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APPLYING FILTERS AND SEISMIC ATTRIBUTES FOR ENHANCING FAULTS IN THE 3D SEISMIC SURVEY OF ALTO DE SIRIRIZINHO (SERGIPE-ALAGOAS BASIN, NORTHEAST BRAZIL)

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ABSTRACT. The 3D seismic data allow that mature oil fields be reevaluated in order to improve the characterization of faults that affect the flow of hydrocarbons. The use of seismic attributes and filtering allows an improvement in the identification and enhancement of these fractures on seismic data. In this study, we used two different filters: the dip-steered median filter to remove random noise and increase the lateral continuity of reflections, and the fault-enhancement filter used to enhance the discontinuities of the reflections. After filtering, similarity and curvature attributes were applied in order to identify the distribution of fractures along the data. The use of these attributes and filters contributed greatly to the identification and enhancement of the continuity of the fractures.

Keywords: fractured reservoir, seismic interpretation, seismic attributes.

RESUMO. Com o advento da sísmica 3D, campos de petróleo maduros podem ser reavaliados melhorando a caracterização das falhas que influenciam o fluxo de hidrocarbonetos. A utilização de filtragens e atributos sísmicos possibilita uma melhora na identificação e no realce dessas fraturas no dado sísmico. No presente trabalho foram utilizados dois tipos de filtros, sendo o *dip-steered median filter*, com a finalidade de retirar os ruídos aleatórios e aumentar a continuidade lateral das reflexões, e o *fault-enhancement filter* para realçar as descontinuidades das reflexões. Após a etapa de filtragem foram aplicados os atributos de similaridade e curvatura, para se identificar a distribuição das falhas. O uso dos atributos e filtragens colaborou fortemente para a identificação e o realce da continuidade das fraturas.

Palavras-chave: reservatório fraturado, interpretação sísmica e atributos sísmicos.

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INTRODUCTION

The evolution of the geophysical techniques such as 3D seismic reflection enabled to re-evaluate or to refine the interpretations made from lower resolution data without lateral continuity. Thus, mature oil fields whose production is dropping can be reanalyzed using these high resolution data. Small faults and folds that were unidentifiable due to the low resolution of the data now can be reinterpreted. This reevaluation can affect greatly the understanding of hydrocarbon flows and reservoir partitioning, since such structures can act as porous that store fluids, as conduits that control the flow and as barriers that allow exploitable volumes of oil and/or gas to be accumulated.

The 3D seismic survey of Alto de Siririzinho where the Siririzinho oil field is located, in the southern portion of the Sergipe-Alagoas Basin (Northeastern Brazil, Fig. 1) was analyzed to map in detail the fractures distribution in the oil reservoirs. The mapping of the main structures (faults and folds) that define the structural framework and the smaller faults (second order structures) that appear more localized was performed in the studied area. A series of filters and seismic attributes were used to enhance second order structures (possibly the main responsible for defining the porous space) and to improve visualization of their orientation and density.

GEOLOGICAL CONTEXT OF THE STUDY SITE

The Sergipe-Alagoas Basin is part of the context of the east Brazilian continental margin and was structured during the rifting episode that led to the separation of the South American and African plates, in Early Cretaceous. The trough of the resulting rift is elongated, NE trending (Fig. 1), parallel to the continental edge, and bordered by crystalline basement that corresponds to the Sergipano Belt, exposed west.

The Sergipe-Alagoas Basin occupies an elongated coastal strip between Sergipe and Alagoas, in Northeastern Brazil, NE trending (Fig. 1). A shallow platform on the continent, the Sergipe-Alagoas Basin is limited by the Jacuípe Basin; to the south, through the platform of Estancia, feature whose northern boundary is the Itaporanga fault (also correlated with the Vaza-Barris fault). To the north, the boundary with the Pernambuco-Paraíba Basin is marked by the Alto de Maragogi (Feijó, 1994). To the west, the basin is limited by a segmented fault zone, which together constitutes the edge fault. The basement of the Sergipe-Alagoas Basin consists of gneissic-migmatitic of the Pernambuco-Alagoas Massif and the metamorphic rocks of the Sergipano Belt, a collisional orogeny associated with the Brasiliano Cycle, from the late Neoproterozoic.

Stratigraphically, the basin consists of twenty-three depositional sequences, grouped into five super-sequences (Paleozoic, pre-rift, rift, post-rift and drift) (Campos Neto et al., 2007). These super-sequences are correlated to evolutionary stages of the eastern Brazilian basins: syneclise, pre-rift, rift and passive margin (or drift) (Schaller, 1969; Feijó, 1994; Campos Neto et al., 2007) (Fig. 2).

The Alto de Siririzinho is regionally inserted in the northern part of Alto Oeste de Piranhas, also known as Alto de Aracaju, and is limited to the east by Baixo de Japaratuba, to west by the Baixo de Santa Rosa and to the north by the SAB edge fault (Lana, 1990).

The Siririzinho oil field was discovered in 1967, in the exploratory drilling campaign of the Sergipe-Alagoas Basin (SAB) that had started in 1959 by PETROBRAS (Sa & Carvalho, 1970). The field is geologically located in the Alto de Siririzinho, in the northwestern portion of the onshore Sergipe Sub-basin (southwestern portion of the SAB), and is geographically positioned to the northern of Aracaju, the capital of Sergipe (Fig. 1).

The horizon corresponding to the top of the Membro Ibura (Muribeca Formation) was interpreted. The Muribeca Formation represents the Post-rift super-sequence developed with the beginning of the thermal subsidence of the basin during the Aptian, which was the first major marine incursion (Campos Neto et al., 2007). The Membro Ibura is described in the literature as a sequence composed of evaporates, microbial carbonates and shales deposited on shallow marine environment influenced by the tides (Campos Neto et al., 2007).

METHODS

The work consisted of three main steps (Fig. 3):

(1) creating a cube that stores the information of direction and relative dip of the reflectors existing on the seismic data, referred to as steering cube (Tingdahl, 1999; Tingdahl et al., 2001);

(2) applying filters to remove random noise and to enhance the structural and stratigraphic features;

(3) applying and analyzing the seismic attributes to characterize faults and fractures (Chopra & Marfurt, 2007).

The seismic data consists of 315 inlines in NW-SE direction, spaced 30 m, and 576 crosslines in NE-SW direction, spaced 15 m, totaling an area of approximately 82 km^2 (Fig. 4). The recording time is 4 s, and the sampling rate of 4 ms.

