Enhancing Coherency analysis for fault detection and mapping using 3D diffraction imaging.

J. Vermeulen (Curtin University), B. Gurevich (Curtin University & CSIRO Petroleum), M. Urosevic (Curtin University) & E. Landa (OPERA University of Pau).*

Summary

Automatic detection of geological discontinuities such as small throw faults, and pinch-outs is an important problem in the interpretation of 3D seismic data. This is commonly done using coherency analysis. However coherency may be affected by noise, which may create false anomalies. We propose a new interpretation workflow for the detection and mapping of faults, which enhances the coherency-type analysis with identification and detection of diffractions produced by the discontinuities. The algorithm utilizes migrated and unmigrated stacked seismic volumes and the cube of stacking (NMO) velocities. Tests on a simple 2.5 D model show that the method is capable in detecting and mapping of faults below seismic resolution.

Introduction

Manual identification of discontinuities such as faults, pinch outs and channels is a time-consuming task that requires large amounts of human involvement and hence becomes impractical in 3-D. It has therefore become common practise to use automatic fault interpretation and extraction of attributes to aid in fault mapping. One popular method of automatic fault detection is based on the coherency analysis.

Seismic coherency is a measure of lateral changes in the seismic response caused by variations in structure, stratigraphy, lithology, porosity and the presence of hydrocarbons (Marfurt et al, 1998). Seismic traces that are cut by the presence of a fault surface or discontinuity show up as lineaments of low coherency. However, the coherency algorithm is subject to inherent weaknesses. Shallow heterogeneities in the overburden as well as some types of coherent noise can lead to coherency anomalies which can be misinterpreted as geological discontinuities.

An alternative approach for fault detection is based on diffraction analysis. The main goal of diffraction detection and imaging is to increase the image resolution, delineate faults and edges, and facilitate interpretation (Khaidukov et al, 2004). The wavefields arising in media with faults and or interface discontinuities are characterised by diffracted waves (Landa and Keydar, 1998). Thus presence of diffractions on seismic sections can be used as an indicator of discontinuities. Moreover, diffractions are more direct indicators of discontinuities than coherency anomalies since they are coherent events with very specific signatures that cannot be created by noise. Diffractions can be automatically detected on 2D and 3D prestack seismic data using their traveltime curves.

A drawback of the diffraction analysis is its relatively low spatial resolution. Since anomalies smaller than a Fresnel zone are undistinguishable, spatial period of less than a Fresnel zone cannot be connected to geology (Thore et al, 1996). Local heterogeneities in the overburden can also affect the accuracy of the diffraction detection algorithm by introducing spurious events which may lead to misinterpretation of the seismic data.

We propose a new interpretation workflow to improve the reliability and accuracy of current fault detection in 3D by incorporating both coherency measurements and diffraction analysis. First, an algorithm similar to coherency analysis is performed on a migrated seismic cube to identify lineaments of low coherency. Then diffractivity analysis is run on an unmigrated NMO stacked cube. By testing if a given coherency anomaly produces a diffraction, we determine if in fact the anomaly was produced by a fault. Tests on synthetic datasets show that the method does a reasonably good job in detecting and mapping of faults below seismic resolution.

Workflow Methodology

Our interpretation workflow for the detection and mapping of faults can be split into four main parts. The first step is to generate a fault attribute that enhances spatial discontinuities. Some type of coherency or confidence attributes must be used to compute the attribute. We can then use the attribute to determine fault orientation. The fault dip and azimuth is calculated in a similar way as reflector dip and azimuth are computed from seismic amplitudes (Tingdahl et al, 2003). We use the gradient structure tensor (GST), which is an adaptation of the structure tensor by Knutsson (1989), as a robust estimator of both orientation and similarity on the post-stack data cube. The GST computes reflector orientation from three gradients, based on gaussian derivatives at a scale σ_g, with one vertical and two horizontal (inline and crossline). At each spatial position the orientation estimate is mapping the to the tensor using the dyadic product and averaged at a scale (σ_T).

The reflector dip and azimuth can then be calculated by expanding the tensor into its corresponding eigenvalue and eigenvector. The eigenvector corresponding to the largest eigenvalue defines the locally dominate orientation. The spatial location of the low coherency values relating to the faults and other coherent noise is mapped and then extracted for comparison with the NMO stacked time section. The resulting 3-D coherency volume is then used as the bases for a forward model.

