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Seismic Attributes and Meta-Attributes in Reflection Data Using Expert Software

Atributos e meta-atributos sísmicos em dados de reflexão a partir do uso de software especialista

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Abstract: This study presents the analysis of two distinct seismic sections processed with the objective of generating attributes and meta-attributes capable of effectively enhancing geological features associated with elements and processes of the oil system, which are directly linked to hydrocarbon accumulations. Using the seismic interpretation software OpendTect, three attributes and three meta-attributes were generated following a predefined workflow. Seismic interpretation of the data enabled the identification of various features of both structural and stratigraphic nature, which may serve as geological traps or migration pathways, as well as prominent geological unconformities. Comparatively, meta-attributes proved more effective than individual attributes by allowing the enhancement of multiple features within a single image that previously required separate visualizations. The supervised and technically grounded application of these processes facilitates the generation of images that support the reduction of exploratory risk in hydrocarbon prospecting.

Keywords: attributes; meta-attributes; reflection seismic

Resumo: O presente trabalho apresenta a análise de duas seções sísmicas distintas processadas com o intuito de gerar atributos e meta-atributos eficientes ao realce de feições geológicas correlatas aos elementos e processos do sistema petrolífero, estes diretamente ligados a acumulações de hidrocarbonetos. A partir do software de interpretação sísmica OpendTect, foram gerados três atributos e três meta-atributos segundo fluxo de trabalho pré-determinado. Com a interpretação sísmica dos dados, foi possível identificar uma série de feições, tanto de cunho estrutural quanto estratigráfico, que podem servir como armadilhas geológicas ou rotas de migração, além de discordâncias geológicas marcantes. De forma comparativa, os meta-atributos se apresentaram mais úteis do que os atributos por permitir o realce, em uma mesma imagem, de feições que antes eram visualizadas em imagens separadas. A execução destes processos de forma supervisionada, tecnicamente embasada, permite gerar imagens que auxiliam na minimização do risco exploratório na pesquisa de hidrocarbonetos.

Palavras-chave: atributos; meta-atributos; sísmica de reflexão

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1. Introduction

In today's society, the hydrocarbon exploration and production industry performs as one of the main drivers of technological and economic developments worldwide. This sector encompasses various facets of scientific knowledge in fields ranging from the exploration of this mineral resource to the manufacturing of refined products used daily in many different areas of activity. Due to the fact that hydrocarbon reserves are located in the subsurface, it is necessary to use investigative methods capable of efficiently and cost-effectively locating them. This specific stage, known as the exploratory phase, involves the participation of geoscience areas such as geophysics and geology.

Among these, exploration geophysics is a science that employs indirect investigation methods, sometimes using sensors placed in the subsurface, aiming at the non-invasive imaging of natural reservoirs. Generally, these methods include measurements of physical properties such as electrical resistivity, magnetism, gravity, acoustic impedance and so on. Regarding hydrocarbon exploration, the most widely used method is seismic reflection, as it provides a high-definition image of subsurface geological structures favorable to hydrocarbon accumulation with a good cost-benefit ratio in terms of depth investigation, as well as horizontal and vertical seismic resolution (Thomas, 2001). This method can be divided into three stages that must be integrated and correlated with the geological knowledge of the area, and are called: acquisition, processing, and interpretation. The present work focuses on the processing (specifically the post-stack phase) and interpretation stages working on the analysis of the seismic signal aimed at generating various attributes and meta-attributes based on the analysis of two marine seismic sections.

In general, seismic attributes can be used to enhance geophysical-geological features of interest and can be described as “any information obtained from seismic data, either by direct measurements or by logical reasoning or experience” (Taner, 2001). A meta-attribute, in turn, refers to the combination of two or more attributes. The main objective of this study was to enhance specific features using the specialist software focused on seismic interpretation, open-source licensed, called OpendTect (by dGB Earth Sciences), determining workflows for generating attributes and meta-attributes suitable for emphasizing geophysical-geological features that indicate characteristics of elements and/or processes of the petroleum system. This information denotes important characteristics to, for example, mitigate exploratory risk in hydrocarbon exploration.

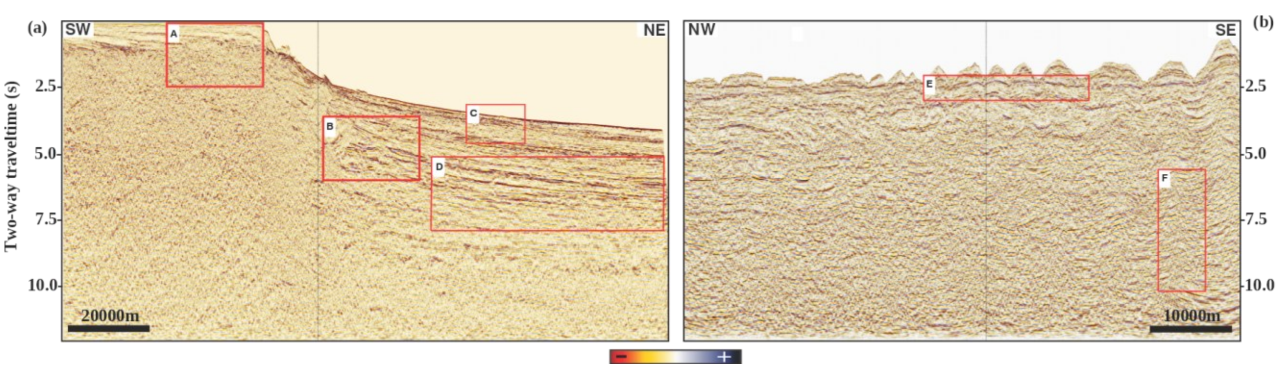

Figure 1 – Amplitude data of marine seismic sections 1 (a) and 2 (b) with details of areas A, B, C, D, E, and F, where geological features of interest were identified (interpreted in subsequent figures). Further details in the text.
Source: Made by the author (2025).

