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Enhancing the eigenstructure-based seismic attribute for discontinuity detection using eigenvectors

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Extended Abstract

Summary

Seismic data often reveal structural discontinuities such as faults, fractures, and stratigraphic features, which are critical for understanding subsurface geology and reservoir characterization. Among the various tools employed for delineating these features, seismic attributes have emerged as powerful instruments, enabling interpreters to quantify hidden patterns within seismic volumes. Among these, the coherence attribute has gained particular prominence due to its capability to highlight structural discontinuities through amplitude and waveform dissimilarities. This study presents an improved approach for computing seismic coherence by incorporating both eigenvalues and eigenvectors of the covariance matrix derived from seismic traces, addressing limitations of conventional methods that rely solely on energy-based metrics.

Introduction

Traditional coherence computation methods primarily fall into two categories: similarity-based and eigenstructure-based. The similarity-based approach evaluates coherence by measuring the alignment of seismic waveforms in a local analysis window, whereas the eigenstructure-based method estimates coherence using the ratio of the largest eigenvalue to the sum of all eigenvalues from the covariance matrix of traces within the analysis window. While the latter offers superior resolution and robustness against noise, it suffers from insensitivity to waveform shape and phase variations that do not involve energy changes. This limitation often results in reduced performance in detecting discontinuities caused by subtle waveform distortions, such as those induced by lithological changes or fluid variations.

To overcome this deficiency, this research proposes a novel coherence attribute that leverages both eigenvalues and eigenvectors of the covariance matrix. Eigenvectors, which represent the principal directions of data variance, are sensitive to waveform shape, orientation, and phase changes. By integrating the directional information from eigenvectors with the energy-based sensitivity of eigenvalues, the proposed method enhances the detectability of discontinuities that would otherwise go unnoticed using traditional techniques.

The performance of the proposed method was evaluated using synthetic and real seismic datasets. Synthetic models were designed to simulate various types of discontinuities, including those involving time shifts (representing normal faults), polarity reversals (simulating impedance contrast across lithologies), waveform distortion (indicating elastic property variation), and a combination of both shape and polarity changes. In all scenarios, the enhanced coherence attribute outperformed traditional similarity- and eigenvalue-based methods. Notably, it demonstrated superior resolution in identifying subtle discontinuities, especially in noise-contaminated environments.

Methodology and Approaches

In the synthetic tests, the enhanced method successfully delineated faults and discontinuities with significantly lower coherence values at the discontinuity locations compared to baseline methods. This behavior was consistent across models involving pure waveform shape changes or polarity reversals in which traditional eigenstructure-based coherence fails due to lack of energy change. The proposed attribute also showed robustness to high levels of random noise, maintaining high interpretive quality even under a signal-to-noise ratio of –3 dB, which further highlights its potential for real-world applications.

Two real-world seismic datasets were used to validate the method: a well-known 3D dataset from the Dutch North Sea (F3 block) and a seismic survey from the Sarakhs gas field in northeastern Iran. In both cases, the enhanced coherence attribute was able to delineate fault networks and discontinuities with higher clarity and spatial precision than the existing techniques. In the F3 dataset, fault zones that were only partially resolved by conventional methods appeared more distinctly and with better continuity when analyzed with the proposed approach. Similarly, in the Sarakhs dataset, the enhanced method not only highlighted known faults with sharper boundaries but also minimized false anomalies present in similarity-based outputs.

Results and Conclusions

The results affirm that incorporating eigenvector information into coherence computation significantly improves the sensitivity of the attribute to structural changes in seismic data. This innovation addresses a longstanding limitation of conventional eigenstructure-based coherence, which is blind to shape-based discontinuities lacking significant energy variations. Moreover, the method maintains the robustness to random noise that is characteristic of eigenstructure techniques.

In conclusion, the enhanced eigenstructure-based coherence attribute, proposed in this study, offers better characterization of seismic discontinuities by simultaneously considering both energy and waveform shape variations. It provides improved resolution, noise robustness, and interpretive accuracy in both synthetic and real data applications. This makes it a promising tool for fault and fracture detection, structural interpretation, and potentially for integration with machine learning frameworks that can be used in automated seismic interpretation.