic interpretation of faults. Nevertheless, with the increasing degree in oil and gas exploration and development, a detailed characterization of the distribution of faults is necessary, particularly in areas characterized by complex faults. Locating these complex faults and identifying their orientations can help geophysicists in both exploration and reservoir fields to benefit from their presence or avoid their annoyances (Al-Dossary et al., 2004). For instance, detecting the fault direction is crucial to optimize well location, fluid infiltration and injection-production strategy design (e.g., Goodman, 1980; Chopra et al., 2000; Hart et al., 2002; Mittempergher et al., 2009). However, the current coherence algorithms seldom focus on the effect of direction.

In this study, we propose detecting the directional details of geological discontinuous edges by utilizing directional complex-valued coherence attributes. To be specific, for a post-stack migrated data volume, we obtain cross-correlation coefficients between neighboring complex seismic traces normalized by their corresponding envelope within a local time window along an arbitrary spatial direction. This is essentially different from the coherence calculation for pre-stack azimuthal data sub-volumes (Chopra et al., 2000; Al-Dossary et al., 2004). And these aforementioned directional coherence attributes primarily reflect the discontinuities perpendicular to the arbitrary chosen direction. The distinction in different directions is generally evident, and the direction perpendicular to structural strikes shows more discontinuities and geologic abnormalities than that parallel to structural strikes. Therefore, we define the minimum value among complex-valued correlation coefficients of multiple directions as the minimum complex-valued coherence attribute to highlight subtle discontinuities.

We start this paper with the derivation of the directional and minimum complex-valued coherence attributes. Then we use a 3D synthetic data and a 3D field data example to illustrate the performances of the proposed directional and minimum complex-valued coherence attributes for edge detection. Finally, we give some conclusions.

2. Method

Based on the complex seismic trace analysis (Taner et al., 1979), the complex seismic trace $s(t)$ corresponding to the real seismic trace $x(t)$ can be described as

$$s(t) = x(t) + ih(t) = |s(t)|e^{i\theta(t)}, \tag{1}$$

where t is time and $h(t)$ is the Hilbert transform seismic trace or orthogonal seismic trace of the real signal $x(t)$. $|s(t)| = \sqrt{x^2(t) + h^2(t)}$ represents the instantaneous amplitude or envelope, which can characterise the subsurface lithological variations, hydrocarbon (bright spot) and gas accumulation. $\theta(t)$ represents the instantaneous phase related to the continuity of seismic events. The phase attribute can be employed to identify features exhibiting weak reflections with poor continuity, such as faults, pinch-outs, dips and seismic sequence boundaries.

To avert the influence of instantaneous amplitude and completely utilize phase attribute that is more sensitive to subsurface anomalies, we consider an instantaneous complex seismic trace $z(t)$ by dividing $s(t)$ by its l_2 norm

$$\mathrm{z}(t) = s(t)/|s(t)| = e^{i\theta(t)}. \tag{2}$$

This normalized instantaneous complex seismic trace $z(t)$ is solely related to instantaneous phase $\theta(t)$. However, calculating coherence using instantaneous phase lacks of robustness in noisy data. To obtain a robust and smooth result for the noisy real data, we utilize the following local mean attribute (Browaeys, 2009) instead of the instantaneous attribute

$$\langle z \rangle_N = e^{i\bar{\theta}(t)} = \frac{1}{N}\sum_{n=1}^{N} e^{i\theta(t_n)}, \tag{3}$$

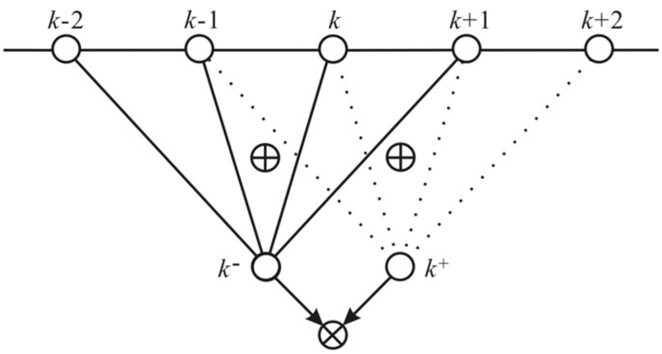

Fig. 1. The schematic of multi-trace local complex-valued coherence calculation for a 2D profile (e.g., take five traces as an example). The open circles marked k-2, k-1, k, $k+1$ and $k+2$ represent five adjacent traces of the kth seismic trace. The circles marked k^{-} and k^{+} represent the two adjacent weighted traces using the former and latter four traces, respectively. The cross-circle ⊕ means weighting operator and ⊗ means coherence operator. We regard correlation coefficient of two adjacent weighted traces as coherence attribute of the kth seismic trace.

where N is the number of time samples. Although the vertical resolution drops with an increase in N, the technique becomes more robust to noise, and vice versa. According to our simulation experience, N is recommended to take as an integer ranging from 3 to 9. The local mean phase is often continuous as the unwrapped phase representation is adopted to avoid a periodic saw tooth jump. Moreover, the cross-correlation calculation using local phase attribute enables us to obtain robust estimates for coherence, even for the zero crossings of seismic reflection events.

Similar to the first-generation coherence (C1) algorithm (Bahorich and Farmer, 1995), coherence directly calculated from only two neighboring local normalized complex seismic traces (i.e., single trace coherence) cannot eliminate the obscure edges and is affected by

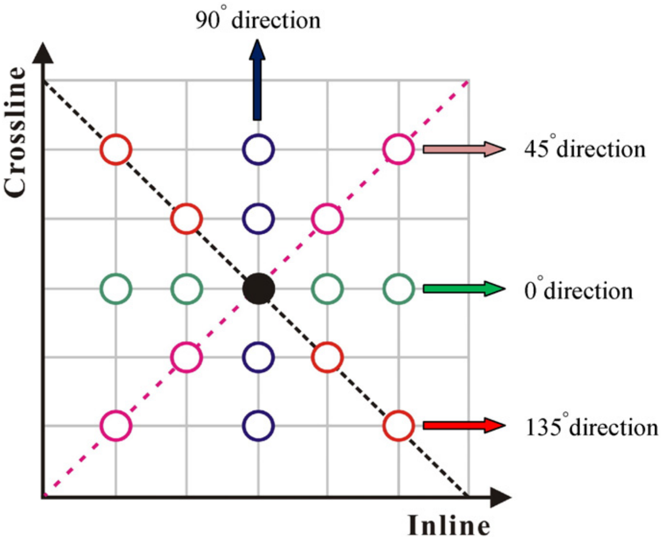

Fig. 2. The schematic of the directional complex-valued coherence calculation for a 3D dataset (e.g., take five traces as an example). The various colored circles stand for different azimuths. The green, pink, blue and carmine open circles represent directional complex-valued coherence along 0°, 45°, 90° and 135° azimuth, respectively. The black solid circle represents minimum complex-valued coherence.