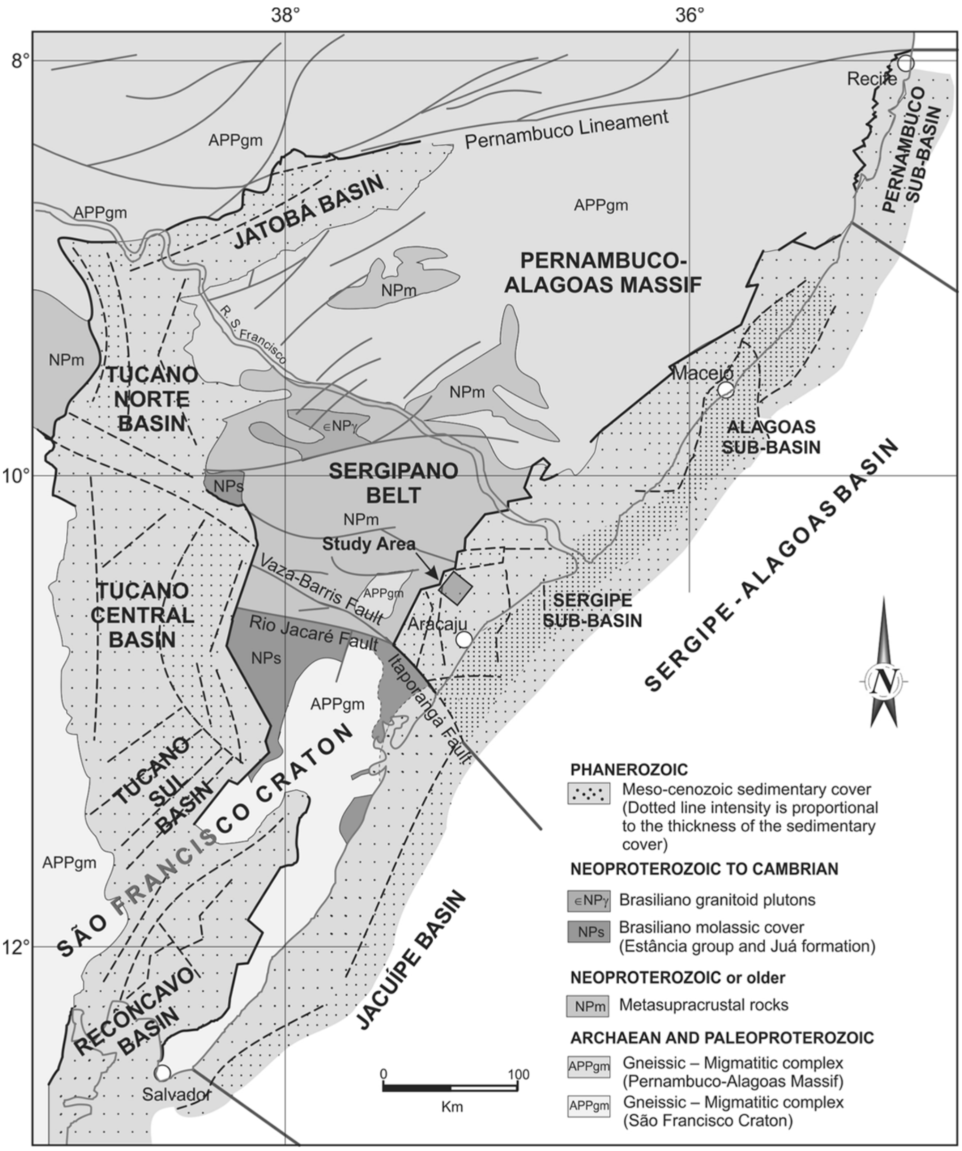

Figure 1 – Map showing the location of the Sergipe-Alagoas Basin in the regional geological context and studied seismic survey (modified from Lana, 1990).

The creation of the steering cube

The steering cube was developed by Tingdahl (1999) and Tingdahl et al. (2001). The process consists of extracting the local dip and azimuth, comparing trace to trace of a seismic data (Fig. 5), enabling the use of filters and seismic attributes that are based on such information, thus improving object resolution and detection power. It is possible to generate two steering cubes depending on the scale of the structures to be enhanced. The detailed steering cube, which will work with input data to enhance small structures when combined with seismic attributes, and the background steering cube that aims to enhance the regional features (Brouwer, 2007).

The steering cube was created using the OpendTect software (dGB Earth Sciences), which has five steering algorithms: Event, BG Fast Steering, Standard, Combined and Precise. The Event algorithm calculates the dip for each trace, searching for the maximum and minimum values in the trace and comparing to the traces beside. The BG fast Steering is based on the vertical and horizontal amplitude gradient analysis while the Standard, Combined and Precise are filters based on the Fourier transform. The Combined algorithm combines the Standard and Precise algorithms. The Precise is used when the Standard results are not good, although it has the disadvantage of requiring a longer processing time (dGB Earth Sciences, 2010). The Precise