2. Methodology

The seismic reflection method consists of investigating the subsurface through the propagation of artificially generated seismic waves, which can be produced by explosive sources or vibroseis in land acquisitions, or by air guns in marine acquisitions. In seismic reflection, the waves generated by the sources propagate through the geological substrate and undergo reflection upon encountering interfaces that separate layers with contrasting impedances. Impedance is a layer property determined by the product of the medium's density and the propagation velocity of the compressional wave within it, in our case treated as acoustic impedance. The greater the impedance contrast, the higher the magnitude of the interface property called the reflection coefficient, and proportionally, the greater the reflected energy. The reflected waves are captured by receivers called geophones on land and hydrophones at sea. These receivers are positioned on or near the surface and record seismic responses, which are stored as wave amplitudes over time intervals predefined by equipment called seismographs.

Seismic processing aims to transform field-acquired data into an image as faithful as possible to the local geological reality. To achieve this, various mathematical algorithms are employed to, among other goals, improve the signal-to-noise ratio and enhance the vertical and horizontal resolutions of the data, highlighting geological features of interest. The seismic processing workflow can be organized according to the geological context in which the data were obtained, with differences in flowcharts for land and marine data, as well as variations in processing step parameterizations based on the data's specificities. The seismic data known as "stacked" (and migrated) are already useful for interpretative work. Additionally, further processes may be performed at the end to improve the resulting seismic image.

Interpretation is the stage where processed seismic data are correlated with the existing geological framework to attempt to build a representative model of the study area. Seismic interpretation can be divided, for example, into structural and stratigraphic. Structural interpretation seeks to identify geological structures representing the geometry of faults, folds, fractures, among other structural elements. Stratigraphic interpretation, on the other hand, relates to understanding the depositional processes and their genetic and chronological relations throughout geological time. Seismic interpretation often presents itself as a highly complex process since the professional's experience (as occurs in acquisition and processing stage) may result in ambiguities whereby different interpretative outcomes may be plausible or consistent with the same data. Therefore, it is always important to consider additional data beyond seismic interpretation, such as well information or pre-existing studies in the area, to obtain greater information reliability and minimize exploratory risk.

Taner (2001) describes seismic attributes as "any information obtained from seismic data." Seismic attributes can be described as quantitative measures of seismic characteristics that may relate to geological features of interest, being widely used in the oil & gas industry for identifying and characterizing hydrocarbon reservoirs, for example.

Over time, several classifications of seismic attributes have been proposed. This work will use the classification proposed by Brown (2004), which generally classifies attributes based on informations about time, frequency, amplitude, and attenuation, dividing each classification into pre- and post-stack, followed by several other more specific attribute classes. According to Brown (2011), attributes derived from seismic data can provide structural information in the subsurface, while amplitude attributes can be used to obtain stratigraphic and more reservoir-specific information; frequency and attenuation attributes can provide stratigraphic and permeability-related information, respectively.

In the context of the seismic attributes used here, the following can be cited:

(a) Similarity: as the name suggests, returns the similarities between seismic traces within a predefined time window. This attribute expresses how similar a trace is to others, represented on a scale from 0 to 1, where 1 indicates total similarity between traces and 0 indicates no similarity (Brouwer and Huck, 2011). The attribute provides excellent enhancement of structural features in seismic data, such as faults and fractures, and is also useful for identifying geometry changes related to stratigraphy. According to Fontes (2018), in similarity, trace samples can be considered components of a vector in a hyperspace and can be defined according to their own distances;

(b) Energy: calculates the quadratic sum of sample values in a predefined time window, divided by the number of samples in that window. Thus, the energy attribute is a measure proportional to reflectivity, so the higher the energy, the higher the amplitude (ALBUQUERQUE, 2018). This attribute can provide information on lateral variations in seismic events, detection of gas chimneys, characterization of rock acoustic properties, and identification of layer thickness;

(c) Pseudo relief: originally described as "Amplitude Volume Technique (TecVA)" (BULHÕES & AMORIM, 2005), this attribute computes the root mean square (RMS) within a sliding time window along the data. According to Bulhões & Amorim (2005), calculating this attribute requires the concept of the elementary seismic layer, which is the layer with the minimum thickness the seismic data can identify, so that the definition of the top and base of this seismic layer composes the time window used to define the number of samples for calculating the moving average for the seismic trace. The attribute is formed from two operations: first, the RMS amplitude or absolute trace value is calculated to obtain the instantaneous amplitude, based on the window defined by two times set by the elementary seismic layer concept; the second operation involves applying the Hilbert transform with the objective of rotating the phase of the RMS amplitude trace.

Several tests were performed with different attributes using the OpendTect software, comparing input and output data at each iteration and selecting those most suitable for each case. Among the attributes, three were chosen (energy, pseudo relief, and similarity), in addition to generating three meta-attributes by weighting and combining these with the original amplitude data. This process was executed using the mathematics function in OpendTect, weighting via an algorithm that merges them to create representative equations that improved the strengths of the individual attributes. All parameters used in defining the attributes were computed through a series of tests involving both specific intention weightings and trial-and-error strategies. The weightings that yielded the best results, both in using attributes and generating meta-attributes, can be seen in Table 1:

Table 1 – Parameters used in simple attributes and equations used in meta-attributes.

