DETECTION OF DISCONTINUITIES IN POST-STACK 3D SEISMIC DATA USING INLINE AND CROSSLINE FILTERING

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Abstract

The detection of seismic discontinuities in reflection seismology has gained prominence in recent years due to the increase in the quality of acquired seismic data, thus enabling a better prediction of structures such as faults and fractures and contributing to the improvement of the interpretation of conventional and non-conventional reservoirs. In view of the aforementioned facts, we present a three-step filtering methodology for detecting discontinuities in post-stack 3D seismic data: (i) firstly, a horizontal filtering (inline followed by crossline) is applied to attenuate most horizontal and sub-horizontal events (mainly associated with reflections in the layers), thus enhancing vertical and sub-vertical structures; (ii) secondly, the Hilbert transform is applied to each dimension of the volume to obtain the complex volume, and finally, (iii) a phase rotation is applied to each dimension of the amplitude volume. The final result is the highlighting the fractures and flaws in the original volume. We illustrate the application of the new methodology in the pre-stack time-migrated of a 3D seismic data of the Alto de Cabo Frio area located between the Santos and Campos Basins. Numerical results demonstrate the aplicability of this methodology for detecting and mapping structural discontinuities in 3D seismic volumes, thus allowing for the delimitation of hydrocarbon reservoirs.

Introduction

Faults and fractures are structural features, generally easy identifiable in outcrops, of great importance in studies of petroleum systems, since they can act as permeability channels that connect source rock to reservoirs, performing as structural traps. The detection of faults and fractures has been highlighted in recent years due to the improvement in the quality of seismic data that allowed a better detection of these discontinuities in the exploration and production phases of oil and gas reservoirs.

For the oil and gas industry, discontinuity modeling is important for predicting the behavior of reservoirs in response to production (Ferreira et al., 2019), especially in relation to the detection of faults and fractures. This prediction can be made at the exploratory level, aiming to evaluate the recoverable reserves of an accumulation in terms of porosities and mainly permeability, and it can also be made in the development, exploiting the reservoir in the best possible way.

Traditionally, faults and fractures are interpreted in sections and time slices of 3D seismic volumes as discontinuities in seismic amplitude or from time slices of a seismic coherence volume. Interactive tools have been developed to assist the interpreter in this process. Hale & Emanuel (2002) published the results of research focused on automatic meshing that could be applied to fault interpretation, and Pedersen et al. (2003) described a semi-automatic process for fault and fracture extraction using a volume of discontinuity in fracture modeling.

Seismic attributes based on detecting discontinuity of events provide useful tools for characterizing faults and fractures (Chopra & Marfurt, 2007). Conditioning the data increases the visual identification of faults and fractures in the seismic data and its attributes. Conditioned data can be processed to improve discontinuity features and therefore the attributes on this processed data will result in better extractions of faults and fracture geometry.

An example of conditioned data is the coherence cube calculated by measuring the similarity between features. Similar traces are mapped with high coherence coefficients, while discontinuities have low coherence. Regions of seismic traces cut by faults, for example, result in sharp discontinuities, generating a low coherence design along the fault planes (Chopra, 2002).

From this historical context on the importance of faults and fractures for the characterization of oil and gas reservoirs and the work already carried out to detect these discontinuities, we will propose a methodology for the detection of faults and fractures in the post-stack seismic data to assist in the quantitative geological interpretation and in the identification of possible accumulations of hydrocarbons. The presentation of this methodology is divided into three stages: In the first stage, an attenuation filter of horizontal and sub-horizontal events is applied, showing vertical and sub-vertical structures. In the second stage, a filter built from the Hilbert transform method is used for each of the three directions of the seismic volume that originates a volume of complex amplitude. In the last stage, a phase rotation is performed for each of the three directions of the complex volume, highlighting discontinuities such as faults and fractures. For a better detailing of this methodology, first the theoretical foundation of the methods used will be

presented. In the next step, an application of this methodology will be presented in the PSTM 3D seismic data of the Alto de Cabo Frio area located between the Santos and Campos Basins.