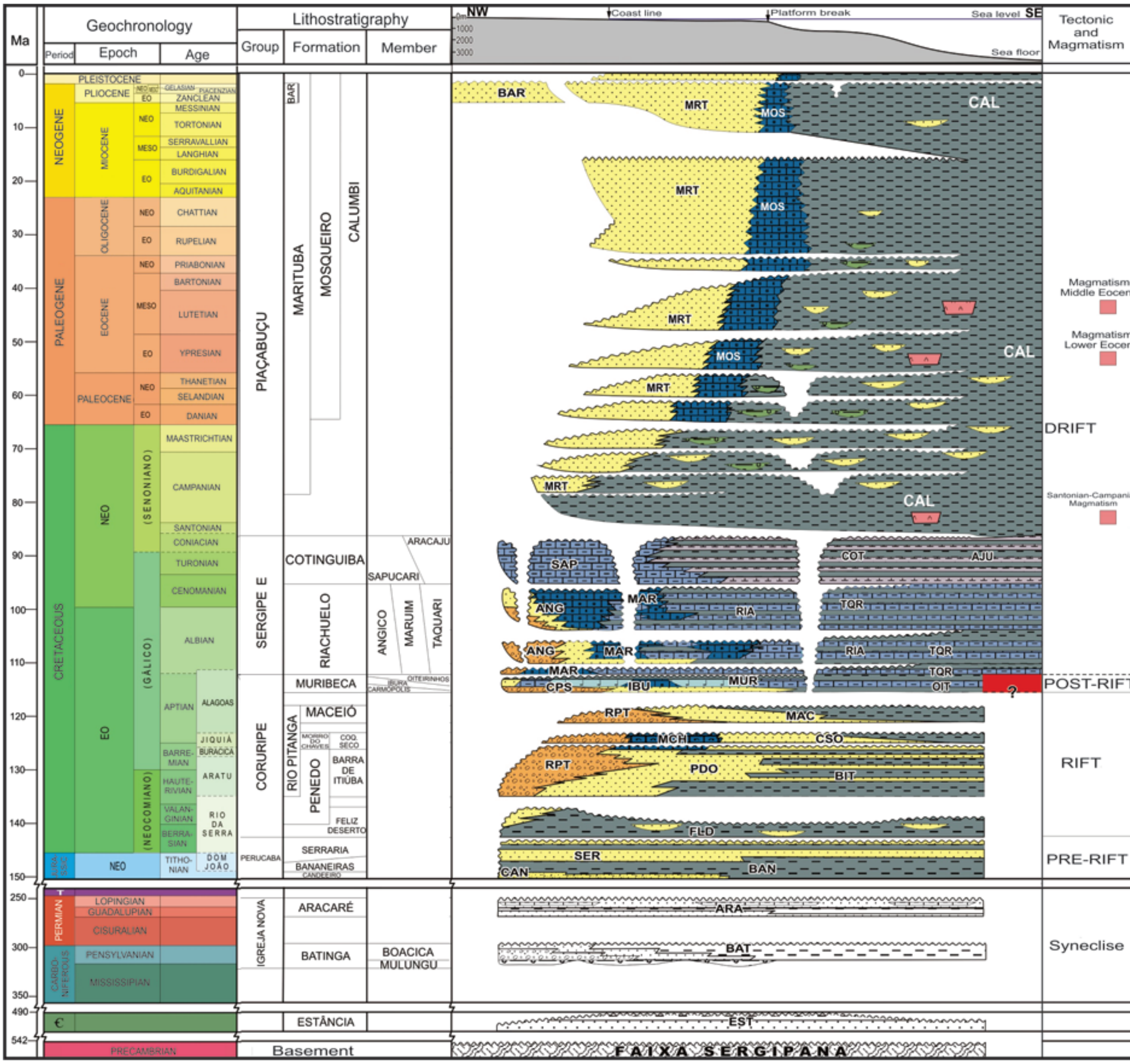

Figure 2 – Chrono-stratigraphic chart of the Sergipe sub-basin (compiled from Campos Neto et al., 2007).

algorithm was used in this study because the results are more accurate, despite taking approximately twice the processing time compared to BG fast Steering.

The three steps proposed by Brouwer (2007) was followed to create the steering cube: (1) creating a raw steering cube with outlet filter 1×1×1 (inline/crossline/number of samples) to eliminate random noise; (2) first filtering (size 0×0×5 – inline/crossline/number of samples) to create the detailed steering cube; and, (3) second filtering (size 5×5×0 – inline/crossline/number of samples) to create the background steering.

The information contained in the steering cube can be used in two ways, central and full steering (Fig. 6). The central steering follows the dips and azimuth of the studied interval, tracking the traces without taking into account the intermediate dips (Rooij & Tingdahl, 2002). The full steering follows the dips and local azimuths of the studied interval in all directions from the analysis of time-frequency applied to the trace, that is, they are extracted from the frequency domain and further presented in the time domain as shown in Figure 6 (Rooij & Tingdahl, 2002).

Applying the Filters

Filters are used to improve the quality of the seismic data, by removing random noise and noise related to the seismic acquisition, increasing the signal/noise ratio, which can enhance the structural and stratigraphic features of the data. The filters used in

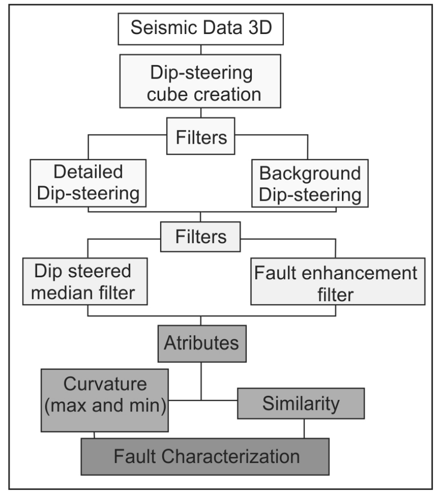

Figure 3 – Flowchart showing the steps treatment and analysis of the studied seismic data.

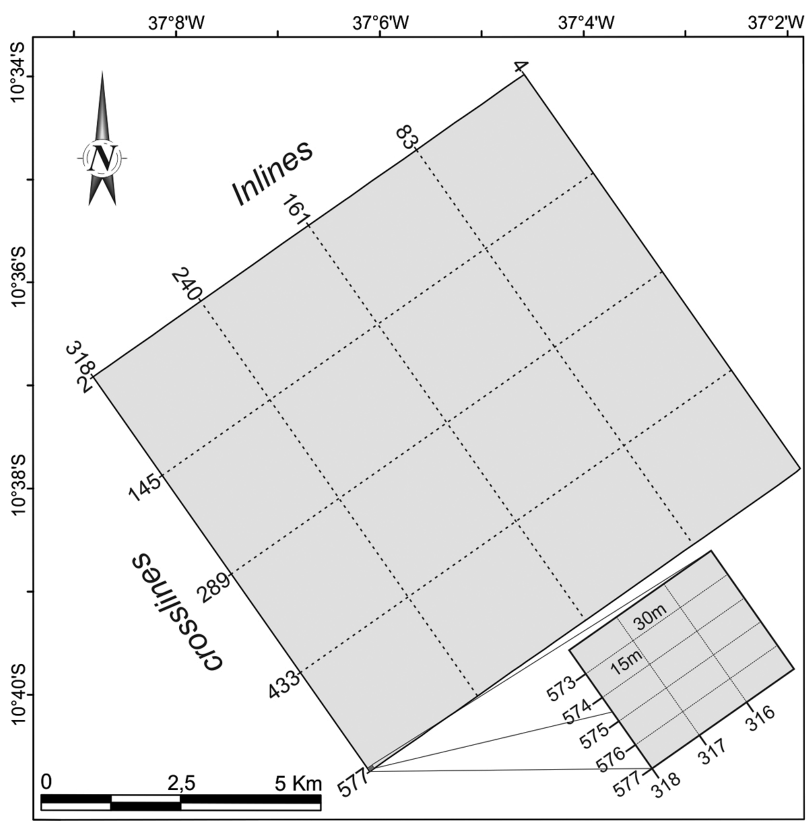

Figure 4 – Detailed map showing the seismic survey area with the distribution and orientation of inlines and crosslines.

this study were the dip-steered median and fault enhancement filters, also known as structurally-oriented filtering (Chopra & Marfurt, 2007), which use the dip and azimuth information extracted from the steering cubes.

The dip-steered median filter removes the random noises and enhances lateral continuity of the reflections in the seismic data, providing a smoothing of the edge effect, increasing the signal to noise ratio. This median filter replaces each sample in the

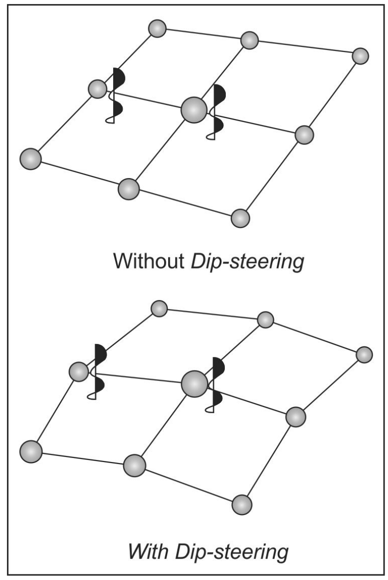

Figure 5 – Schematic figure of the distribution of the seismic traces with and without steering (modified from Brouwer, 2011).

