A new method for dip estimation based on seismic waveform curvature/flexure analysis

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Summary

This study presents a new method for accurate dip estimation based on the 3D curvature/flexure analysis of seismic waveforms in a seismic section/volume, denoted as the waveform curvature/flexure. Such waveform analysis is capable of measuring the most and least apparent variation of the local waveforms (or reflector continuity) in 3D space, and the corresponding measuring azimuths are associated with the normal direction and dipping direction of the seismic reflectors, respectively. Integrating both directions leads to the dip attribute that is commonly used in seismic interpretation. The proposed method is applied to the F3 block over the Netherlands North Sea, and its accuracy is well verified by performing seeded picking of eight reflectors (including four peaks and four troughs) that is purely guided by the generated reflector dips.

Introduction

With recent advances in signal processing and algorithm development, reflector dip estimation has been the routine process for 3D seismic interpretation. Over the past few decades, lots of efforts have been devoted into developing efficient methods/algorithms for accurate dip estimates, and the major ones include the complex seismic trace analysis (Barnes, 1996, 2007), the waveform similarity-based discrete scanning (Marfurt et al., 1998), and the gradient structure tensor (Hoecker and Fehmers, 2002). In particular, Luo et al. (1996) and Barnes (2006) present the method of estimating vector dip based on the instantaneous frequency attribute, which is a 3D extension of the concept of the complex seismic trace described by Taner et al. (1979). The gradient structure tensor is used by Bakker et al. (1999) and The method of discrete scanning was first proposed by Finn (1986) based on the lateral similarity of seismic signals, and then Marfurt et al. (1998) generalize it to work for 3D seismic data with enhanced accuracy and efficiency. Hoecker and Fehmers (2002) in their structure-oriented filtering work, which is constructed by computing the outer product of the gradient with itself. A summary of these methods could be found in Marfurt (2006).

In this paper, we present an innovative method for reflector dip estimation based on the curvature/flexure analysis of seismic waveforms, here denoted as waveform curvature and waveform flexure. First, we illustrate the principle of the waveform curvature/flexure analysis-based dip estimation. Then, the proposed dip method is applied to the F3 block over the Netherlands North Sea and provides us with volumes of reflector dips. Finally, the dip estimates are used to guide the picking of eight reflectors from manually-defined seeds. The result demonstrates subtle misfits between the pickings and the original seismic image, verifying the accuracy of the proposed dip-estimation method.

Methodology

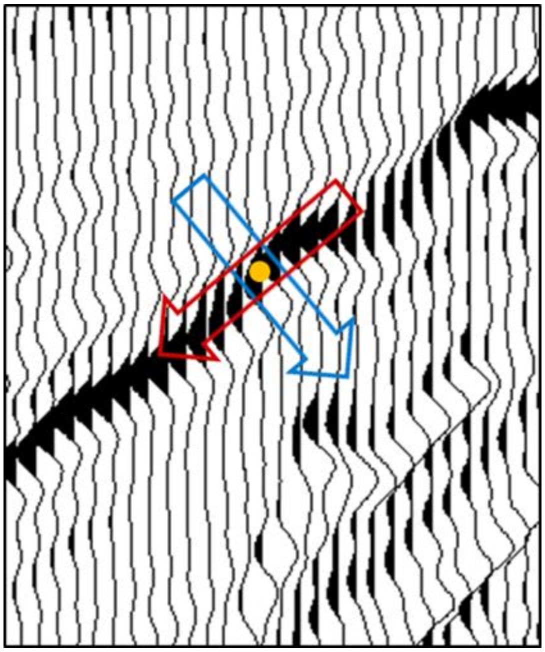

Figure 1: The diagram for illustrating the dip estimation by performing the curvature/flexure analysis on the waveforms in a seismic vertical section. At any given sample (denoted by orange dot), there exist two orientations, with one related to signed maximum curvature (denoted by blue arrow) and the other related to the signed minimum curvature (denoted by red arrow). The former is perpendicular to the reflector, whereas the latter is parallel to the reflector, both of which are closely related to the dipping of the reflector.

