Seismic fault enhancement using spectral decomposition assisted attributes

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SUMMARY

Seismic attributes provide an efficient tool for fault identification and delineation in seismic data. Coherence followed by smoothing, sharpening, and skeletonization have significantly improved fault images. Traditionally, we apply coherence and fault enhancement processes to the full-bandwidth seismic data. These resulting images may still be disappointing in the presence of strong seismic noise, or juxtaposition of relatively similar reflectors across a fault. We develop a seismic fault enhancement method based on spectral decomposition assisted attributes. Certain spectral components often exhibit higher signal-to-noise (S/N) ratio over other components, sometimes because of the seismic data quality and sometimes due to the underlying geologic features including tuning and reflector alignment. Because the phase is different for different spectral components, alignment effects occur for only a few spectral components not all components, which helps to fill the coherence gap due to the similar reflectors across faults. In the proposed seismic fault enhancement method, we first perform a structure-oriented filtering (SOF) on the original seismic amplitude volume, to improve the data quality. Next, we compute the multispectral coherence, to further reduce the noise and fill the coherence gap, thus improving the continuity of the faults. Finally, we provide the enhanced fault images by computing a directional skeletonization on the multispectral coherence volume, which further suppress other structural discontinuities and improve the resolution of faults. We evaluate this seismic fault enhancement method with the Opunake 3D seismic survey acquired in the offshore Taranaki Basin, New Zealand.

INTRODUCTION

Faults play an important role in reservoir modeling and characterization. The traditional approach for fault interpretation is to hand-pick a suite of coarsely spaced (e.g. every 10) lines oriented perpendicular to the fault strike. This approach is not only time-consuming task but faces the risk of incorrectly linking faults that would be seen to be different if every line were interpreted. A more modern workflow is to examine time slices through seismic attributes, including coherence, volumetric dip, and curvature to confirm whether the faults seen on vertical amplitude images are laterally continuous or disjoint.

Coherence attributes (Bahorich and Farmer, 1995; Marfurt et al., 1998) measure the seismic trace similarity, and has been widely used to identify faults. We generally compute the coherence volume using the full-bandwidth seismic data. The quality of the coherence attribute images is dependent on the quality of the input seismic data, which motivates us to perform data conditioning before coherence computation, such as structure-oriented filtering (SOF), spectral balancing, or other noise attenuation methods (Chopra and Marfurt, 2007). However, if there are relatively similar reflectors juxtaposing across the faults, in the coherence images the faults often appear segmented as coherence gaps (Libak et al., 2017). The coherence attribute also highlights stratigraphic discontinuities other than faults, such as channel edges, slumps, condensed sections, and angular unconformities, which may mask the fault images of interest.

Multispectral coherence (Alaei, 2012; Dewett and Henza, 2016; Marfurt, 2017; Li et al., 2018; Lyu et al., 2018) improves the quality of the coherence images by combining the coherence results from different spectral components. It better delineates the seismic edges and boundaries over the coherence from the full-bandwidth seismic data. Qi et al. (2016) compute a 3D fault skeletonization on the coherence to further highlight the fault images by suppressing other structural discontinuities. Dewett and Henza (2016) compute coherence from each spectral component, sharpen them using a swarm intelligence algorithm, then combine the results using self-organizing mapping.

In this paper, we evaluate a seismic fault enhancement workflow using spectral decomposition assisted attributes. We first introduce our workflow, which includes three key methods: structure-oriented filtering (SOF), multispectral coherence, and spectral decomposition assisted fault skeletonization. We then show the effectiveness of the workflow using the Opunake 3D seismic survey located in Taranaki Basin, New Zealand. Finally, we provide a brief conclusion.