ATTRIBUTES					
Attribute name	Time window (ms)	Compute Gradient	Extension	Stepout	Steering
Amplitude	- 4 : + 4	--	--	--	--
Energy	- 8 : + 8	Yes	--	--	--
Similarity	- 8 : + 8	--	All directions	4	No
Pseudo-relief	- 1 : + 1	--	--	--	--
META-ATTRIBUTES					
Meta-attribute 1	Meta 1 = Amplitude + sqrt(Pseudo-relief)				
Meta-attribute 2	Meta 2 = Amplitude^Energy				
Meta-attribute 3	Meta 3 = Amplitude/(Similarity^3)				

Source: Made by the author (2025).

3. Results

The research results involve the phases of attribute generation and, subsequently, the combination and weighting in the production of meta-attributes. In this case:

3.1 – Amplitude data

In this attribute (Figure 1), the seismic sections were divided into areas where geological features of interest were identified. In this context, section 1 (Figure 1a) contains four areas designated A, B, C, and D. Area A (Figures 2a and 2a') contains a sequence of normal faulting near the slope break. Area B (Figures 2b and 2b') contains three features of interest labeled 1, 2, and 3, which are a reverse fault, a normal fault, and a pinch-out , respectively. Area C (Figures 2c and 2c') also presents a pinch-out , and area D (Figures 2d and 2d') shows a series of planar-parallel reflectors, which can be seen in Figures 16 and 18, respectively. In section 2 (see Figure 1b), two areas labeled E and F are highlighted. Due to a low signal-to-noise ratio, it was not possible to identify many geological features with good seismic character. However, in area E, sinuous reflectors can be visualized, which are enhanced through the generated attributes and meta-attributes described later. Additionally, in area F, several hyperbolas are noticeable, which were also enhanced by a meta-attribute. These hyperbolas may be significant in the geological context both as signals, potentially associated with features of interest, but they may also result from inadequate or inefficient seismic processing, thus considered noise in this case. Therefore, the identification and enhancement of these features are important from the standpoint of interpretative ambiguity.

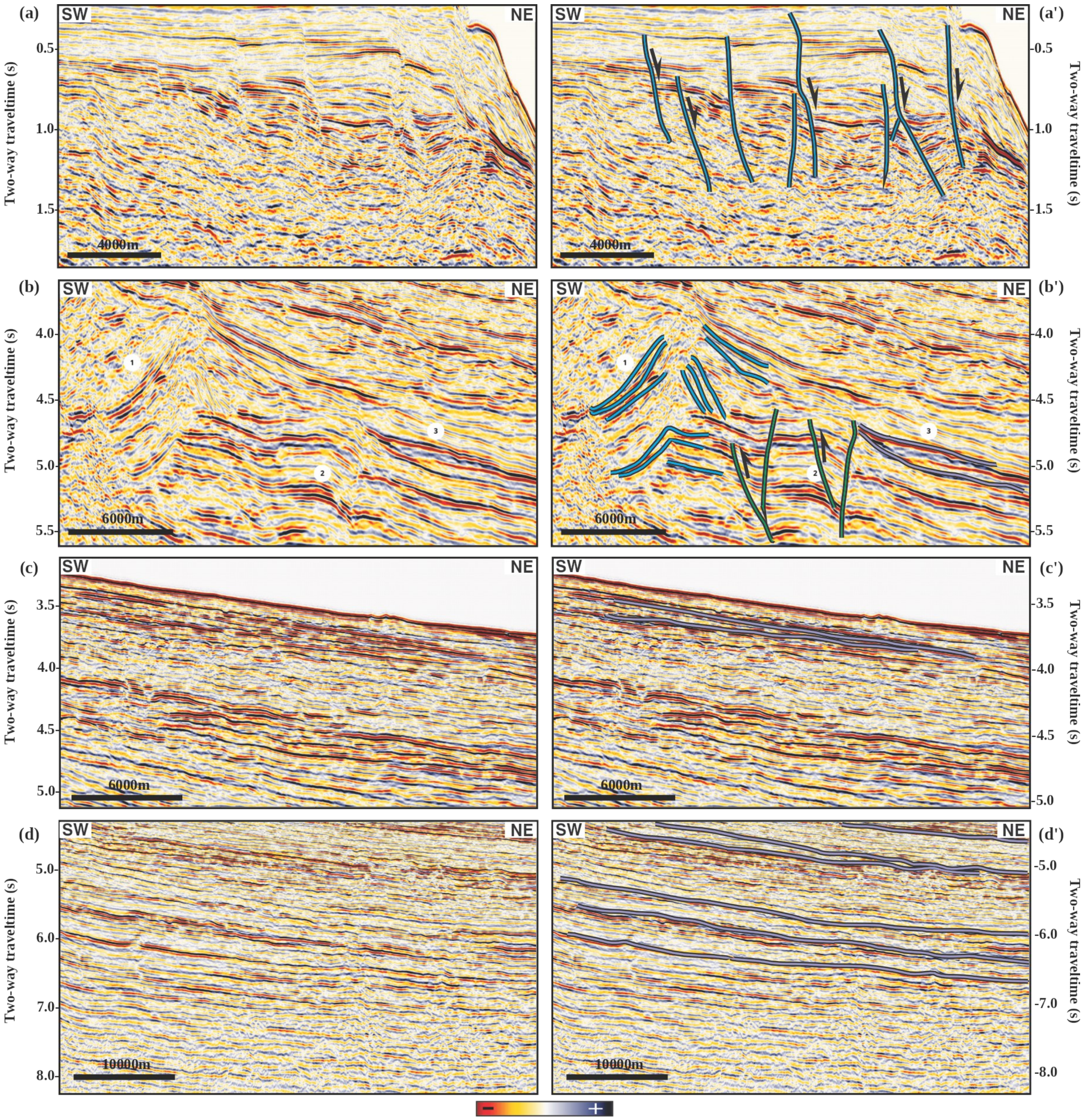

Figure 2 – Detail of rectangles A, B, C, and D highlighted in section 1 (Figure 1a), corresponding respectively to pairs "(a)/(a'), (b)/(b'), (c)/(c'), and (d)/(d')", indicating the uninterpreted sections (left column) and interpreted sections (right column). Numbers 1, 2, and 3 in (b)/(b') mark features of interest described in the text. Blue lines in (a') and (b') represent normal faults; the green line in (b') indicates a reverse/inverse fault; lilac lines in (c') and (d') indicate wedging features.
Source: Made by the author (2025).

