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A New Volumetric Fault Attribute Based on First Order Directional Derivatives

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Abstract. In this work we present an edge-detection-based method for fault enhancement. The proposed method is simple to implement and has a strong mathematical background. As is well known, faults can be viewed as discontinuities along horizons. Thus, in order to enhance these discontinuities we apply a first-order directional derivative. Here, we use the vector perpendicular to the instantaneous phase gradient as orientation vector. This orientation vector is calculated analytically. In addition, we describe an approach to combine the attributes in order to capture discontinuities in inline and crossline directions. To assess the proposed method, we use the volume of the Netherlands offshore F3 block downloaded from the Opendtect website and compare the obtained results with variance attribute. We concluded that our method is sufficiently accurate and do not enhance acquisition footprint.

Keywords: fault enhancement, orientation, instantaneous phase, horizon indicator attributes, edge-detector

Resumo. Este trabalho apresenta um método de realce de falhas baseado na teoria de detecção de arestas. O método proposto é simples de implementar e tem um forte embasamento matemático. É conhecido na literatura que as falhas podem ser interpretadas como discontinuidades ao longo dos horizontes sísmicos. Desta forma, com objetivo de realizar essas discontinuidades é aplicado um operador de primeira derivada orientada. O vetor perpendicular ao gradiente da fase instantânea é utilizado como vetor de orientação e é calculado de forma analítica. Adicionalmente, é descrita uma abordagem para combinar os atributos com objetivo de capturar as discontinuidades nas direções inline e crossline. Para validar o método proposto foi utilizado o volume sísmico F3 block obtido no site do Opendtect e os resultados foram comparados com o atributo de variância. Pode-se concluir que o método é suficientemente preciso e não realça ruído de aquisição.

Palavras-chave: realce de falhas, orientação, fase instantânea, atributos identificadores de horizontes, detector de arestas

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1 Introduction

Fault detection plays an important role in seismic interpretation, since knowing the location of the faults is critical to better understand geological systems. However, manual fault picking is a labor-intensive and time-consuming task which requires very well-trained interpreters. Thus, fault enhancement can be a useful tool for streamlining fault mapping and consequently improving the seismic interpretation process.

Several works focus on an attribute that helps the interpreters visualize and better understand the fault system. Dip-magnitude, dip-azimuth and coherence attributes have been used for the detection of faults and fractures since the early to mid-1990s ([10]). Moreover, since faults appear in seismic data as discontinuities, edge detection methods are commonly applied for identifying such geological features. Based on image processing theory, many works apply first-order derivative filters in order to enhance geological features in seismic data, such as faults and channels. In this context, the gradient magnitude of modified Sobel operators are widely used ([9], [2], [1]).

Song *et al.* ([14]) describe a modified edge-detection filter applied to seismic amplitude data and guided by the structural dip, which can be accomplished by gradient structural tensor, complex trace analysis or other algorithms. In order to reduce noise, the authors resample the seismic data using a bivariate cubic function. With a similar approach, Dave Hale ([5]) proposed local dip filters to attenuate or enhance features that are based on approximations to directional derivatives of images. Recently, Dave Hale also proposed a method for computing 3D fault images, extracting fault surfaces and estimating fault throws ([7]).

Orientation is a fundamental step of the methods described above, since they are based on directional filters. Horizon indicator attributes are used for seismic volume rendering, reflector dip and azimuth estimation and curvature computation ([13], [11]). We use the instantaneous phase gradient as the orientation of the edge-detection filter. This is an important aspect of our method, since the instantaneous phase represents the horizon as a level surface.

In this extended abstract, we present a fault-enhancement method based on image processing techniques for edge detection. The output of this method is an attribute that enhances faults, since we are looking for maximums and minimums of the first-order derivative. Additionally, we can apply a post-processing step that enhances the faults detected by our attribute. In order to evaluate the proposed method, we use the volume of the Netherlands offshore F3 block downloaded from the Opendtect website and compare the obtained results with the results of the variance attribute. We conclude that our method is simple, sufficiently accurate, and detects faults without enhancing acquisition footprint. Furthermore, the results show that the instantaneous phase gradient provides consistent dip estimation.

2 Edge-detection Oriented Filter

In this section, we describe the proposed edge-detection-based method for enhancing faults in 2D seismic data. The whole method is composed of five main steps (Seismic Amplitude Gradient Calculation, Horizon Indicator Attribute Calculation, Horizon Indicator Attribute Gradient Calculation, Frist Directional Derivative Calculation and Direction

Derivative Combination) and two optional steps (Preconditioning to reduce noise and Post-processing to enhance the faults detected). Figure 1 provides an overview of the proposed method.