Seismic fault enhancement workflow using spectral decomposition assisted attributes

WORKFLOW

In Figure 1, we show the workflow of fault enhancement using the spectral decomposition assisted attributes. It is common practice to perform seismic noise attenuation before coherence computation. There are many kinds of filtering methods. The fault enhancement workflow requires preserving the minor faults. We follow the suggestion of Chopra and Marfurt (2007), to apply a structure-oriented filtering (SOF) on the post-stack seismic data, which suppresses incoherent noise and coherent footprint, but preserves the subtle geologic features.

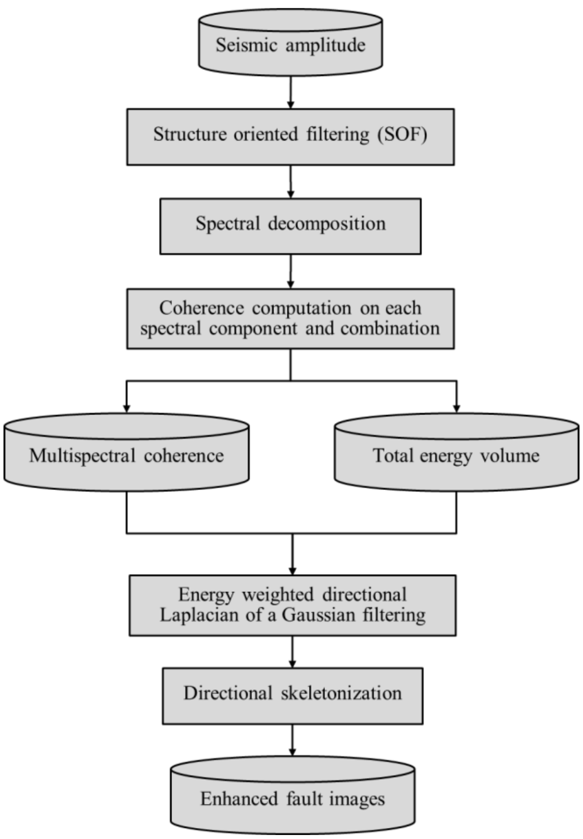


Figure 1: Seismic fault enhancement workflow using the spectral decomposition assisted attributes.

Next, we decompose the full-bandwidth SOF filtered seismic data into different spectral components. Then we compute coherence on each component based on the energy ratio of eigenvalues of the covariance matrix (Gersztenkorn and Marfurt, 1999). Finally, we build the covariance matrix from the spectral voices (Marfurt, 2017), using both magnitude and phase information, and then combine the coherence results from different spectral components into one data volume. Multispectral coherence better delineates the seismic discontinuities over the result using the full-bandwidth seismic data, due to higher S/N ratio of certain spectral components over the others. Specifically, the full-bandwidth coherence behaves segmented if relatively similar reflectors are juxtaposed across the faults. In contrast, multispectral coherence fills these coherence gaps and provides more continuous fault surfaces in these areas.

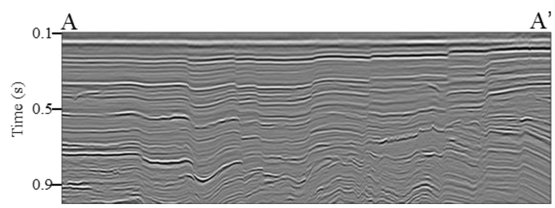
To further suppress other structural discontinuities and sharpen faults, we apply a Laplacian of a Gaussian filter (Machado et al., 2016; Qi et al., 2019) on the multispectral coherence volume. We then compute a directional skeletonization (Qi et al., 2016) along with the fault plane on the filtered multispectral coherence, providing enhanced fault images.