3.2 – Pseudo-relief and Meta-attribute 1

The highlights of the pseudo relief attribute and meta-attribute 1 lie in the enhancement of features present in details B and C of section 1, as well as in the sinuous reflectors of section 2, which can be observed in Figures 3 and 4. It is possible to see that high-energy reflectors are already well emphasized in the pseudo relief attribute, allowing features such as the pinch-outs in areas B and C to become more prominent, facilitating their visualization. However, as observed in Figure 3, features such as the reverse fault (1) and normal fault (2) are faded. Satisfactorily, when comparing the pseudo relief attribute with meta-attribute 1 (amplitude + sqrt(pseudo relief)), this deficiency is corrected, as the meta-attribute recovers information from adjacent reflectors, making it possible to enhance both stratigraphic features and structural features. Similarly, in the detail of area C (Figures 3c, 3c’, 3d, and 3d’), the improvement in reflector continuity provided by meta-attribute 1 allows for better definition of the thinning of reflectors characterizing the pinch-out.

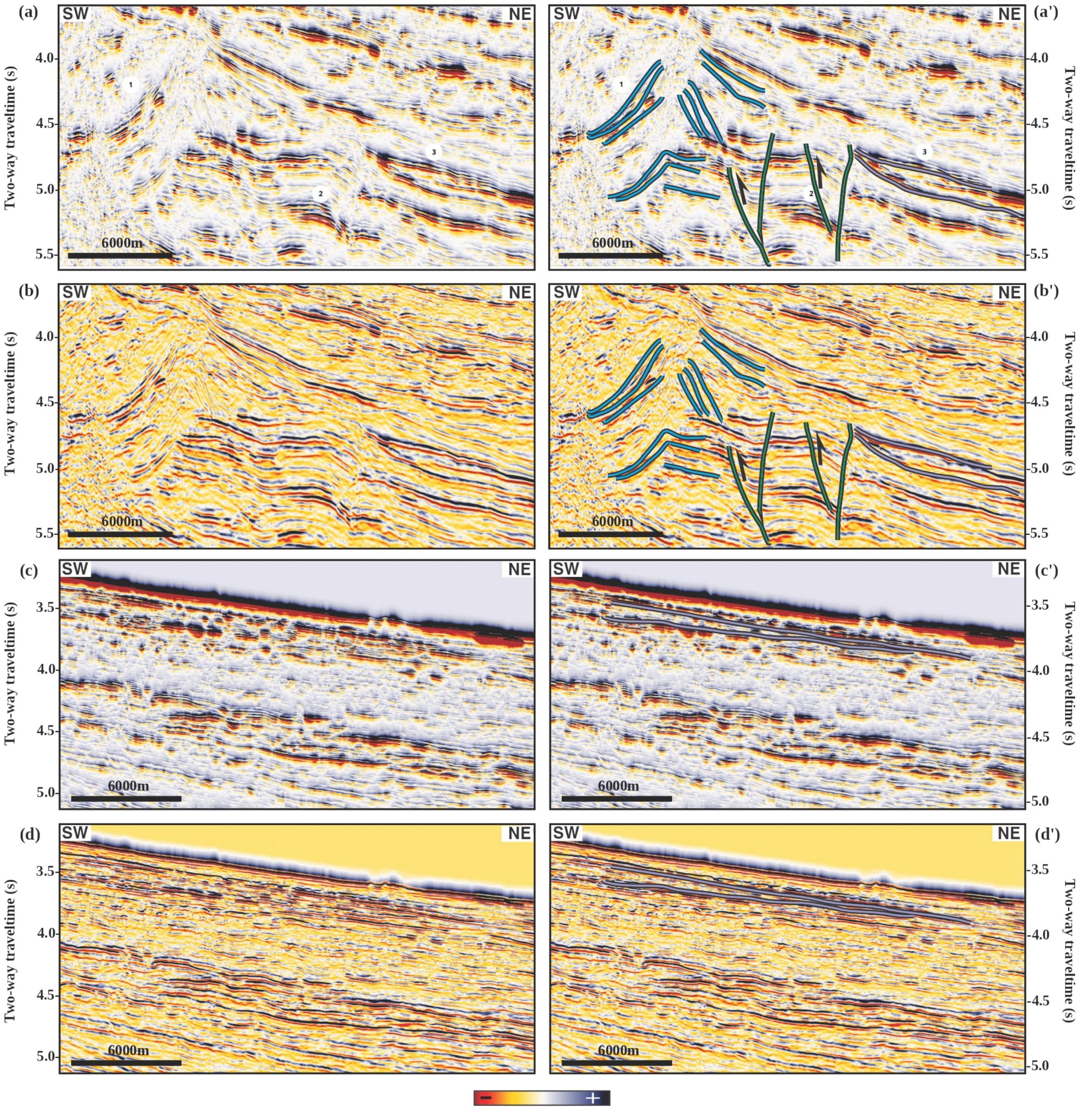

Figure 3 – Detail of rectangles B and C highlighted in section 1 (see amplitude data in Figure 1a). Pairs (a)/(a’) and (b)/(b’) illustrate, respectively, the pseudo relief attribute and meta-attribute 1 applied to rectangle B. Similarly, pairs (c)/(c’) and (d)/(d’) show the application of these attributes to rectangle C. The left column represents uninterpreted data; the right column, marked with (‘), shows interpreted sections. Blue lines in (a’) and (b’) represent normal faults; the green line in (b’) indicates a reverse/inverse fault; lilac lines in (c’) and (d’) indicate wedging features. Source: Made by the author (2025).