The second step involves taking the low coherency anomalies and producing point diffractors from their spatial location. This is then used as an input to forward modeling. (e.g., by means of an exploding reflector-type finite difference algorithm). As a result of forward modeling, we obtain a seismic cube which should only contain diffractions. The semblance-based 3-D diffractivity analysis is then performed on unmigrated, stacked cubes from both the finite-difference model and the NMO stacked time volume. The diffractivity analysis consists in the detection of diffracted waves by concentrating the signal amplitudes from diffracting points on the seismic section, using the cube of stacking velocties. This is done using a correlation procedure that enhances the amplitude of the seismic signal at the location of line diffractors on the seismic section. The method is similar to those proposed by Landa et al. (1987), Kanasewich and Phadke (1988) and Bruner and Landa (1991) where a common-diffraction section is constructed by stacking the signal along a diffraction hyperbola instead of the conventional CMP hyperbola. It also shares some similarity to the semblance-based coherency analysis proposed by Marfurt et al, (1998). The algorithm takes semblance (discrete search) of amplitude energy along the travel time surface for diffracted waves through a range of varying dip and azimuth to determine maximum signal strength and hence orientation. The amplitude energy is summed along the curve to search for line fragments of diffractions in 3D. The resulting output is again similar to the coherency attribute with a volume of high values at the locations of line diffractors and low values elsewhere. The diffractions point of origin is determined by the resulting high correlation values to accurately locate the line scatterer (i.e., the edges of the fault). The resulting diffractions locations are mapped in a similar way to the coherency attribute values with a 3-D volume of diffractivity attribute as the final output.

The final step involves the combination of both the coherency values and diffractivity values from the point scatterers with those of low coherence values and hence maps the fault location. This is done by combining the three 3-D data volumes from the coherency attribute and diffraction results. Firstly we compare the diffractivity analysis volume produced from both the NMO stacked time volume, with that produced from the finite difference-modeling, based on the earlier defined coherency anomalies volume. We essentially test each of the coherency anomalies to see if they produce a diffraction. Any highly correlated values that do not match the NMO stacked volume results are deemed to be produced from anomalies not associated with faults and are hence discarded. The remaining diffractivity volume is then correlated with the original coherency volume producing a new fault attribute volume and associated orientation volume.

Synthetic data examples

The synthetic model use for the coherency and diffractivity analysis was produced using an exploding reflector type finite difference modeling scheme (Figure 1). The model used has very simple geology with a near vertical, normal fault and two layers with velocities of 2100 and 2200 respectivily. This gives an overall fault throw of approximately 20m The frequency used for the finite modeling was 20Hz which correspondingly gives an overall wavelength of approximately 100m. The resulting coherency attribute produced from the initial velocity model (Figure 2), clearly defines the edges of the fault. The corresponding zero-offset section (Figure 3) and (Figure 4) produced from the coherency anomalies and velocity model respectively, consist of 400 traces with receiver and shot spacings of 10m and a sample rate of 4 ms. The synthetic reflection data volumes used for the diffractivity and coherency analysis was produced by 2.5D modelling. The results from the diffractivity analysis (Figure 5) and (Figure 6) have evidently highlighted the diffracted waves produced by the discontinuities in both zero-offset sections. Although there is some evidence of interference from the reflectors (Figure 5), the higher correlation values are centered over the diffraction locations. This shows that the final diffractivity image is in agreement with the initial coherency analysis, and that all the coherency anomalies on the section are related to faults.

Conclusions

By combining diffraction analysis with coherency attribute we have shown that we are able to detect and map faults with vertical displacements less than a wavelength. The main difference with this method is that the fault orientation does not rely on and is calculated independently of any type of attribute.

We have shown that the structure tensor can be used as a fast and robust orientation estimator. The diffractivity analysis is also robust and can detect diffractions in data with a low signal to noise.

This further supports a more general idea that diffracted waves are a very useful component of the wavefield and not considered to be "redundant" information and can be used to improve coherency estimation.

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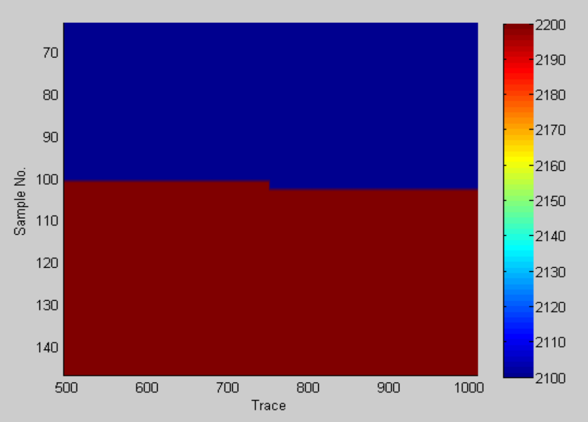