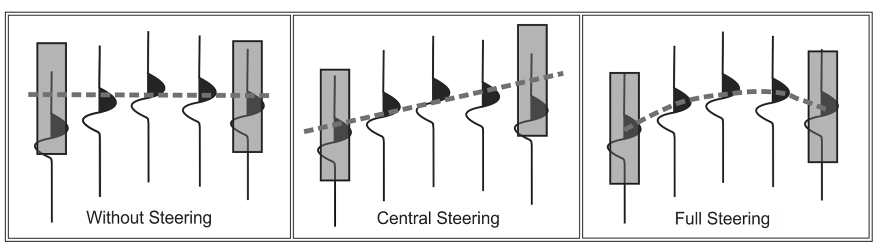

Figure 6 – Flowchart of the operation of full and central steering (and comparison with the data without steering) representing the seismic traces, dip and azimuth information (dashed line) and the survey interval (rectangles) (compiled from dGB Earth Sciences, 2010).

seismic trace window by the median of the samples (Fig. 7) while window size is usually defined by an odd number, 3×3 or 5×5 (Chopra & Marfurt, 2007).

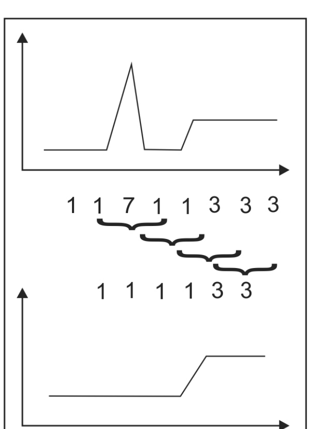

Figure 7 – Schematic figure shows the dip-steered median filter (3×3) noise removal, represented by the peak (number seven) (reproduced from Brouwer, 2011).

The fault-enhancement filter is used to enhance the discontinuities of the reflections that, in some cases, may be related to the presence of faults and fractures. According to Hocker & Fehmers (2002), the successful use of orientation filters requires three features: (i) orientation analysis to determine the orientation of reflections; (ii) edge detection to determine possible terminations of reflections; and (iii) preserving the edges with smoothing filter in the direction of local orientation, without filtering the edges. Following the assumptions of Hocker & Fehmers (2002) the fault-enhancement filter works as the combination of dip-steered median filter, dip-steered diffusion filter, steering cube and seismic data. When the quality of the seismic data is good (that is, similarity is high), the dip-steered median filter is used to remove noise and smooth the reflections; however, if the quality is not good, the dip-steered diffusion filter is used to promote breaking effect on the termination of the reflection. Note that if the dip-steered diffusion filter is applied too strong can generate false structures, distorting the results.

Using Seismic Attributes

Similarity is a coherence attribute that expresses how similar two or more traces are to each other either in the crossline or inline directions (Chopra, 2001). Trace discontinuities of the seismic data may be the result of the faults or stratigraphic features, which change the trace characteristics in a way that the seismic traces lose similarity (Bahorich & Farmer, 1995).

The attribute shows how similar the traces are on a scale varying from zero to one, where zero is the value attributed to completely dissimilar areas while one is attributed to areas with maximum similarity.

On the other hand, curvature attributes are being increasingly used to characterize faults and fractures, based on the fact that certain areas with curved surfaces are related to discontinuity zones, which can be represented by faults and fractures (Roberts, 2001). The curvature attribute emphasizes the positive (antiforms) and negative (sinforms) curvatures, whereas on a flat surface or in inflection zones the curvature is zero (Fig. 8) (Roberts, 2001).

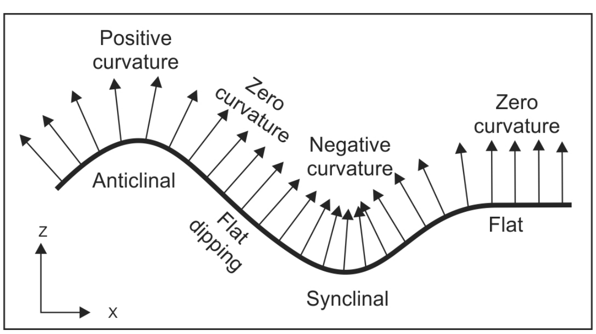

Figure 8 – Curvature definitions. The syncline feature has negative curvature and the anticlinal feature has positive curvature while the flat features have curvature equal to zero (reproduced from Roberts, 2001).

The curvature attributes selected for the study were the most-positive and the most-negative curvatures. According to Roberts (2001), these attributes identify the surfaces with the most positive and the most negative curvatures, highlighting features isolated from each other, enabling to distinguish and locate the structures and making the results less ambiguous than those generated by other types of curvature attributes.

It is agreed that curvature attributes are used in horizons (interpreted seismic reflectors) properly filtered, so that the signal to noise ratio is as high as possible and the attribute response is clear of "artifacts", bringing information more geologically plausible. However, when the curvature attribute is used together with the full steering, the dip and azimuth information are followed trace by trace simulating the mapping of a "local horizon" that can be used to assign values to the local curvature, enabling the use of the attribute in the whole data (timeslices), and not only in already interpreted horizons (Rooij & Tingdahl, 2002).

RESULTS AND DISCUSSION

To analyze the seismic data from Siririzinho, the detailed and background steering cubes were created to serve as input information in the creation of filters and application of attributes. The filters did not show large differences in the final results when the detailed and background steering cubes were used; however, the attributes displayed good results, especially the curvature attribute.

The use of structural orientation filters decreased significantly the random noise, improved continuity (after the dip-steered median filter) and enhanced discontinuity (after the fault-enhancement filter) of the reflectors (Figs. 9 and 10). The fault traces became sharper and more continuous, especially in smaller-scale faults (Figs. 9 and 10), helping in the interpretation and visualization of fracture distributions that were little visible or imperceptible in the original data.

The similarity attribute was applied to the original seismic data and to the filtered data to compare which one promotes the best enhancement of the discontinuities (faults and fractures). The attribute applied to the original data shows the individualization of some faults when compared to the amplitude data; however, smaller faults are still obscured by the large amount of noise. When the dip-steered median filter is applied to the data, the faults are greatly enhanced showing more continuous and sharper features (Figs. 11 and 12). However, the result obtained by the use of fault-enhancement filter was better, because in addition to enhancing larger faults and fractures, it also improved the visualization of smaller-scale discontinuities (Figs. 11 and 12). When the original data were applied over to the similarity data of the fault-enhancement filter, a good correlation of the faults could be seen between the two datasets (Fig. 12), evidencing the veracity of the information obtained from the attribute.