Regarding section 2 (see Figure 1b), the pseudo-relief attribute (Figures 4a and 4a') was effective in highlighting the sinuous reflectors in area E, while meta-attribute 1 not only enhanced these features further but also better defined the "smiles" of hyperbolas identified as noise (area F) present in the data, as can be seen in Figure 4.

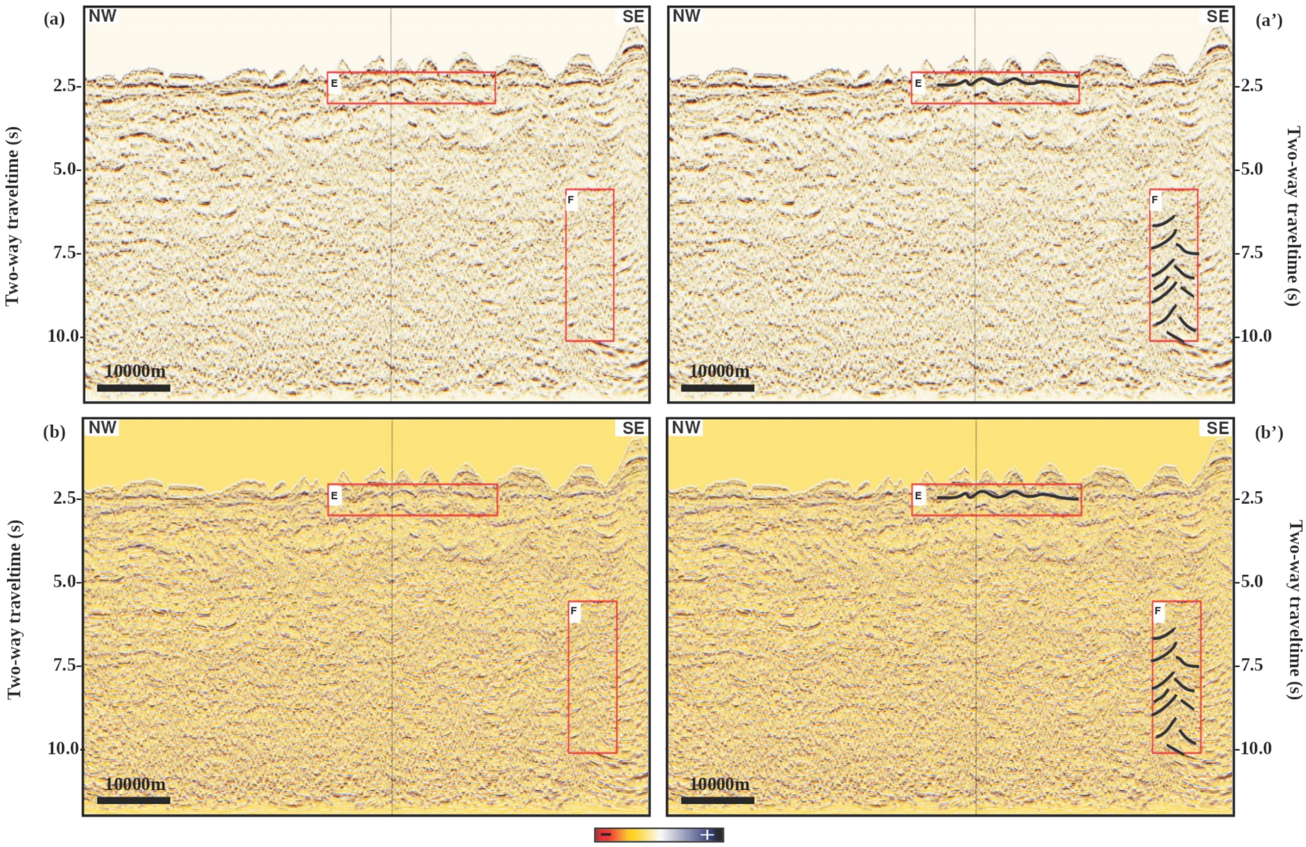

Figure 4 – Application of the pseudo relief attribute (pair (a)/(a')) and meta-attribute 1 (pair (b)/(b')) to seismic line 2 (see original data in Figure 1b). The left column represents uninterpreted data; the right column, marked with ('), shows interpreted sections. Black lines in area E represent undulating reflectors, likely caused by the propagation of the oceanic substrate sinuosity, while in area F they indicate hyperbolic features interpreted as noise.
Source: Made by the author (2025).

3.3 – Energy and Meta-attribute 2

The highlights of the energy attribute and meta-attribute 2 are found in the rectangles of areas B and D of seismic section 1 (Figure 5). Similar to the pseudo-relief attribute, the energy attribute (Figures 5a, 5a') also enhances high energy reflectors by simultaneously muting their surroundings while emphasizing them. It is also noticeable that the pinch-out feature is satisfactorily imaged, while the reverse fault (1) and normal fault (2) remain muted. However, when using meta-attribute 2 (amplitude^energy), Figures 5b and 5b', their geometry is almost perfectly defined, allowing the majority of reflectors to be visualized individually due to increased continuity. Additionally, due to the improved visualization of reflectors enabled by meta-attribute 2, planar-parallel reflectors shown in the detail of area D (Figures 5d and 5d') can be identified, which was not possible with the energy attribute alone, as it only highlighted reflectors with higher energy (Figures 5c and 5c').