Methods

1. Attenuation of horizontal and sub-horizontal reflections

In this first step, a single-channel filtering is performed in the inline direction followed by the crossline direction, in order to attenuate sub-horizontal and horizontal events. Although for the attenuation of sub-horizontal events (dominantly reflections in the layers), different filters can be used (derivative filters, Melo et al., 2009)), after several tests, we chose to use the symmetric and simple filter, which subtracts the amplitude of the original data mean of the L samples in front of and behind its central position.

Let D represent the 3D seismic volume with Ns, Nx, Ny samples in the time, inline and crossline directions, respectively.

$$f(n) = \{f(-L), \cdots, f(-1), f(0), f(1), \cdots, f(L)\}$$
$$= \left\{\frac{-1}{2L}, \cdots, \frac{-1}{2L}, 1, \frac{-1}{2L}, \cdots, \frac{-1}{2L}\right\}. \quad (1)$$

The filter $f(n)$, which has 2L+1 coefficients, is applied in cascade, initially in the inline direction,

$$D_x = f(n) * D(j) = \sum_{n=-L}^{L} f(n)D(j-n), \quad (j = 1, ..., Nx) \quad (2)$$

and subsequently in the crossline direction,

$$D_{xy} = f(n) * D_x(k) = \sum_{n=-L}^{L} f(n)D_x(k-n), \quad (k = 1, ..., Ny) \quad (3)$$

Where $*$ represents convolution.

2. Getting the amplitude of the complex 3D volume

Usually the complex trace is obtained using the Hilbert Transform applied in the time direction, $H_t[D]$) (Claerbout, 1976; Taner *et al.*, 1979). In this section we will use the Hilbert transform, also in the inline, $H_x[D]$, and crossline, $H_y[D]$ directions. For that we will use the quadrature operator, antisymmetric, or Hilbert filter.

As shown by Claerbout (1976), the series representing the Hilbert transform can be obtained with the Fast Fourier Transform method, taking the imaginary part of the inverse Fourier transform of the doubled frequency spectrum of the signal or doing the inverse Fourier transform over the frequency spectrum, multiplying the positive frequency components by i and the negative frequency components by $-i$. Another usual procedure is to convolve the sign with the quadrature operator, $h(n)$, given by the following expression:

$$h(n) = \frac{1}{2\pi}\int_{-\pi}^{\pi}\frac{-i\omega}{|\omega|}exp(-i\omega n)d\omega = \begin{cases} 0 & n \quad \text{even} \\ \frac{-2\pi}{n} & n \quad \text{odd} \end{cases} \quad (4)$$

As we use a fixed and small number of coefficients n (in this work we use the value of $n = 3$) in the operator $h(n)$, we need to apply a scale factor in the amplitudes that represent $H[D_t]$ to ensure that the energy of the signal and its Hilbert transform are equal. This scale factor that we call β is defined as:

$$\beta = \sqrt{\frac{\sum D_t^2}{\sum H[D_t]^2}}. \quad (5)$$

For simplicity of notation we call the result of the first step (eq. 3) $B = D_{xy}$, and we obtain the complex volumes in the time directions, inline and crossline, which we call directions $\{t, x, y\}$, respectively.

$$\begin{cases} B_t = B + iH_t[B], & (6a) \\ B_x = B + iH_x[B], & (6b) \\ B_y = B + iH_y[B]. & (6c) \end{cases}$$

where $H[\circ][B]$ represents the Hilbert transform of B in the direction $\circ$, obtained by convolving $h(n)$ (eq. 4) with the volume traces B collected in the corresponding directions.