In math, the curvature and flexure measures the second- and third-order variation of the geometry of a curve/surface, respectively. When applied to a 3D seismic survey, traditionally, it is performed on the seismic reflectors in the horizontal plane, which assists the subsurface structural interpretation from 3D seismic data, such as fault detection and fracture characterization (e.g., Roberts, 2001; Al-Dossary and Marfurt, 2006; Gao, 2013; Yu, 2014; Di and Gao, 2017). However, such analysis is also applicable to the seismic waveforms in the vertical planes, denoted as waveform curvature and waveform flexure, and holds great implications for assisting seismic interpretation (Di et al., 2017).

In 3D space, an infinite number of curvatures/flexures could be estimated at any given sample, with each representing one possible orientation along which the variation of the local waveform is evaluated. As illustrated in Figure 1, among all possible orientation, there always exist two orientations at any given sample, with one related to the most apparent waveform variation (or least reflector continuity), and the other related to the least apparent waveform variation (or best reflector continuity). In particular, the former is perpendicular to the reflector and thereby represents the normal direction at the sample, whereas the latter is parallel to the reflector and thereby represents the dipping direction at the sample, both of which could be readily converted to the dip attribute commonly used in seismic attribute analysis. To be clear, among various algorithm for 2D/3D curvature/flexure analysis (e.g., Roberts, 2001; Al-Dossary and Marfurt, 2006; Di and Gao, 2014, 2016), this study implement the algorithm presented by Di and Gao (2016) for estimating the signed maximum/minimum curvatures and flexures as well as the associated azimuths.

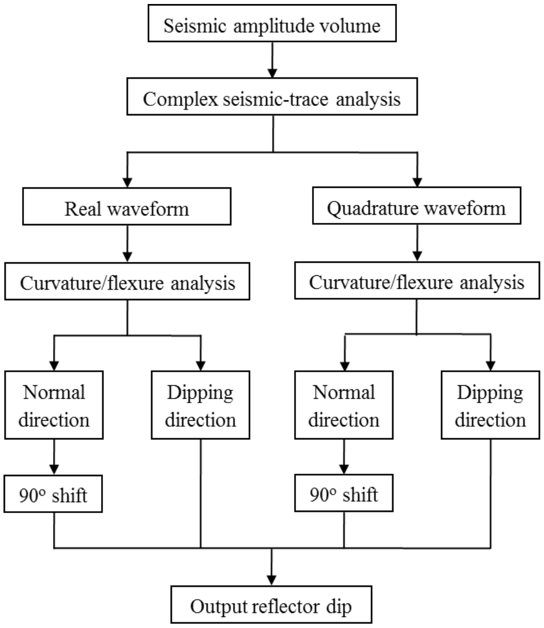

Figure 2: The workflow chart of the proposed method for dip estimates based on waveform curvature/flexure analysis.

Figure 2 illustrates its workflow of three steps. First, the complex seismic-trace analysis converts the original seismic data into two volumes, the real waveform and the quadrature waveform. Second, the curvature/flexure analysis is performed on the complex waveforms and generates two sets of orientations, normal direction and dipping direction. Finally, the reflector dip is estimated as the average of the four directions with the normal ones shifted by 90^o.

Results and applications

For demonstrating the values of the proposed dip-estimation method, we use a subset of the F3 seismic volume over the Netherlands North Sea as the testing dataset, and Figure 3 displays the post-stack amplitude of the vertical section of crossline 625, in which we notice a set of subparallel reflectors. Figure 4 displays the corresponding reflector dip of the vertical section by the proposed method, which well delineates the first-order variation of the reflector geometry, with the upward dipping in negative values (in red) and the downward dipping in positive values (in blue), respectively.

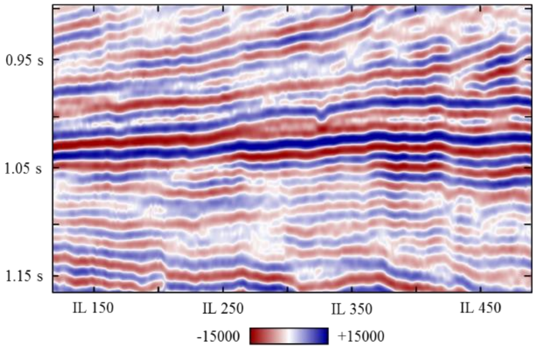

Figure 3: The vertical section of crossline 625 from the F3 seismic dataset over the Netherlands North Sea for illustrating the proposed dip method based on seismic waveform curvature analysis.