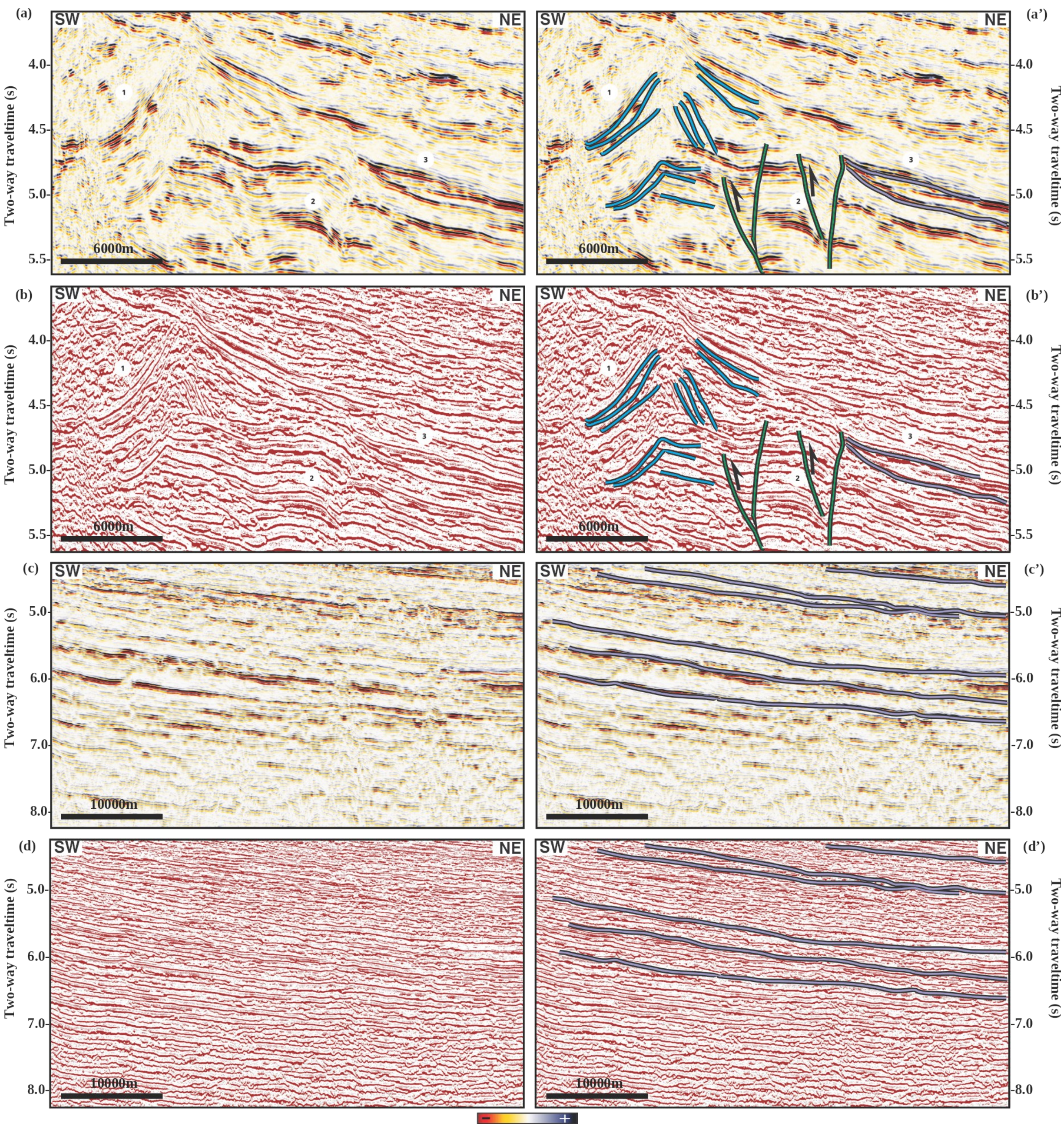

Figure 5 – Detail of rectangles B and D highlighted in section 1 (see amplitude data in Figure 1a). Pairs (a)/(a') and (b)/(b') illustrate, respectively, the energy attribute and meta-attribute 2 applied to rectangle B. Similarly, pairs (c)/(c') and (d)/(d') show the application of these attributes to rectangle D. The left column represents uninterpreted data; the right column, marked with ('), shows interpreted sections. Blue lines in (a') and (b') represent normal faults; the green line in (b') indicates a reverse/inverse fault; lilac lines in (c') and (d') indicate wedging features.
Source: Made by the author (2025).

3.4 – Similarity and Meta-attribute 3

The highlights of the similarity attribute lie in the improved visualization of features in the details of areas A and B of section 1, as well as in the visualization of hyperbolas informally known as “migration smiles” in the detail of area B of section 2 (Figure 6). Analyzing Figure 6, one can notice the significant difference between the similarity attribute and meta-attribute 3. In the similarity attribute, fault-like features are satisfactorily imaged, allowing them to be easily distinguished from other information presented by the attribute (see right column in Figure 6). However, when using meta-attribute 3 (amplitude / (similarity^3)), the reflectors intersected by these faults are clearly visualized (Figures 6b, 6b’, 6d, and 6d’), with the normal fault throw distinctly determined. Besides improving the visualization of structural features such as the faults analyzed so far, meta-attribute 3 also enhances both the pinch-out feature and the reverse fault present in area B of section 1 (Figures 6d and 6d’).