From the complex volumes, $\{B_t, B_x, B_y\}$, we get the volumes of the corresponding amplitude envelope (eq. 7). The envelope is defined according to Taner et al. (1979), as the total energy of the seismic trace, thus emphasizing the amplitude changes and independent of the phase. In this work, the total energy of the seismic trace corresponds to the energy of the filtered data B plus the energy of the complex trace of the Hilbert transform of B in the directions t, x and y.

$$\begin{cases} A_t = \sqrt{B^2 + H_t[B]^2}, & (7a) \\ A_x = \sqrt{B^2 + H_x[B]^2}, & (7b) \\ A_y = \sqrt{B^2 + H_y[B]^2}. & (7c) \end{cases}$$

And so we get the average volume of the amplitudes,

$$\bar{A} = \sqrt{\frac{A_t^2 + A_x^2 + A_y^2}{3}}. \quad (8)$$

3. Enhancement of fractures and faults

In this third and last step of the process, we use again the Hilbert operator for phase rotation of the amplitude volume (eq. 7), in the directions $\{t, x, y\}$. Through phase rotation (eq. 9), we were able to organize the polarity and improve the enhancement of the filtered seismic signal. This resource is the same used in the Volume Amplitude Technique (tecVA, Bulhões et al.,

2005) which allows a better visualization of the seismic signal.

$$C = \frac{H_t[\bar{A}] + H_x[\bar{A}] + H_y[\bar{A}]}{3}. \quad (9)$$

Results

The filtered data in step 2 was not used in the analysis of the results of this work because it presents a similar result to the filtered data C calculated in step 3. In addition, the filtered data C highlights the structures present in the filtered data in step 2, allowing a better visualization.

In the first step of the methodology, an horizontal attenuation filter with $L = 1$ and three coefficients was used (number of filter coefficients is 2L+1), as this parameterization presented better results than filters with $L > 1$. The attenuation filter was applied to the PSTM 3D seismic data from the Alto de Cabo Frio area (Figure 1) in cascade (as detailed in section 2.1), that is, the filtering operator was applied in the inline direction and then the filtering operator was applied from the crossline direction, originating the filtered data B. With this, it was observed that in the filtered data B (Figure 2) there was an attenuation of the horizontal and sub-horizontal structures that highlighted the vertical and sub-vertical events.
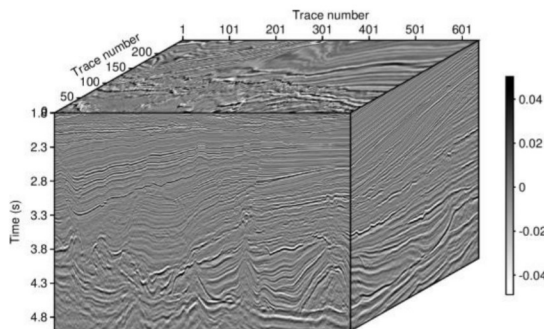

Figure 1 - Original PSTM 3D seismic volume from the Alto de Cabo Frio area.
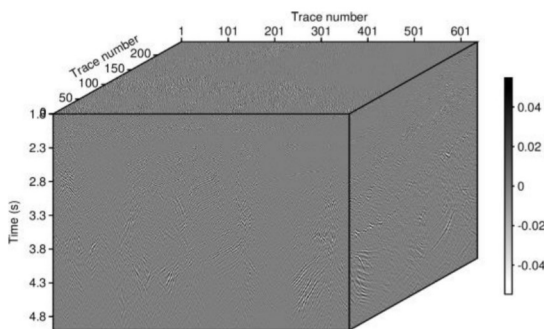
Figure 2 - B-filtered data calculated from the application of the attenuation filter on the PSTM 3D seismic data of the Alto de Cabo Frio area.