Next, for quantitatively evaluating the accuracy of the dip estimates, we perform seeded picking of eight reflectors (four peaks and four troughs), in which each picking starts from a pre-defined seed and grows forwardly and backwardly purely based on the estimated dips. Ideally, the picking is expected to fit the reflectors exactly if the reflector dip is estimated accurately; on the contrary, any errors in the dip estimates would accumulate from the seed location towards both sides. The larger the dip is inaccurately estimated, the more apparent misfit we would observe between the picking and the actual reflector. Figure 4 displays the results of the seeded-picking based on the waveform curvature analysis, from which we notice good match between the pickings and the seismic images, indicating the accuracy of the proposed dip estimation method.

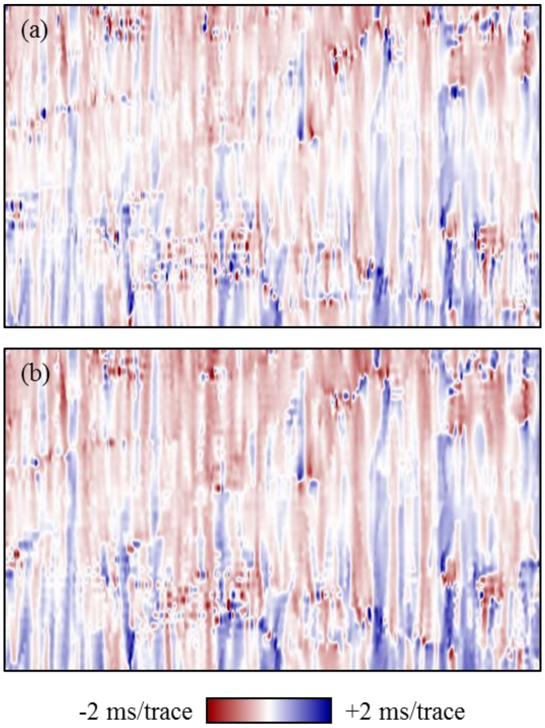

Figure 4: The dip estimates by the proposed (a) waveform curvature and (b) waveform flexure analysis.

Conclusions

Accurate dip estimation is a fundamental tool for subsurface structural interpretation from 3D seismic surveying. This study has presented a new method based on the curvature and flexure analysis of seismic waveforms. In particular, at a given sample, the signed maximum waveform curvature/flexure is indicative of the most apparent variation of local waveforms (or least reflector continuity), and thereby the corresponding azimuth represents the normal direction of the reflectors. Similarly, the signed minimum waveform curvature/flexure is indicative of the least variation of local waveforms (or best reflector continuity), and thereby the corresponding azimuth represents the dipping direction of the reflectors. Integrating both the normal and dipping directions leads to reliable estimates of reflector dips in the presence of seismic noises.

Acknowledgments

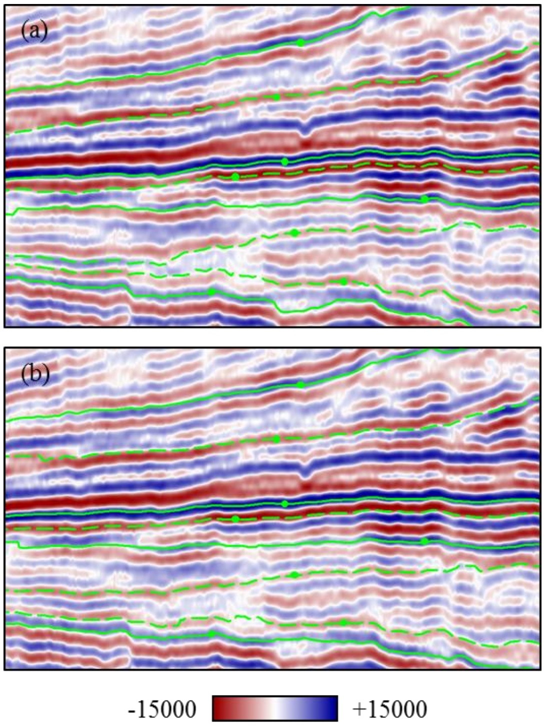

Figure 5: The seeded picking of eight reflectors based on the dip estimation from the proposed (a) waveform curvature and (b) waveform flexure analysis. The initial seeds are denoted by green dots. Four peaks and four troughs are denoted by solid lines and dotted lines, respectively.

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EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2017 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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