Regarding the steering cube, the curvature generated by the detailed and background steering cubes displayed different magnitudes (Figs. 13 and 14). The background steering cube enhanced wider and more continuous curvatures while the detailed steering cube enhanced shorter wavelength and less continuous curvatures (Figs. 13 and 14). Geologically, these narrow curvatures (detailed steering) may be related to systems of localized fractures, possibly representing fracture zones (Figs. 13 and 14), which does not mean that this type of curvatures cannot be related to large faults, as well. Background steering curvatures may be related to regional structures (Figs. 13 and 14).

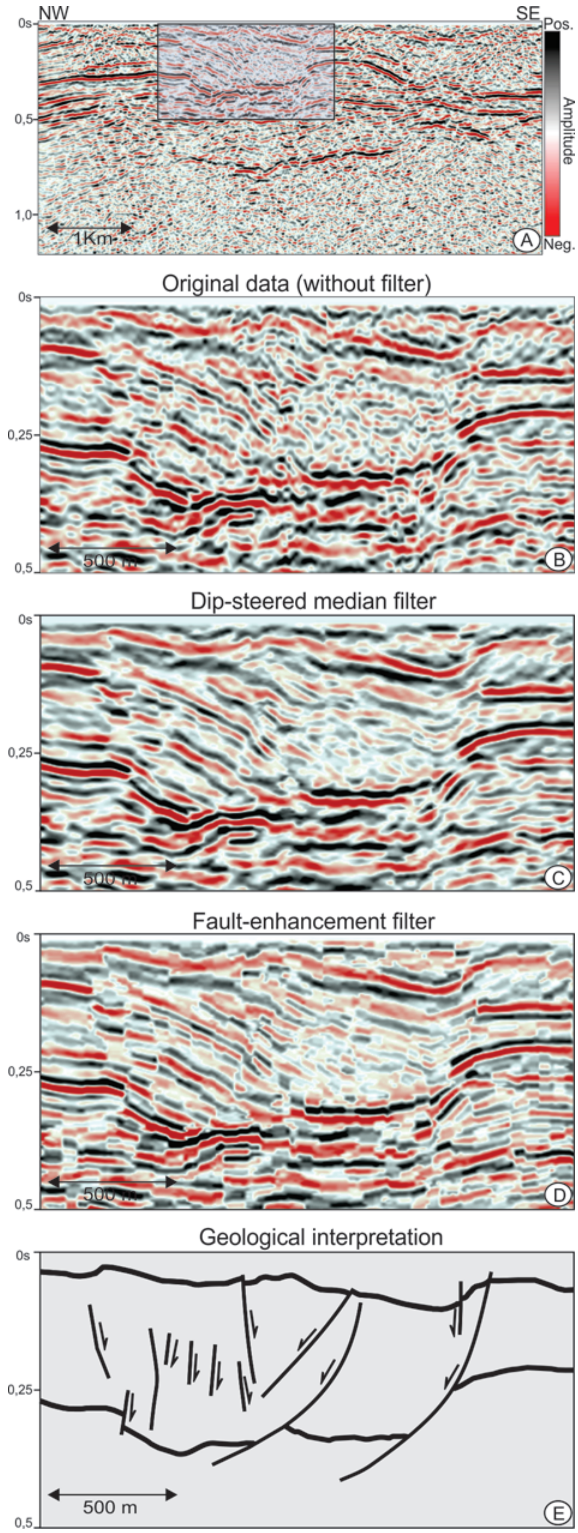

Figure 9 – Inline 304 shows the original data without filters (A) and (B); while (C) and (D) show the data treated with dip-steered median filter and fault-enhancement filter respectively, showing the improvement in the continuity of the reflections and enhancement of faults, when compared with the original data and geological interpretation in (E).

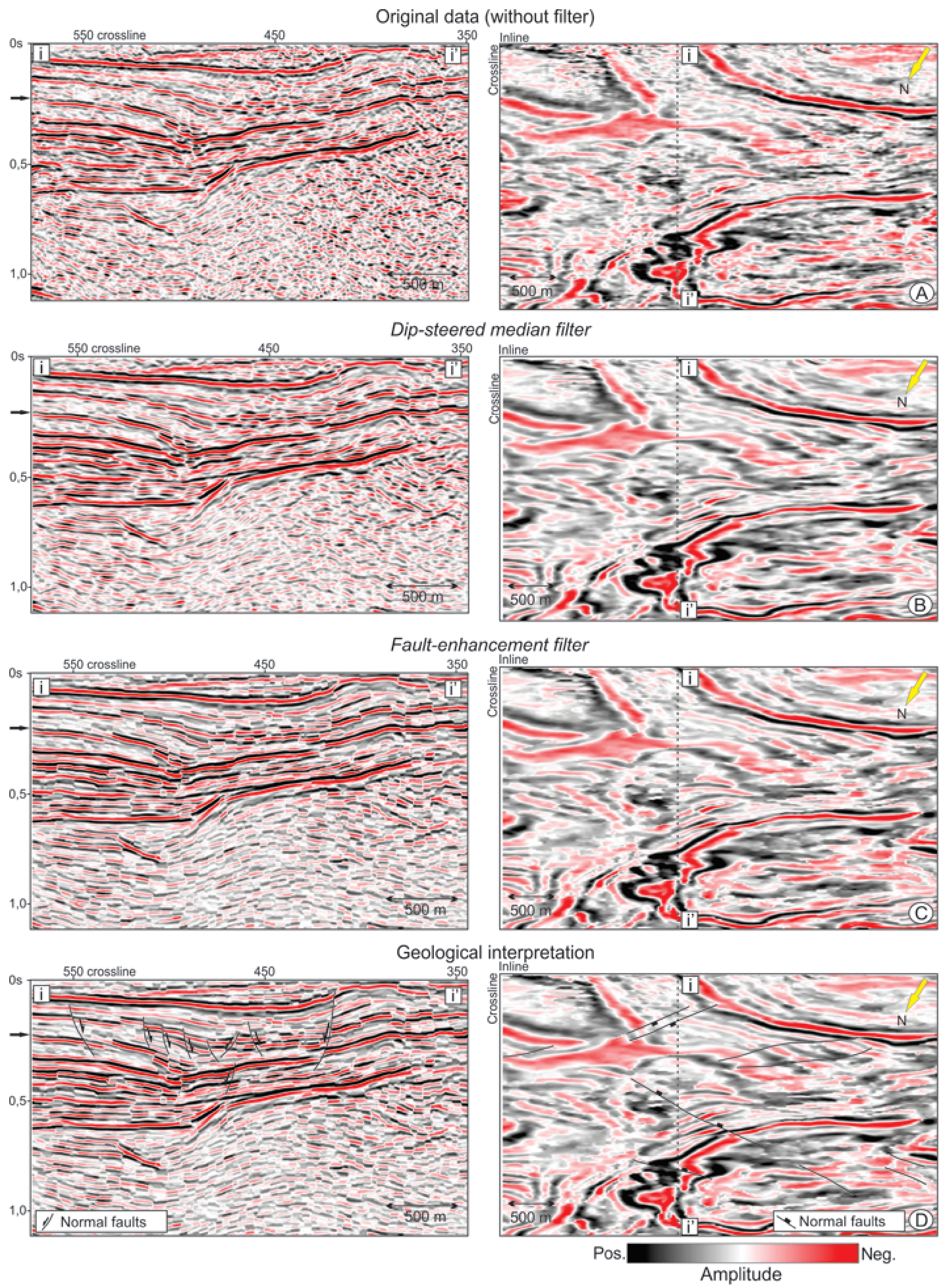

Figure 10 – Inline 59 and timeslice in 224 ms show the original data without filter (A); (B) using the dip-steered median filter showing the removal of the random noise; (C) using the fault-enhancement filter to enhance fault traces, especially small-scale faults and (D) geological interpretation of some faults.