The filtered data C (Figure 3) calculated from the

application of the Hilbert filter in the last step of the methodology highlighted the vertical and sub-vertical structures, allowing a better visualization of faults and fractures.
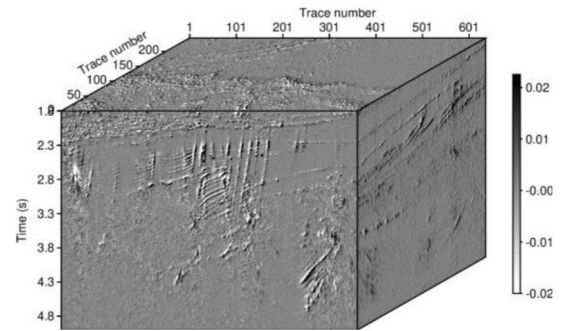

Figure 3 - C-filtered data generated from the application of the Hilbert operator in the last step of the methodology.

Observing the average amplitude spectrum of the filtered data (Figure 4), it can be seen that the filtered data B decreases the amplitude of low frequencies, preserving and increasing the amplitude of high frequencies when compared to the original seismic data. This increase in contrast between low and high frequencies allows a better visualization of discontinuities such as faults and fractures. The filtered data C increases the content of low frequencies up to 5Hz, allowing the rise of the enhancement of vertical and sub-vertical structures.
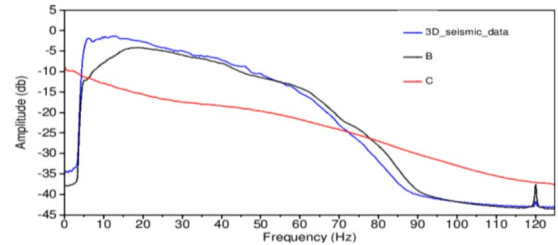
Figure 4 - Average amplitude spectrum that compares the frequency range of the PSTM 3D seismic data from Alto de Cabo Frio with the frequency range of the filtered data B and C.

Subsequently, to verify the effectiveness of the methodology, the filtered data C was used as input for the generation of geobodies that individualized faults and fractures in a 3D visualization software (dGB, 2022). This confirmed that the results were satisfactory, demonstrating a good continuity of faults and fractures throughout the seismic volume (Figure 5).
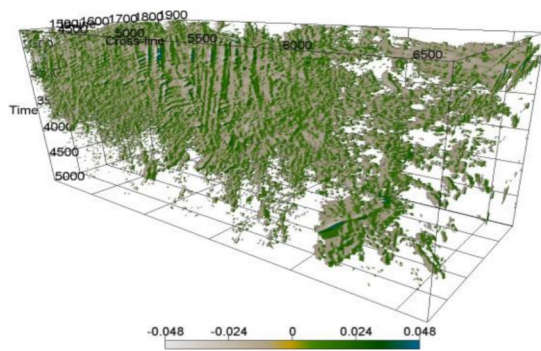
Figure 5 - Geobodies created in OpendTect that individualize faults and fractures generated from filtered data C.

Discussion

The main similarity of the methodology presented in this work in relation to the works cited in the introduction section, such as the case of the coherence cube, is the provision of a tool capable of highlighting discontinuities, however there is a big difference: the coherence cube uses a measure statistics of seismic traces to determine discontinuities, but despite providing good results, it highlights all events present in the seismic data (Figure 6), while the methodology presented in this work uses filters built to highlight discontinuities in certain directions, removing the influence of other events that are not important for the objective presented here, which is the enhancement of vertical and sub-vertical structures such as faults and fractures. This difference in relation to traditional methods of detection of discontinuities ends up being the main advantage of the method used in this work.
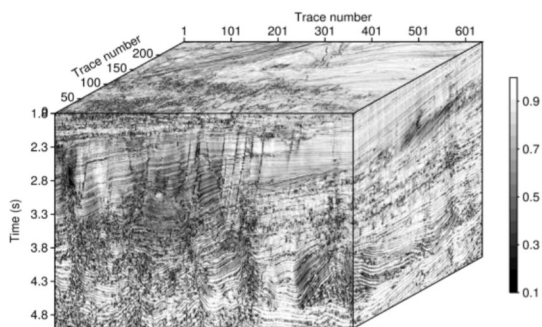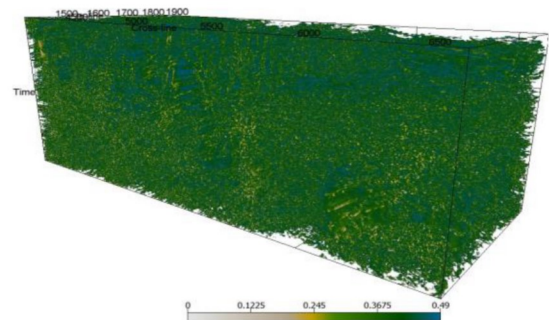