APPLICATION

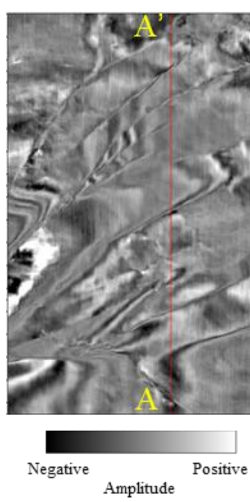
We apply this seismic fault enhancement workflow to the Opunake 3D seismic survey, located in the south-eastern part of offshore Taranaki Basin, New Zealand. The study area is cut by the Cape Egmont Fault Zone and its splay. Representative vertical slice (Figure 2a) and time slices at 0.44 s (Figure 2b) through the original seismic data indicate a complex fault system. The survey also suffers from random noise and acquisition footprint. We show the coherence images of different steps in our workflow using the vertical (Figure 3) and time slices (Figure 4).

We first apply SOF to the original seismic data, improving the data quality by suppressing the random noise and much of the footprint. Then we compute the multispectral coherence on the SOF filtered data. In addition to footprint, the coherence images computed from the original full-bandwidth seismic data (Figure 3a, 4a) suffer from low coherence stratigraphic anomalies that parallel to the reflectors. This “noise” may be either seismic (low amplitude shale-on-shale reflections overprinted by larger amplitude noise) or geologic (condensed sections or other unconformities). The noise makes it difficult to delineate the fault system, especially some minor faults are smeared. The S/N ratio in the coherence images using the SOF filtered data (Figure 3b, 4b) is improved by suppressing the events that cut through the stronger reflectors. SOF does not remove all noise, nor does it change stair-step artifacts in Figure 3b and 4b. The multispectral coherence (Figure 3c, 4c) further suppress the noise, improving the quality of fault images. We can also notice that there are fewer stair-step artifacts in the multispectral coherence (Figure 3c).

We can easily identify the primary faults using the multispectral coherence images, but the resolution is still not good enough to delineate the minor faults precisely. We then provide the enhanced fault images by computing a directional skeletonization on the multispectral coherence volume after applying a Laplacian of a Gaussian filter. We show the enhanced fault images of vertical (Figure 3d) and time slices (Figure 4d), which further suppress other structural discontinuities and improve the resolution of the fault imaging.

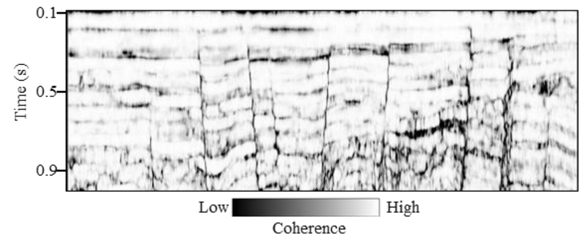


(a)

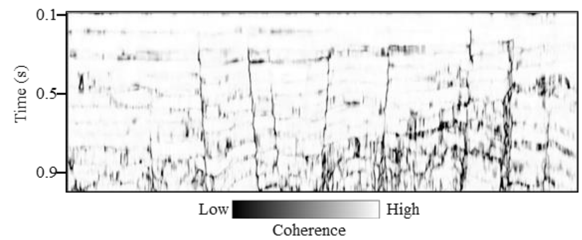


(b)

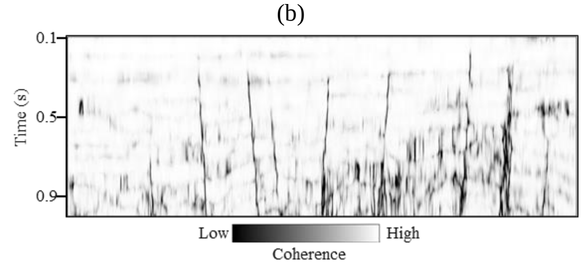
Figure 2: A representative vertical slice AA' (a) and time slice at 0.44 s of original seismic amplitude.