Faults can be viewed as discontinuities along horizons. It is well known from image processing theory that the edges we are interested in appear as maximums and minimums when we use first-order derivatives. Thus, in order to highlight these discontinuities in the seismic data, we apply the first directional derivative. The orientation vector is given by an attribute that represents the horizon as a level surface, as presented below.

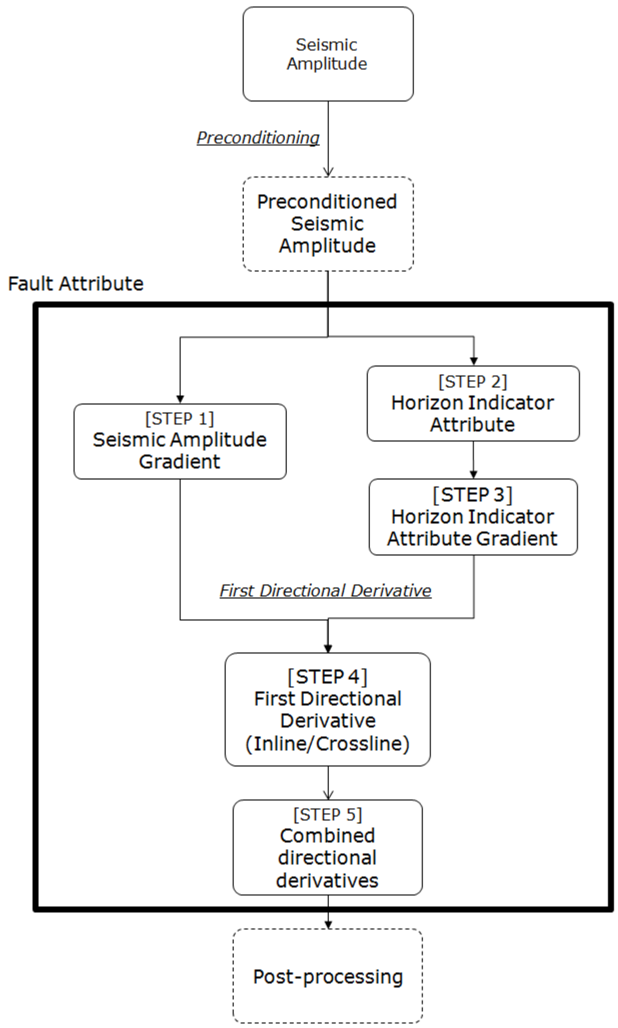

Figure 1: Data flow of the proposed method. The dot lines represent two optional steps of preconditioning the input data and post-processing the output attribute, respectively.

The seismic amplitude is the input data of our method (Fig. 1). Generally, this kind of data has a high level of noise which interferes significantly in the visualization of the discontinuities. Consequently, some noisy regions are wrongly enhanced and may be misinterpreted as faults. Thus, in order to attenuate this shortcoming and improve the final result a preconditioning step is required.

Several works address methods for filtering seismic data while preserving faults ([8], [6]). In spite of that, the main goal of this work is to describe an edge-detection-based method for fault enhancement. Here, we applied a structure smoothing filter with the aim of reducing coherent noise and footprint acquisition.

The first step of the proposed method consists in computing the gradient of the seismic amplitude ∇X by applying a simple derivative operator, such as Sobel, Prewitt or central difference, among others.

In the second step, we compute the horizon indicator attribute. In this work, we use the instantaneous phase. Thus, according to [13] and [11], the horizons can be viewed as a level surface, and therefore its gradient can be used as orientation vector. The instantaneous phase is discontinued in π and $-\pi$, and these discontinuities appear as unwanted edges. However, as shown by [3], this can be solved by using the analytical equations of the instantaneous phase gradient in directions x and t, respectively, as presented in the follow equations. Thus, considering this particularity in the calculation of the instantaneous phase gradient, the second and the third step are performed in a single step. The output of the third step is a vector field that is tangential to the horizons.

$$\frac{\partial \phi}{\partial t} = \frac{1}{X^2 + Y^2} \left(XY_t - X_t Y \right) \tag{1}$$

$$\frac{\partial \phi}{\partial x} = \frac{1}{X^2 + Y^2} \left(XY_x - X_x Y \right) \tag{2}$$

where X and Y represent the amplitude and the Hilbert transform, respectively. The result of this step is an orientation vector field. Note that the orientation vector is perpendicular to the instantaneous phase gradient vector, as illustrated in Figure 2. The orientation vector field represents the direction in which we detect the discontinuities. It is important to emphasize that the final result depends on the accuracy of the orientation vector field.