Figure 6 - Coherence cube created in OpendTect (dGB, 2022) from the original PSTM 3D seismic volume of the Alto de Cabo Frio area. It is observed that structures such as faults and fractures are highlighted, but events in other directions are also enhanced.

Observing the average amplitude spectrum of the coherence cube (Figure 7) and comparing it with the spectra of the original PSTM 3D seismic data and the filtered data B and C, an increase in the low and high frequencies can be seen, as well as in the data filtered C, however its curve presents a noise of sinusoidal aspect and it is not observed in the other curves present in the graph of the spectrum of average amplitude.
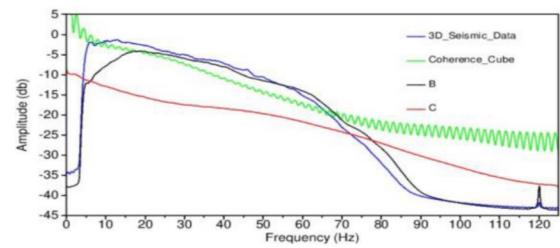
Figure 7 - Average amplitude spectrum comparing the frequency range of the PSTM 3D seismic datafrom Alto de Cabo Frio with the frequency range of the coherence cube and filtered data B and C.

As was done in the filtered data C, we used the coherence cube as input for the generation of geobodies in a 3D visualization software (dGB, 2022). As seen in Figure 8, we were not able to clearly individualize structures such as faults and fractures, because the coherence cube also highlights events in other directions, unlike what is shown in Figure 5 with the geobodies created from the filtered data C.

Figure 8 - Geobodies created in OpendTect from the coherence cube.

Faults and fractures are tectonically distinct features. In the fracture there is no displacement of the two sides of the structure, while the fault is characterized with a surface where there is a relative displacement between two sides of this structure. The algorithm implemented in the article cannot accurately differentiate what is fault or fracture. With this, the results obtained with the application of the algorithm only serve as an auxiliary in the exploratory interpretation. This allows the interpreter to define which are the areas where faults or fractures occur. The interpreter will analyze the results obtained and with this will verify, overlaying the original seismic, the discontinuities that make it possible to observe the tailings and will interpret them as faults, and where it is not possible to observe the tailings, the interpreter will be able to classify them as fractures.

As the methodology presented in this work was built only for the detection of vertical and sub-vertical structures, this fact ends up becoming its main limitation, however, the filtering direction can be redefined to detect seismic events in other directions, if you want to change the purpose of discontinuity detection.

Conclusions

The detection of discontinuities using filtering methods oriented according to certain directions (horizontal or vertical depending on the proposed objective) in the post-stack seismic data, such as those presented in this work, provide important tools for the characterization of faults and fractures. The precision and quality of these filtering methods are directly proportional to the signal/noise ratio of the seismic data, that is, the higher this ratio, the better the quality of the filtered data generated. The results presented with the application of the attenuation filter of horizontal and sub-horizontal structures improved the visual identification of vertical and sub-vertical structures in the seismic data, which benefits the exploratory interpretation. In addition, the filtered data C was able to satisfactorily highlight some discontinuities present such as faults and fractures, thus facilitating the delimitation of hydrocarbon reservoirs.

Acknowledgments

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