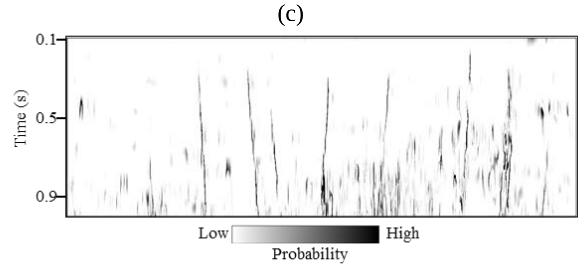
(a)



(b)



(c)



(d)

Figure 3: Coherence vertical slices computed using (a) original full-bandwidth data and (b) SOF filtered full-bandwidth data, (c) multispectral coherence, and (d) enhanced fault image after directional skeletonization.

Especially, if there are relatively similar reflectors which juxtapose across the faults, such as the example in the enlarged seismic amplitude displays co-rendered with different coherence results in Figure 5, we face the challenge of coherence gap. The coherence image using SOF filtered full-bandwidth data (Figure 5b) improves the S/N ratio over the coherence from the original full-bandwidth data (Figure 5a), but they both exhibit segmented (green arrows). The multispectral coherence image (Figure 5c) fills the coherence gap (green arrow), providing more continuous result over the full-bandwidth coherence results. The enhanced fault image (Figure 5d) further improves the resolution.

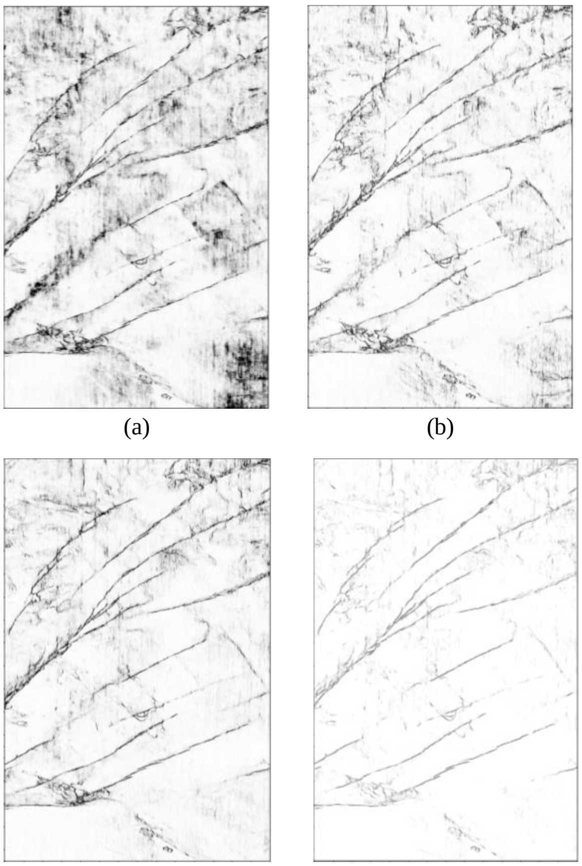


Figure 4: Coherence time slices computed using (a) original full-bandwidth data and (b) SOF filtered full-bandwidth data, (c) multispectral coherence, and (d) enhanced fault image after directional skeletonization.

CONCLUSIONS

We evaluate a seismic fault enhancement workflow using the spectral decomposition assisted attributes, with the Opunake 3D survey in offshore Taranaki Basin, New Zealand. We first apply SOF to attenuate the random noise and strong reflection artifacts. Next, we use multispectral coherence to further increase the S/N ratio of the coherence images and reduce the stair-step artifacts. Especially, multispectral coherence images appear more continuous by filling the coherence gaps over the full-bandwidth coherence in the areas where relatively similar reflectors are juxtaposed across the faults. Finally, we provide the enhanced fault images using a directional skeletonization method, further suppressing other structural discontinuities and improving the resolution of fault imaging.