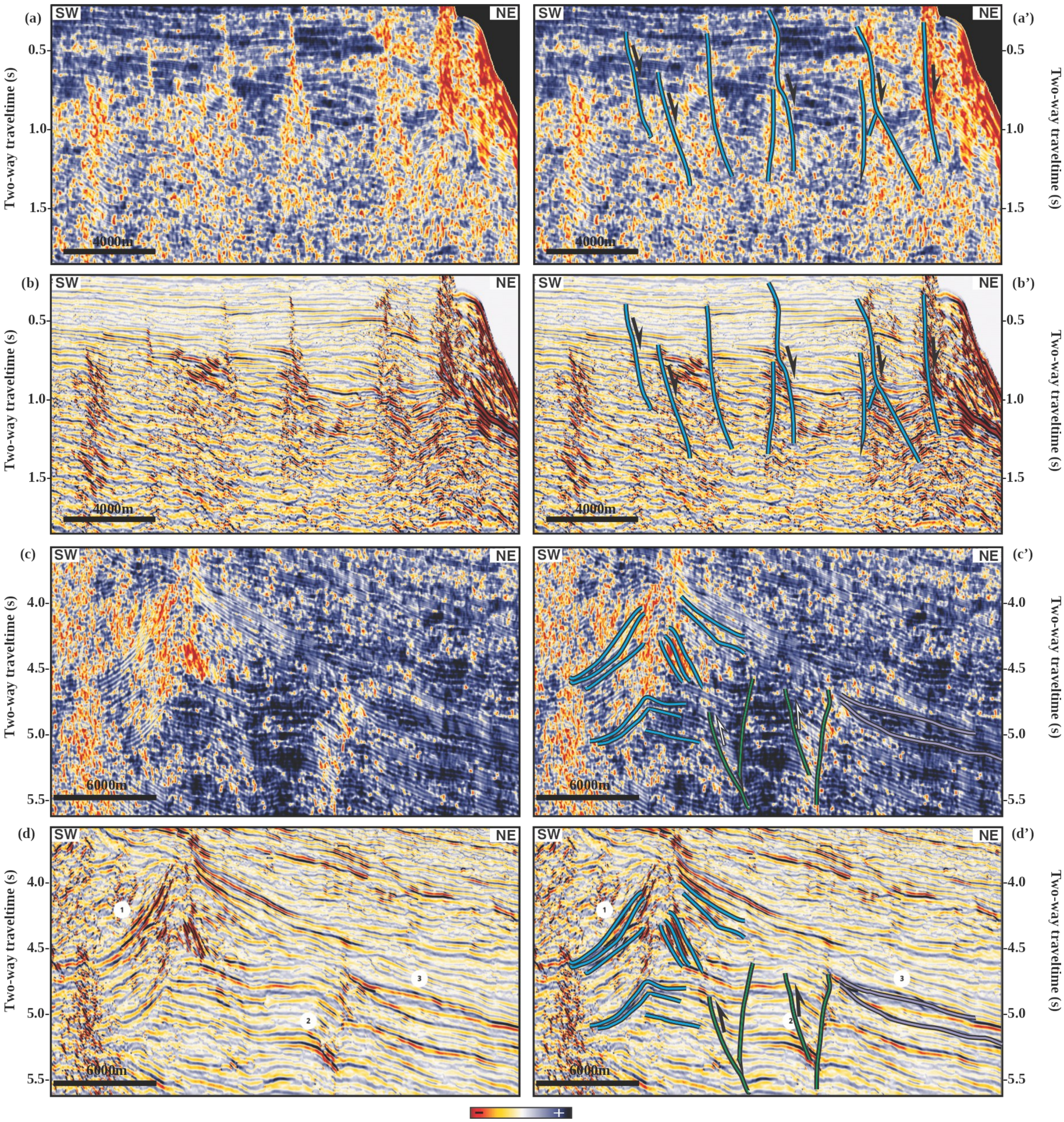

Figure 6 – Detail of rectangles A and B highlighted in section 1 (see amplitude data in Figure 1a). Pairs (a)/(a') and (b)/(b') illustrate, respectively, the similarity attribute and meta-attribute 3 applied to rectangle A. Similarly, pairs (c)/(c') and (d)/(d') show the application of these attributes to rectangle B. The left column represents uninterpreted data; the right column, marked with ('), shows interpreted sections. Blue lines in (') represent normal faults; in (c') and (d'), the green line indicates a reverse/inverse fault, and lilac lines indicate wedging features.
Source: Made by the author (2025).

Regarding section 2, meta-attribute 3 performed differently. As observed in Figure 7, the features enhanced this time are the hyperbolas interpreted as noise in the data. Enhancing noise is not entirely negative, as it allows confirming the inherent ambiguity in the interpretative process, exemplified here by the indiscrimination of features of interest. Specifically, such hyperbolas are common in data where, during processing, an inappropriate velocity field (higher than necessary) was used. This makes sense in this situation because the lateral velocity variations caused by the morphology of the oceanic substrate itself (relative highs and lows) induce sinuosity in reflectors that should not be associated with the geological context. Keeping this information in mind, together with the confirmation provided by meta-attribute 3 that the data is extremely noisy, helps reduce interpretative ambiguity.