Figure 1: Close-up of small throw fault Synthetic Velocity model

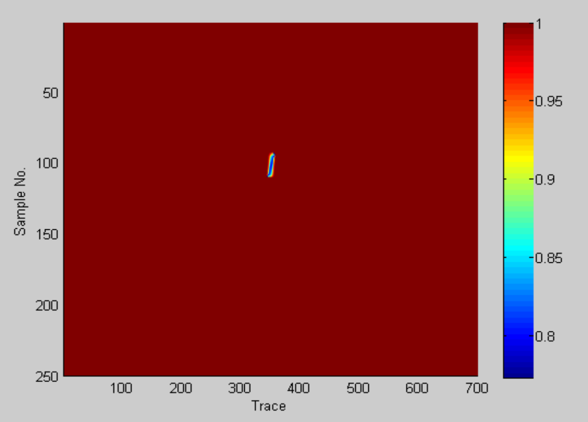

Figure 2: Fault attribute (Coherency) result of fault model.

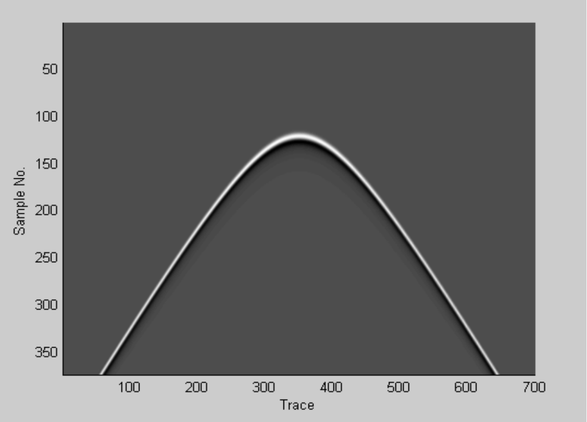

Figure 3: Synthetic seismogram (zero-offset) model of coherency anomaly

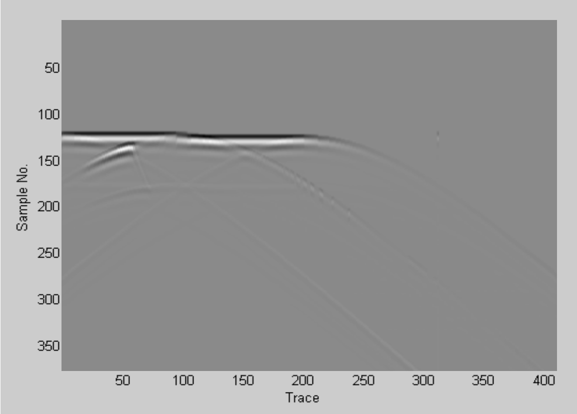

Figure 4: Synthetic seismogram (zero-offset) model of fault model

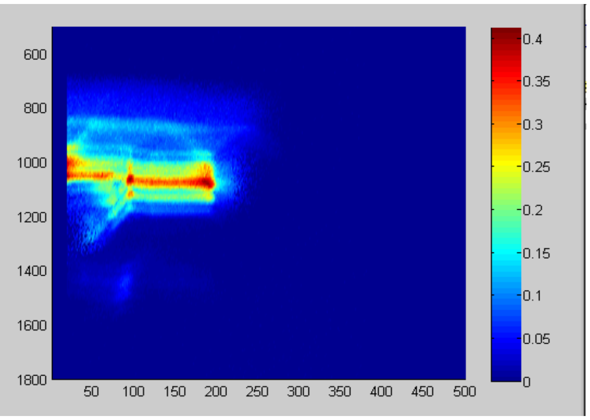

Figure 5: Diffractivity results of fault model

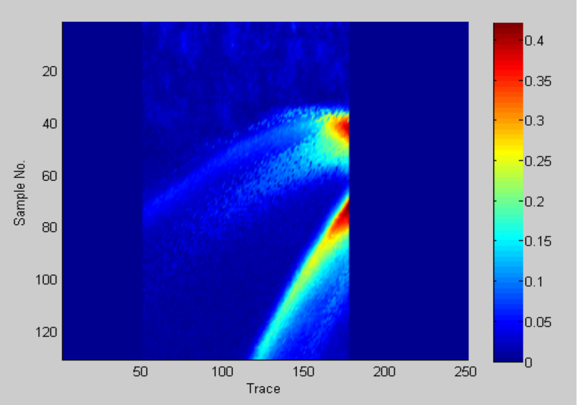

Figure 6: Diffractivity results of fault model

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