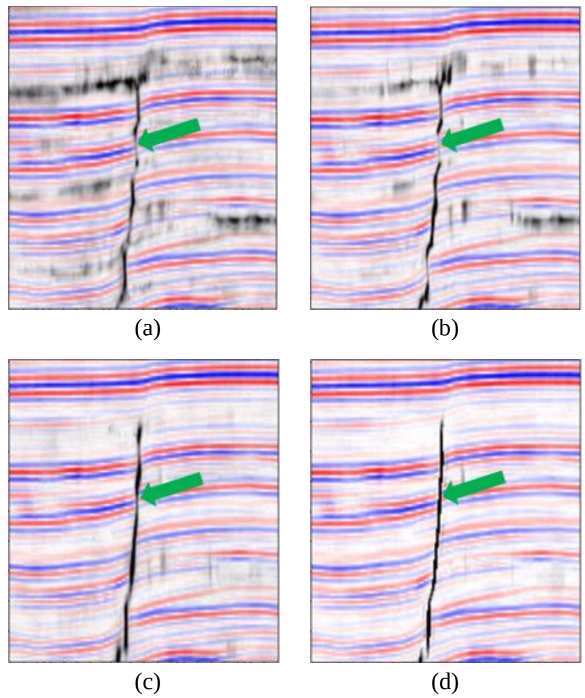


Figure 5: Enlarged vertical seismic amplitude slice co-rendered with the coherence images from (a) original full-bandwidth data and (b) SOF filtered full-bandwidth data, (c) multispectral coherence, and (d) enhanced fault image. Note that the coherence gap is improved by the multispectral coherence (green arrows).

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REFERENCES

Alaei, B., 2012, Improved fault imaging by integration of frequency decomposition and fault attributes, example from mid Norwegian sea: Proceedings of the 3rd EAGE Fault and Top Seal Conference, C13.

Bahorich, M. S., and S. L. Farmer, 1995, 3-D seismic coherency for faults and stratigraphic features: The coherence cube: The Leading Edge, **14**, 1053–1058.

Chopra, S., and K. J. Marfurt, 2007, Seismic attributes for prospect identification and reservoir characterization: SEG.

Dewett, D. T., and A. A. Henza, 2016, Spectral similarity fault enhancement: Interpretation, **4**, SB149-SB159.

Gersztenkorn, A., and K. J. Marfurt, 1999, Eigenstructure-based coherence computations as an aid to 3-D structural and stratigraphic mapping: Geophysics, **64**, 1468–1479.

Li, F., J. Qi, B. Lyu, and K. J. Marfurt, 2018, Multispectral coherence: Interpretation, **6**, T61-T69.

Libak, A., B. Alaei, A. Torabi, 2017, Fault visualization and identification in fault seismic attribute volumes: Implications for fault geometric characterization: Interpretation, **5**, B1–B16.

Lin, T., and K. J. Marfurt, 2017, What causes those annoying stair step artifacts on coherence volumes?: AAPG Explorer Geophysical Corner, March, Article 37830.

Lyu, B., F. Li, J. Qi, T. Zhao, and K. J. Marfurt, 2018, Highlighting discontinuities with variational mode decomposition based coherence: 88th Annual International Meeting, SEG, Expanded Abstracts, 1798-1802.

Machado, G., A. Alali, B. Hutchinson, O. Olorunsola, and K. J. Marfurt, 2016, Display and enhancement of volumetric fault image: Interpretation, **4**, SB51–SB61

Marfurt, K. J., S. L. Farmer, M. S. Bahorich, and R. L. Kirlin, 1998, 3-D seismic attributes using a semblance-based coherency algorithm: Geophysics, **63**, 1150–1165.

Marfurt, K. J., 2017, Interpretational aspects of multispectral coherence: 79th Annual International Conference and Exhibition, EAGE, Extended Abstracts.

Qi, J., F. Li, B. Lyu, B. Zhang, O. Olorunsola, and K. J. Marfurt, 2016, Seismic fault enhancement and skeletonization: 86th Annual International Meeting, SEG, Expanded Abstracts, 1966–1970.

Qi, J., B. Lyu, A. Alali, G. Machado, Y. Hu, and K. J. Marfurt, 2019, Image processing of seismic attributes for automatic fault extraction: Geophysics, **84**, O25–O37.