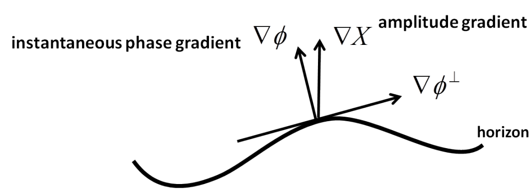

Figure 2: Scheme illustrating the vectors used in our method.

We observe from advanced calculus theory that the first directional derivative can be obtained by the dot product between the two vectors that are functions of the same variables. Thus, in the fourth step we compute the directional derivative as the dot product between the amplitude gradient ∇X in directions x and t, and the orientation vector $\nabla\phi^{\perp}$, as shown in Equation 3. Considering F as our fault attribute, the maximums and minimums of F represent the discontinuities detected in the perpendicular direction of the instantaneous phase gradient. As a result, if there is any discontinuity along the horizon, such as faults, it is detected as an edge.

$$F = | < \nabla\phi^{\perp}, \nabla X > | \tag{3}$$

where $\nabla\phi^{\perp}$ represents the vector perpendicular to the analytical gradient of the instantaneous phase, and ∇X represents the gradient of amplitude data.

The fifth step consists in combining the attribute computed in inline and crossiline directions. We combine these two seismic volumes getting the maximum value for each voxel, as shown in Equation 4.

$$F_{final} = MAX(F_{inline}, F_{crossline}) \tag{4}$$

Considering that faults may often be revealed as weakly connected ridges, we apply a post-processing method to extract and improve the continuity of the faults detected by our attribute.

3 Results

In this section we present some results and discussions. In order to evaluate the proposed method, we use the volume of the Netherlands offshore F3 block downloaded from the Opendtect website. This volume has several faults in the inline direction and it is used in other works for reporting results of fault-detection methods. We also compare the obtained results with variance attribute.

We used the same pre-conditioned amplitude seismic volume to compute the variance and the proposed attribute. In the preconditioning step, we applied the structural smoothing filter available at Petrel software ([4]). The variance attribute was computed using a range of 3 samples in inline and crossline directions and a vertical window of 15 samples. To compute the proposed attribute we used a 3x3 operator filter to calculate the seismic amplitude gradient (step 1) and the horizon indicator attribute (step 2).

As described in the previous section, we compute the first-order directional derivative by means of the dot product between the seismic amplitude gradient and the orientation vector. Thus, if we use the seismic amplitude as the horizon indicator attribute, the result of such dot product is zero. For that reason, the faults are more evident when we use the instantaneous phase gradient than when we use the amplitude gradient.

Figure 3 presents the results obtained with our method and the variance attribute for a slice in crossline direction. We can see that the proposed method correctly identified the fault. We can also observe that, unlike the variance attribute, Figure 3 (a), our results do not highlighted discontinuities perpendicular to the horizon.

Although our method provides satisfactory results without a post-processing step, we observe in Figure 4 (a) and (b) that our attribute has some discontinuities. These discontinuities can be solved by applying the ant tracking ([12]), as shown in Figure 4 (c).

We apply the ant tracking in both, the proposed attribute and the variance attribute. The ant tracking input parameters were the same. The parameter that restricts the dip direction in which faults are preferentially highlighted is fixed as 60 degrees and the ants were configured as passive.

Figure 5 compare the ant tracking outputs. Figure 5 (b) shows the result of ant tracking applied to the variance attribute. Despite faults have been identified correctly, it can be seen that several acquisition footprint are highlighted. This may make the interpretation process more difficult. On the other hand, the result of the proposed attribute, shown in Figure 5 (c), indicates that our method is less susceptible to the acquisition footprint. This is a highly desirable feature when researching an attribute for fault detection.

4 Conclusions

Edge detection is a powerful tool used in the identification of geological features. In this extended abstract, we presented an edge-detection-based method for fault enhancement. The proposed method is simple to implement and has a strong mathematical background. By applying the first-order directional derivative we are able to enhance faults, since they appear as discontinuities in the seismic data. In this work, the orientation is given by the vector perpendicular to the instantaneous phase gradient. It is worth mentioning that this orientation vector is calculated analytically.