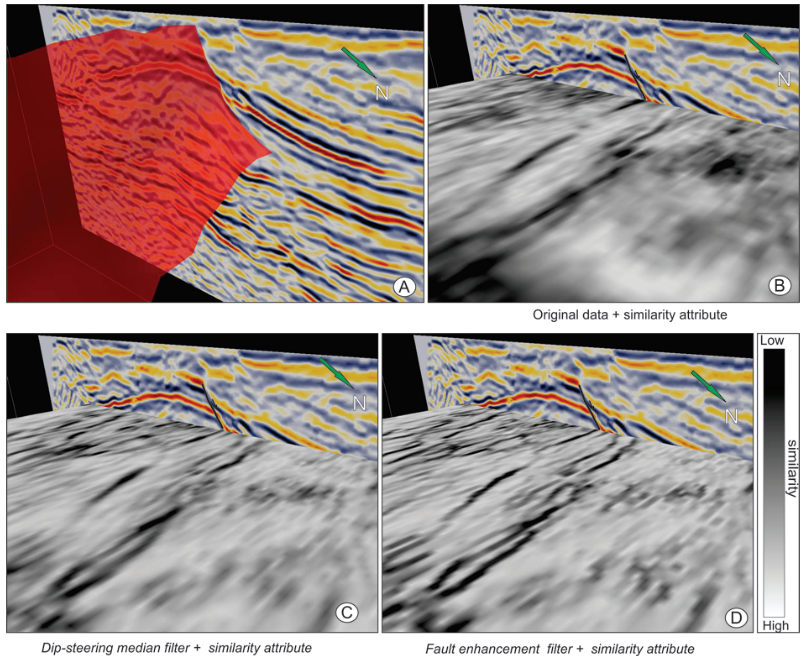

Figure 11 – Tridimensional interpretation of the fault (A) and using the similarity attribute (B, C and D) showing enhanced faults in timeslice, in the original data (A) and using the filters, dip-steered median (C) and fault-enhancement (D). Timeslice in 255 ms and inline 255.

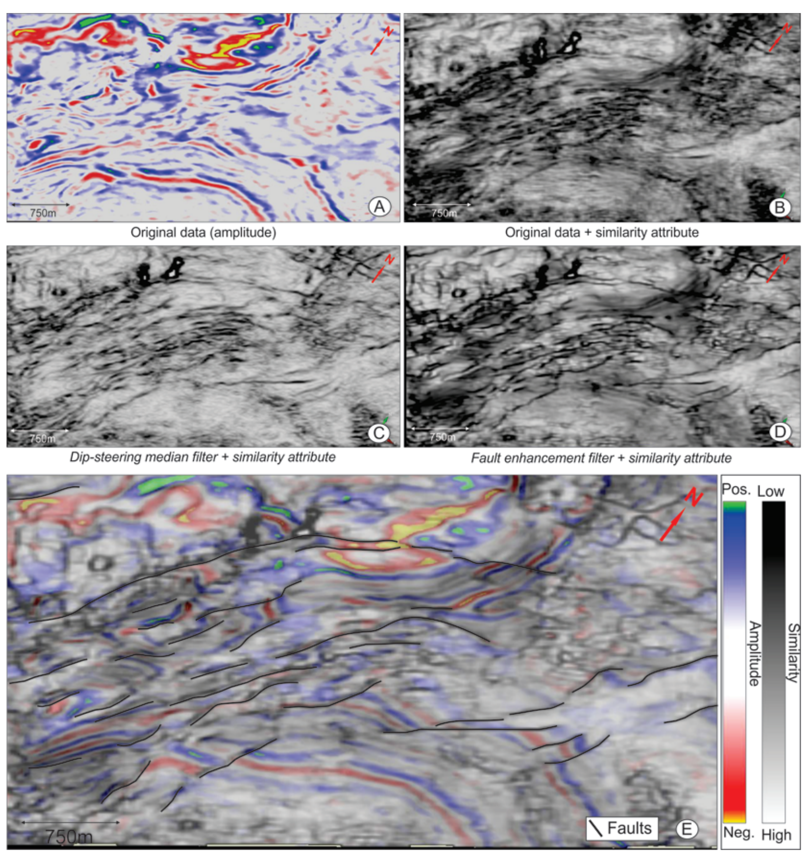

Figure 12 – Timeslice in 192 ms of the original data in amplitude (A) and using the similarity attribute (B, C and D) showing enhanced faults, with original data (B) and using the filters, dip-steered median (C) fault-enhancement (D). (E) Shows the overlay of the data in amplitude over the similarity attribute from the fault-enhancement filter with the direct relationship of discontinuities enhanced by the similarity attribute.

