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Research article

Interpretation of Palaeozoic geoforms with the use of seismic attributes in a region of the Eastern Plains, Colombia

Interpretación de geoformas paleozoicas con el uso de atributos sísmicos en una localidad de los Llanos Orientales, Colombia

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Abstract

This study focused on producing maps of Palaeozoic geoforms in the subsoil of a region of the Eastern Planes basin, Colombia. The results provide novel Palaeozoic information for the study area suggesting a possible shallow marine depositional environment in the Ordovician and a slightly deeper shallow marine environment in the Cambrian. This information was obtained from the analysis of both seism stratigraphic sequences and gamma ray well logs and from the seismic interpretation of possible geological structures at depth, using a seismic cube, four 2D seismic lines and four wells. The results were complemented with the application of the seismic attributes of coherence, variance, RMS amplitude and spectral decomposition to highlight geological characteristics such as structures and lithology. The information was integrated and analyzed to generate maps of geoforms corresponding to the Middle Ordovician, Lower Ordovician and Cambrian sequences.

Keywords: Eastern Plains basin, seismic, well logs, seismic attributes, Palaeozoic geoforms.

Resumen

Este estudio se enfocó en producir mapas de geoformas paleozoicas en el subsuelo de una región de la cuenca de los Llanos Orientales de Colombia. Aportó resultados innovadores del Paleozoico para el área de estudio que sugieren un posible ambiente deposicional marino somero para el Ordovícico, y un ambiente marino somero ligeramente más profundo para el Cámbrico. Esto se obtuvo de los análisis tanto de secuencias sismoestratigráficas como de registro de pozo gamma ray, y de la interpretación sísmica de posibles estructuras geológicas en profundidad, la cual se realizó mediante el uso de un cubo sísmico, cuatro líneas sísmicas 2D y cuatro pozos. Estos resultados se complementaron con la aplicación de los atributos sísmicos de coherencia, varianza, amplitud RMS y descomposición espectral para resaltar características geológicas como estructuras y litología, con el fin

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de integrar al análisis de la información y generar mapas de geoformas correspondientes a las secuencias Ordovícico medio, Ordovícico inferior y Cámbrico.

Palabras clave: cuenca de los Llanos Orientales, sísmica, registros de pozo, atributos sísmicos, geoformas paleozoicas.

1. Introduction

Seismic exploration is a geophysical method that consists in generating elastic waves that propagate and reflect in a medium to determine the shape, composition and distribution of different lithological units at various depths (Telford et al., 1990).

This method has become an indispensable tool for obtaining information from the subsoil. In the Eastern Plains of Colombia, the The high density of information concerning the Cenozoic and Mesozoic area collected by the ANH [Agencia Nacional de Hidrocarburos] and the Universidad Nacional de Colombia is due to the hydrocarbon potential in the Eastern Plains of Colombia (Villamizar and Castillo, 2016).

Nevertheless, the Palaeozoic era has been little studied in Colombia (Suárez and Solano, 2012). Among the most relevant work is that of Martínez-González (2008), in which the characterization of different geological events of the sub-Andean basins in the Palaeozoic stands out. This project aims to contribute to these studies with different analyses of the geophysical information found (through 2D-3D seismic and well logs) in a region located southeast of the Eastern Plains basin (Figure 1). This was possible particularly because the seismic data used for this project were reprocessed to highlight elements of Palaeozoic formations in the deepest section; however, it is important to mention that the decrease in seismic resolution at greater depths made it difficult to interpret the different geological elements in detail.

This study was developed based on the interpretation of geological structures in a seismic cube, which was assessed by seismostratigraphic, electrofacial (Schlumberger, 1981) and sequential analyses of wells in the Palaeozoic section. Finally, the seismic attributes of coherence, spectral decomposition, variance and RMS amplitude were integrated into the seismic interpretation of structures (Brown, 1996), stratigraphies and lithologies (Chopra and Marfurt, 2007). As a result, the evaluation, integration and analysis allowed the generation of geoform maps with geological information on the sedimentation environments in the study area (Esquivel, 2020). Interpretations were performed for the Palaeozoic sequences corresponding to the Middle Ordovician, Lower Ordovician and Cambrian periods.

2. Geological framework

The Eastern Plains basin a low relief region located to the east of the Eastern Cordillera. It is characterized as a foreland due to its geometry and is limited by the Guaicáramo fault system to the west and by the Guyana Shield to the east.

The formation of the Eastern Plains basin results from different tectonic and sedimentary processes throughout geological time. At the beginning of the Palaeozoic, in the Cambrian period, a divergent passive margin contributed to the formation of an epicontinental basin. Due to the normal faults gene-

Figure 1. Location of the study area in the Eastern Plains basin in Colombia

rated by this event, a partial collapse occurred in which clastic and silicoclastic successions were deposited due to an increase in sea level (Cediel, 2019).

Then, at the beginning of the Ordovician, the *Caparonensis* orogeny was produced due to a retroarch accretion between Laurasia and Gondwana. During this event, high rates of subsidence, land accretions and fault inversions occurred in the previously filled partial collapse. These events caused extensive deposition of transgressive marine sequences, formed by intercalations of shales and sandstones (Cediel, 2019). During the Silurian, the process followed an extensional regime and continued a compressional regime in which the oceans began to close to form Pre-Pangea (Martínez-González, 2008).