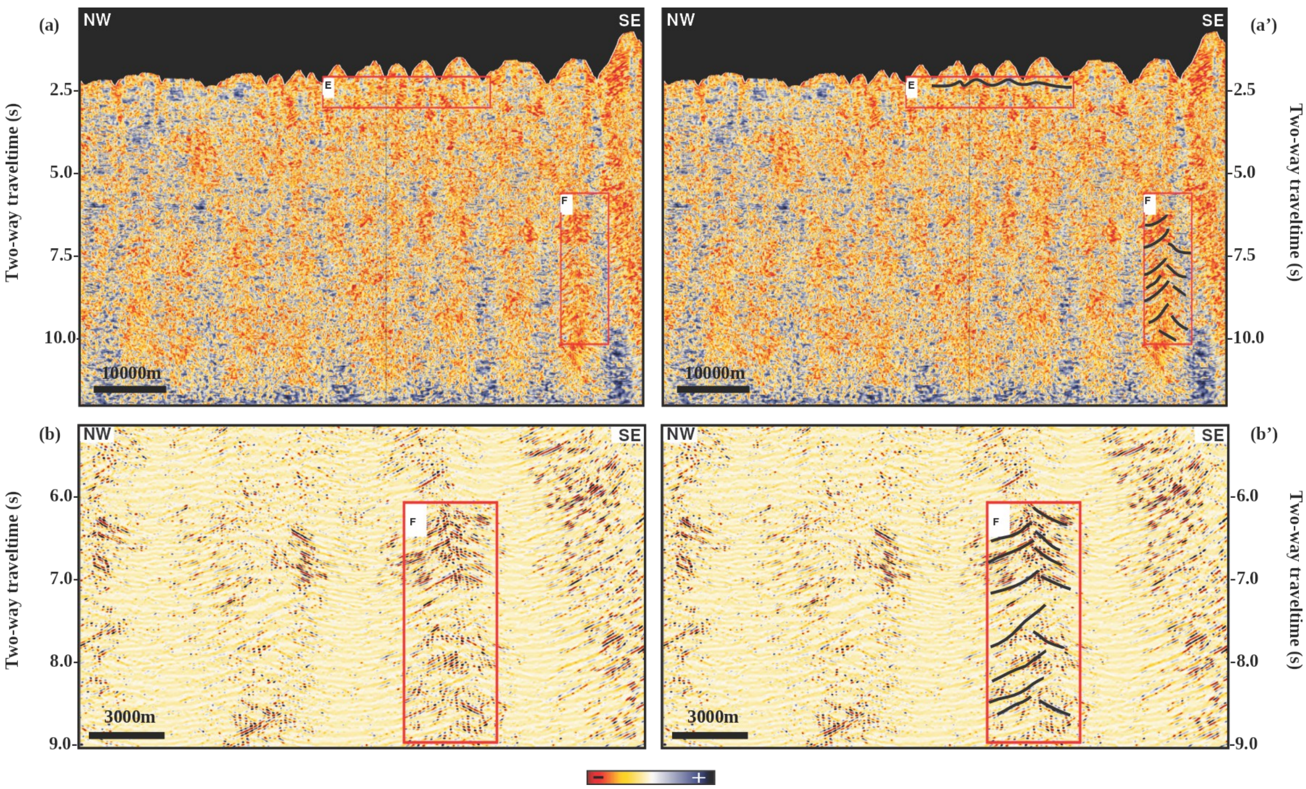

Figure 7 – Detail of rectangles E and B highlighted in section 1 (see amplitude data in Figure 1a). Pairs (a)/(a') and (b)/(b') illustrate, respectively, the similarity attribute and meta-attribute 3 applied to rectangle E. Similarly, pairs (c)/(c') and (d)/(d') show the application of these attributes to rectangle B. The left column represents uninterpreted data; the right column, marked with ('), shows interpreted sections. Blue lines in (') represent normal faults; in (c') and (d'), the green line indicates a reverse/inverse fault, and lilac lines indicate wedging features.
Source: Made by the author (2025).

4. Final considerations

Based on the work developed, some considerations can be highlighted. Firstly, the best responses, presented by the pseudo-relief attribute, were observed in areas B and C of seismic section 1 and area A of seismic section 2, where the main reflectors are emphasized, along with the attenuation of adjacent reflectors. In seismic section 2, this attribute shows similar behavior. Meanwhile, meta-attribute 1 overcomes the deficiencies presented by the pseudo-relief attribute while reinforcing other geological features of interest. The energy attribute, like the pseudo-relief, allows enhancement of some point features, such as the pinch-outs found in section 1 (in specific cases potentially acting as stratigraphic traps), the sinuous reflectors of section 2, as well as some planar-parallel reflectors with higher reflection energy present in section 1. However, it is not efficient in enhancing features such as the reverse and normal faults existing in section 1. Meta-attribute 2, on the other hand, has the capacity to delimit the vast majority of reflectors in either section analyzed, with its main characteristic being the improvement of reflector continuity. The similarity attribute proves interesting by enhancing faults present in areas A and B of seismic section 1 (in the petroleum system context, preferential fluid migration pathways) but attenuates other stratigraphic features. Meta-attribute 3 satisfactorily enhances the qualities presented by the similarity attribute while enabling visualization and definition of other features observed in seismic section 1, in addition to allowing the definition of the apparent throw of normal faults by highlighting adjacent reflectors, acting as kinematic markers. Satisfactorily, this attribute also helps mitigate interpretative ambiguity in section 2 by enhancing hyperbolas commonly referred to as migration smiles. Finally, the efficiency of using specialized software for enhancing geological features of interest is evident, especially regarding the improvement of seismic imaging in the post-stack processing stage, culminating in the definition of elements of the petroleum system. Thus, it assists the overall interpretation process, making it possible to minimize exploratory risk in hydrocarbon exploration.

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