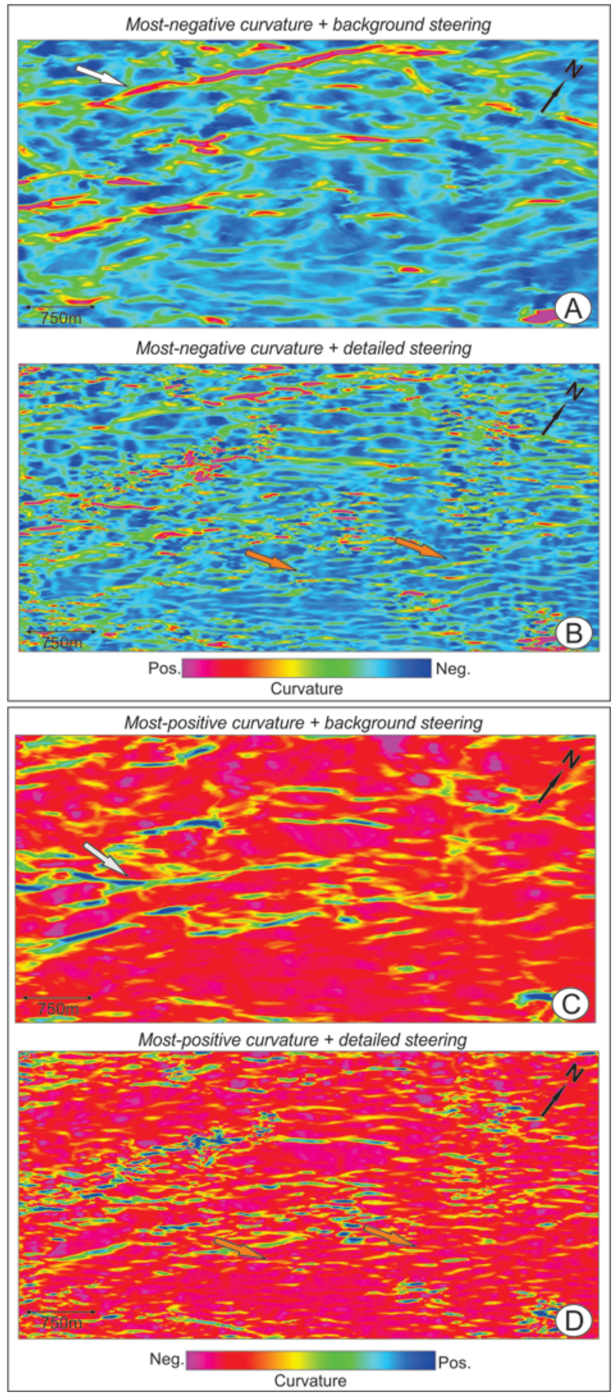

Figure 13 – Most-positive (A and B) and most-negative (C and D) curvature attributes in timeslice 192 ms. A and C illustrate the use of background steering enhancing the regional curvatures (white arrow). B and D show the use of detailed steering enhancing small-scale curvatures (orange arrow).

The application of curvature on the mapped horizon, as well as, on top of Membro Ibura (Fig. 14) and on timeslice (Figs. 13 and 14) allowed identifying the trends of faults predominantly NE, consistent with the direction of the regional structuring of Sergipe-Alagoas Basin. The attributes of the more positive and more negative curvature, in some cases, show the direct relationship with the fault geometry, as observed by the fault interpreted in the inline 255 (Fig. 11A) and the response of the curvature attribute on the horizon of the top of Membro Ibura in Figure 14.

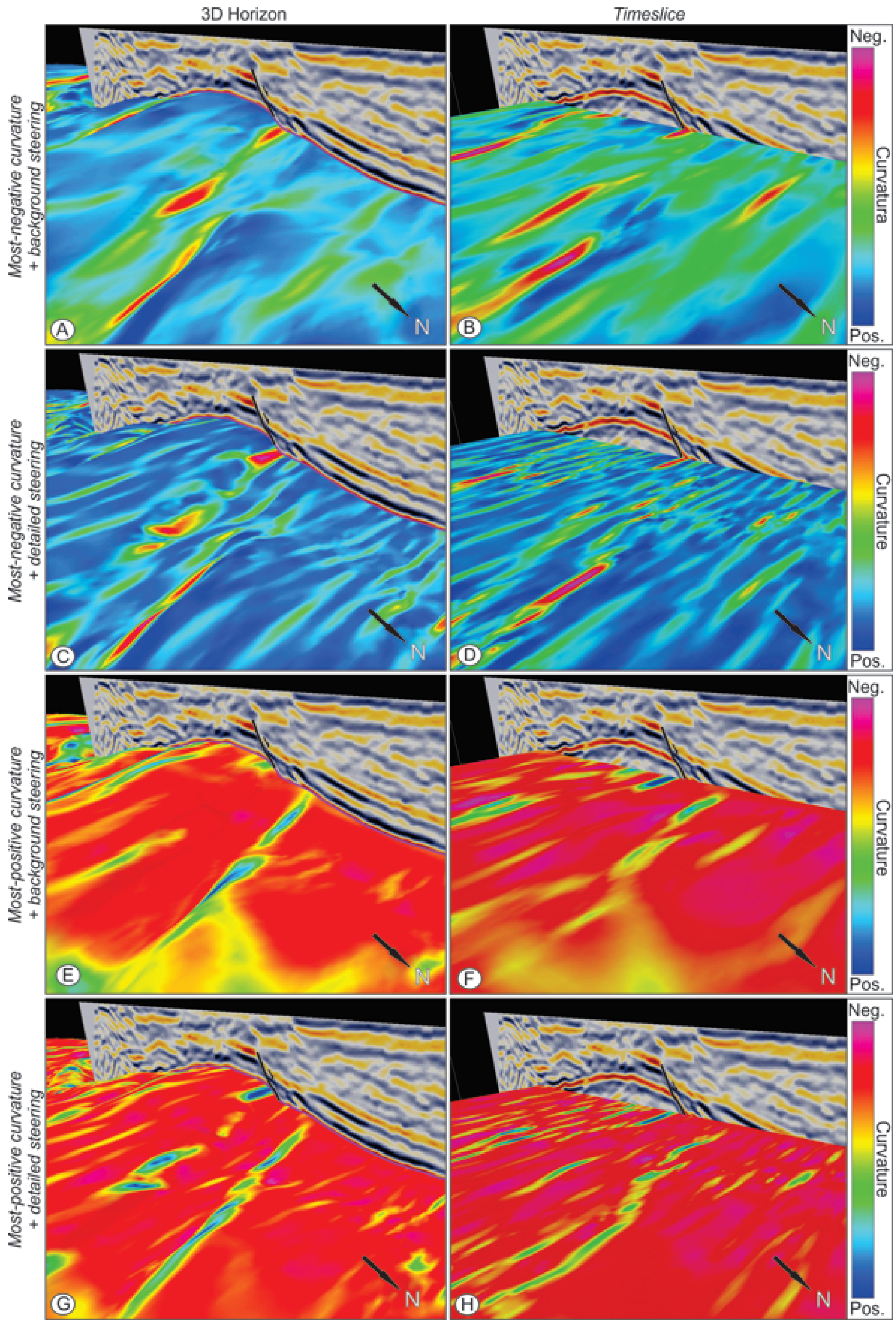

Figure 14 – The horizon of the top of Membro Ibura (A, C, E and G) and timeslice in 255 ms (B, D, F and H). The most-negative curvature (A, B, C and D) and most-positive curvature (E, F, G and H) attributes enhancing the flexures caused by faulting. Curvature attribute (A, B, E and F) using background steering enhancing wider curvatures and (C, D, G and H) using detailed steering enhancing narrower and less continuous curvatures.