Preliminary results suggest that this well-known concept of advanced calculus can be efficiently used to improve the visualization of fault systems. Another important contribution is that our attribute proved less sensitive to the acquisition noise and do not show response between the horizons. These features are highly desirable for fault interpretation and make the fault visualization easier for the interpreter.

Future works involve studying other horizon indicator attributes, such as the vertical derivative of the seismic trace and ridge/valley detector, as well as evaluating their contribution for detecting faults in seismic data. We also intend to extend the proposed methodology to a multi scale approach. We believe that a multiscale approach for calculating the orientation vector field will improve the continuity of the proposed attribute. Although the proposed method provides satisfactory results using the Sobel operator, we intend to study the use of other first-derivative operators, like Prewitt, to compute amplitude gradients.

5 Acknowledgments

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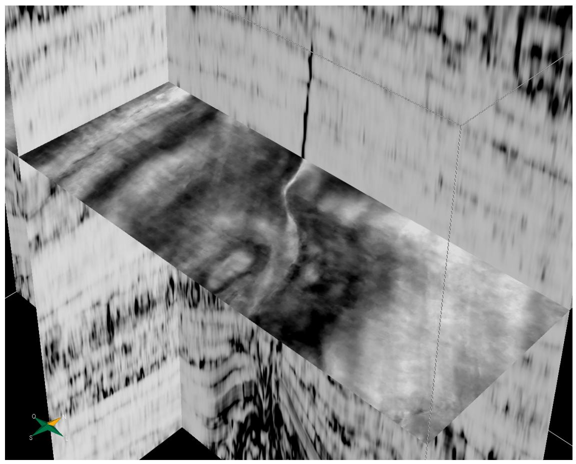
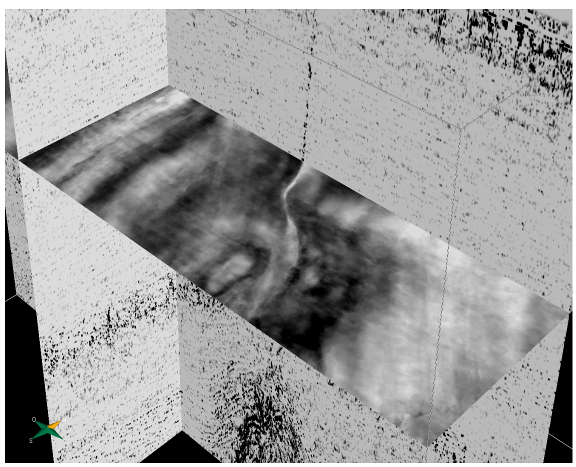
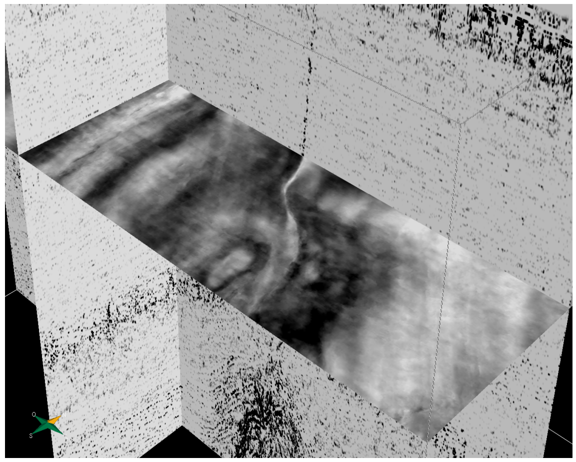


(a)

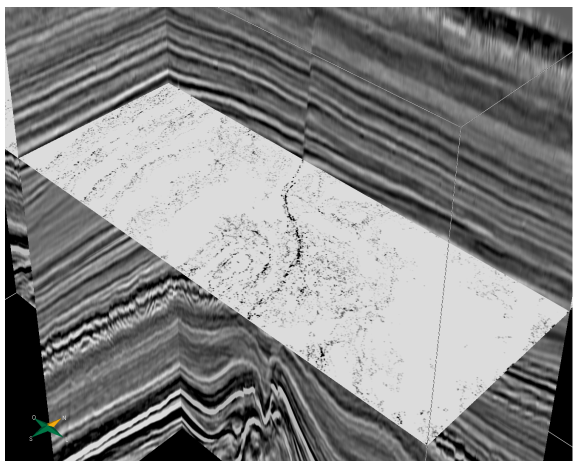


(b)