The curvature attributes were compared to the similarity attributes of the fault-enhancement filter, in the timeslice 192 ms as shown in Figures 12 and 13, in order to visualize the direct relationship of the curvatures with the discontinuities enhanced with similarity (Figs. 15 and 16). This relationship showed that the curvatures are governed by the faults and fractures in the Sirizinho field. The curvature created with the detailed steering cube (Figs. 15B and 16B) showed a greater relation of both positive

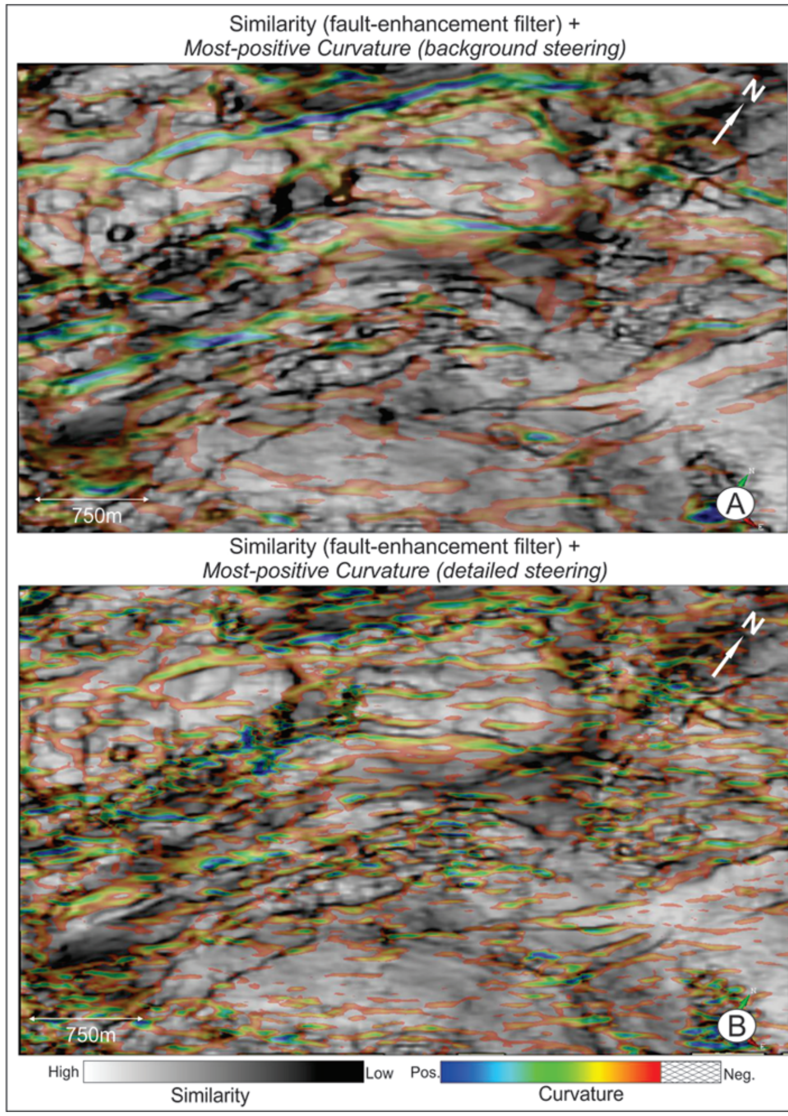

Figure 15 – Overlay of the similarity attribute using the fault-enhancement filter in the most-positive curvature. (A) Background steering cube and (B) detailed steering cube showing the relationship between the curvatures and discontinuities. Timeslice in 192 ms.

and negative curvatures with the discontinuities, allowing to infer the direction of the dips according to curvature positions. It is expected that negative curvatures represent the fault ceiling and that positive curvatures represent the fault floor (in the context of typical normal faulting), assuming that the layers close to the faults display drag feature.

CONCLUSIONS

The methodology allowed removing random noise using the dip-steered median filter, enhancing the faults using the fault-enhancement filter, improving visualization and fault and fracture continuity using the similarity and curvature attributes.

Using the steering cubes in the attributes enhanced the more regional (background steering) and local (detailed steering) curvatures of the seismic data while it was possible to correlate the curvatures directly with the discontinuities obtained with the similarity attribute, from the fault-enhancement filter, enabling to observe fault orientation and density in the data.

The use of the fault-enhancement filter enhanced the faults and fractures. However, caution is advised when using this filter since it can generate artifacts in some cases.

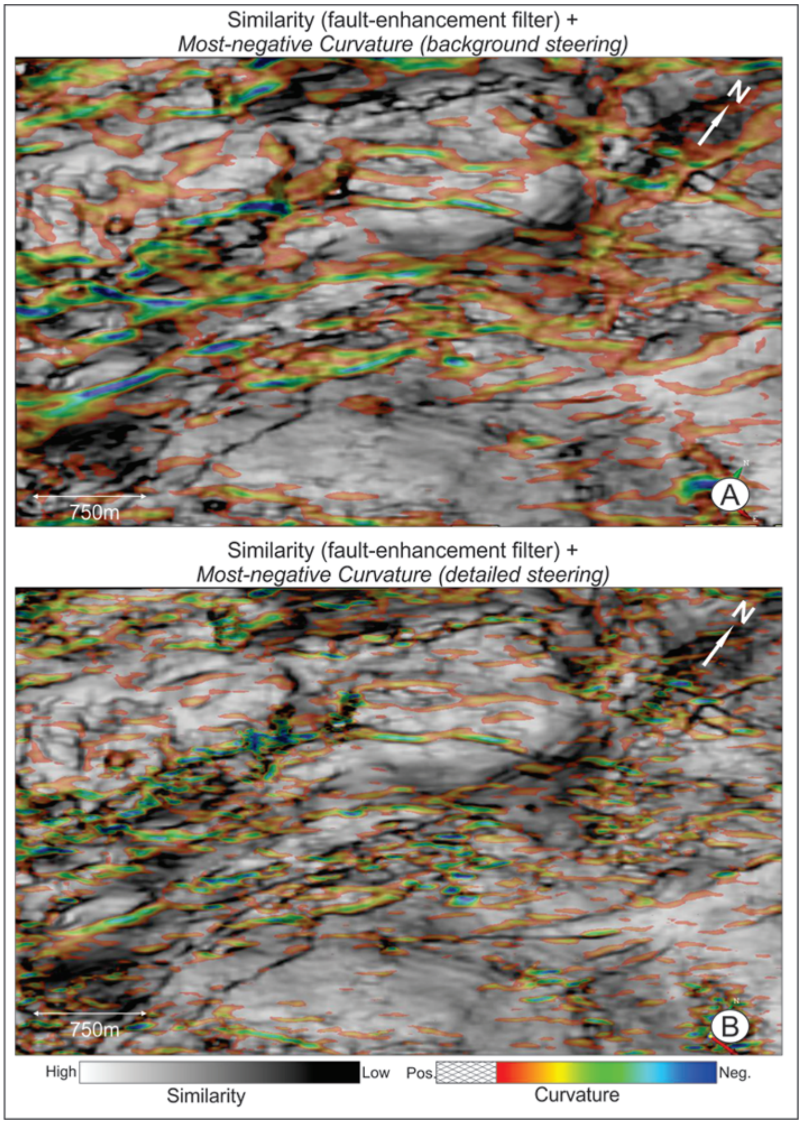

Figure 16 – Overlay of the similarity attribute using the fault-enhancement filter in the most-negative curvature. (A) Background steering cube and (B) detailed steering cube showing the relationship between the curvatures and discontinuities. Timeslice in 192 ms.

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