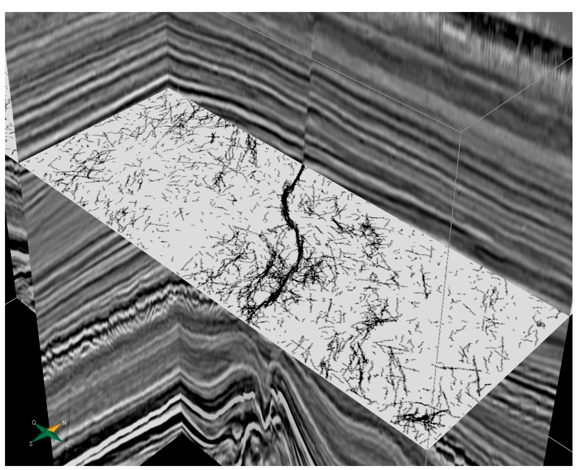
Figure 3: Results provided by the variance attribute (a) and the proposed edge-detection-based method for fault enhancement (b), respectively.



(a)

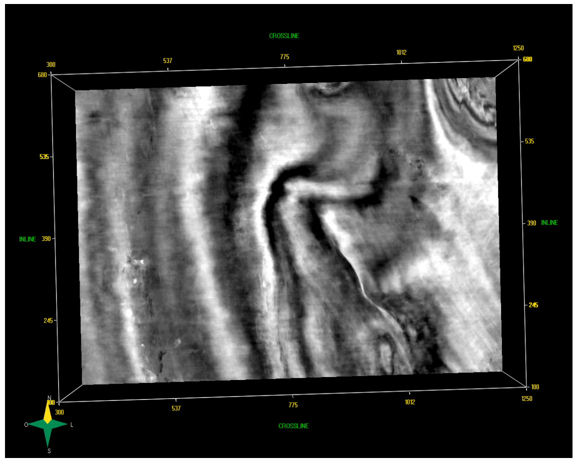


(b)

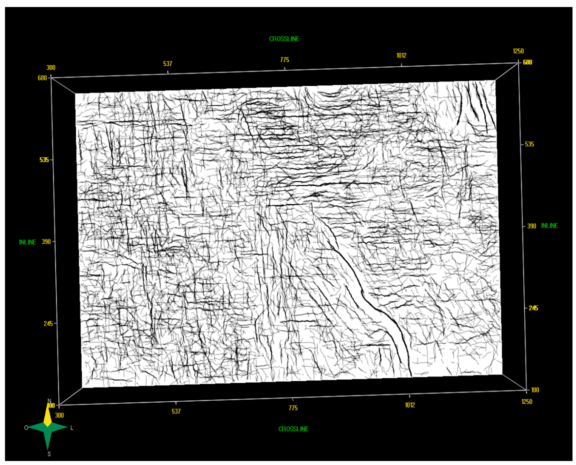


(c)

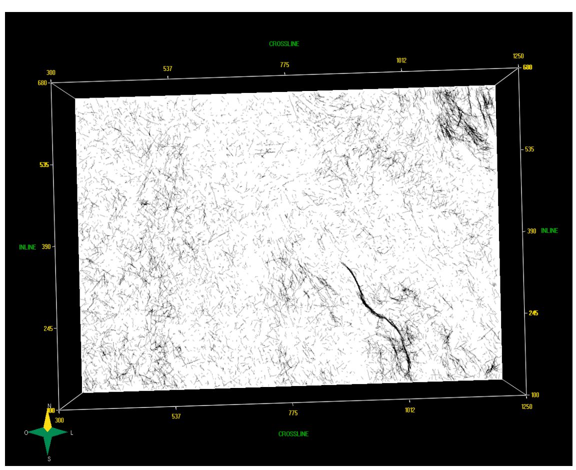
Figure 4: Results obtained with the proposed attribute: (a) obtained result in inline and crossline slices. (b) Result of the proposed method applied in the time slice 640. (c) Result of our attribute with post-processing step. 8



(a)



(b)



(c)

Figure 5: Outputs of ant tracking algorithm: (a) Preconditioned amplitude data. (b) Result of the ant tracking applied to the variance attribute in the time slice 640. (c) The same time slice with the result of the proposed attribute given as the input data of ant tracking.