At the end of the Devonian and the beginning of the Carboniferous, a marine transgression occurred with claystone, sandstone and limestone sediments. Subsequently, a compressional event occurred due to the *Hercynian* orogeny, which raised the sub-Andean basins and exposed them to erosive events. At the end of the Carboniferous, this same orogeny led to the assembly of Pangea due to the collision of Gondwana with Laurasia (Martínez-González, 2008).

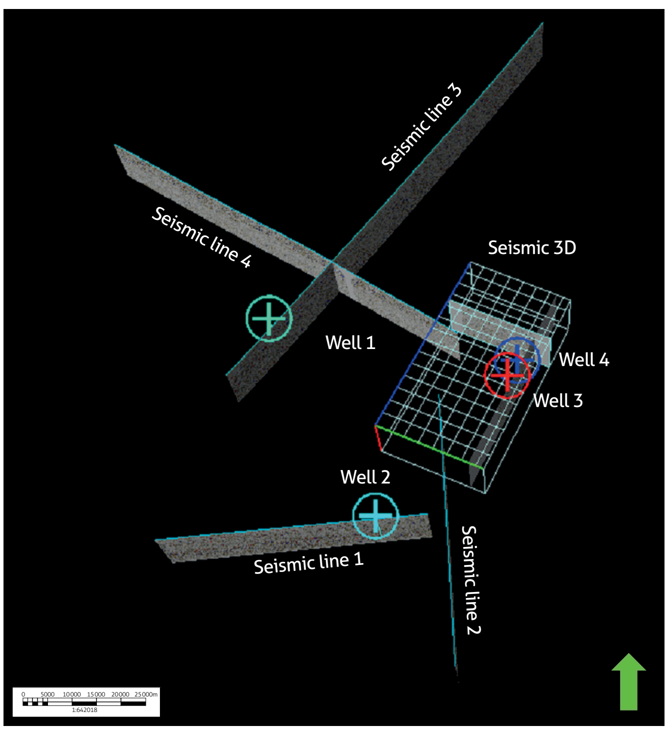


Figure 2. Distribution of 2D, 3D and well seismic information

3. Data and methods

The seismic and geophysical information used for this project was provided by the Colombian Geological Service (SGC) (Figure 2) and consisted of a) a 297 km^2 3D seismic block with *prestack time migration* (PSTM) seismic processing; b) four seismic lines (35.5 km, 77 km, 60 km and 33 km); and c) four wells with a set of basic records.

The methodology used in the present study was based on the integration of available information. Initially, a bibliographic compilation was carried out on the geology of the study area, focused on stratigraphy (Annex 1) and structural events that affected the Eastern Plains region (Ecopetrol and Beicip, 1995; Lozano and Zamora, 2014; Sarmiento, 2011). Additionally, the information available in the well reports used was analysed.

Subsequently, the geophysical data interpretation software *PETREL*, version 2017, was used to analyse the data provided (Appendix 2). The seismic and well logs were loaded into this software and correlated with synthetic seismograms following the methodology described by Beltrán Jiménez (2015) (Appendix 2.1); the results correlate the seismic lines with the distribution of reported geological formations at depth in the wells with the seismic data. It is important to mention that 2D seismic lines and wells 1 and 2 were used only as control formations near the study area. The methods for analysing this information consisted of the following:

- » Sequence stratigraphy, according to the methodology described by Stuart et al. (2014): Discontinuities and stratigraphic cycles were defined based on the fall and rise of the eustatic curve.
- » Seismo-stratigraphy or stratigraphy, according to the methodology proposed by Vail et al. (1977) and Mitchum et al. (1977): Seismic sequence limits and unconformities were identified.
- » Seismofacies analysis, according to the methodology described by Sangree and Widmier (1977), allowed the generation of AB/C maps.

Finally, the seismic attributes of coherence, spectral decomposition, RMS amplitude and variance were applied to the top of each sequence corresponding to the Palaeozoic (Neidell and Tanner, 1971). The results of these attributes were integrated with the information previously analysed to obtain the distribution of geoforms in the study area.

4. Results

4.1. Sequence stratigraphy

For the sequential analysis, the GR (gamma ray) and resistive logs were used only from well 3 because it was within the seismic block, and well 4 did not provide information associated with the Palaeozoic. Three demarcated surfaces of maximum flooding (SMF) were identified from the GR log data from well 3; thus, we obtained the information illustrated in Figure 3, which was constructed based on the interpreted data (without including the information found in the Guayabo formation, which was not taken into account for this study). It is important to mention that sequence B was divided into inferior and superior due to a slight change in treatment from high to low transgressive levels. However, because the interval of interest was in the Palaeozoic, the interpretation corresponding to that marker was performed (Figure 4).

The marker corresponding to the top of the Palaeozoic, well C sequence, has a limit close to 443 Ma and is biostratigraphically dated as belonging to the Ordovician (according to reports from well 3). Under this surface, an event is identified that shows a decrease in the A/S (deposition/sediment) ratio;

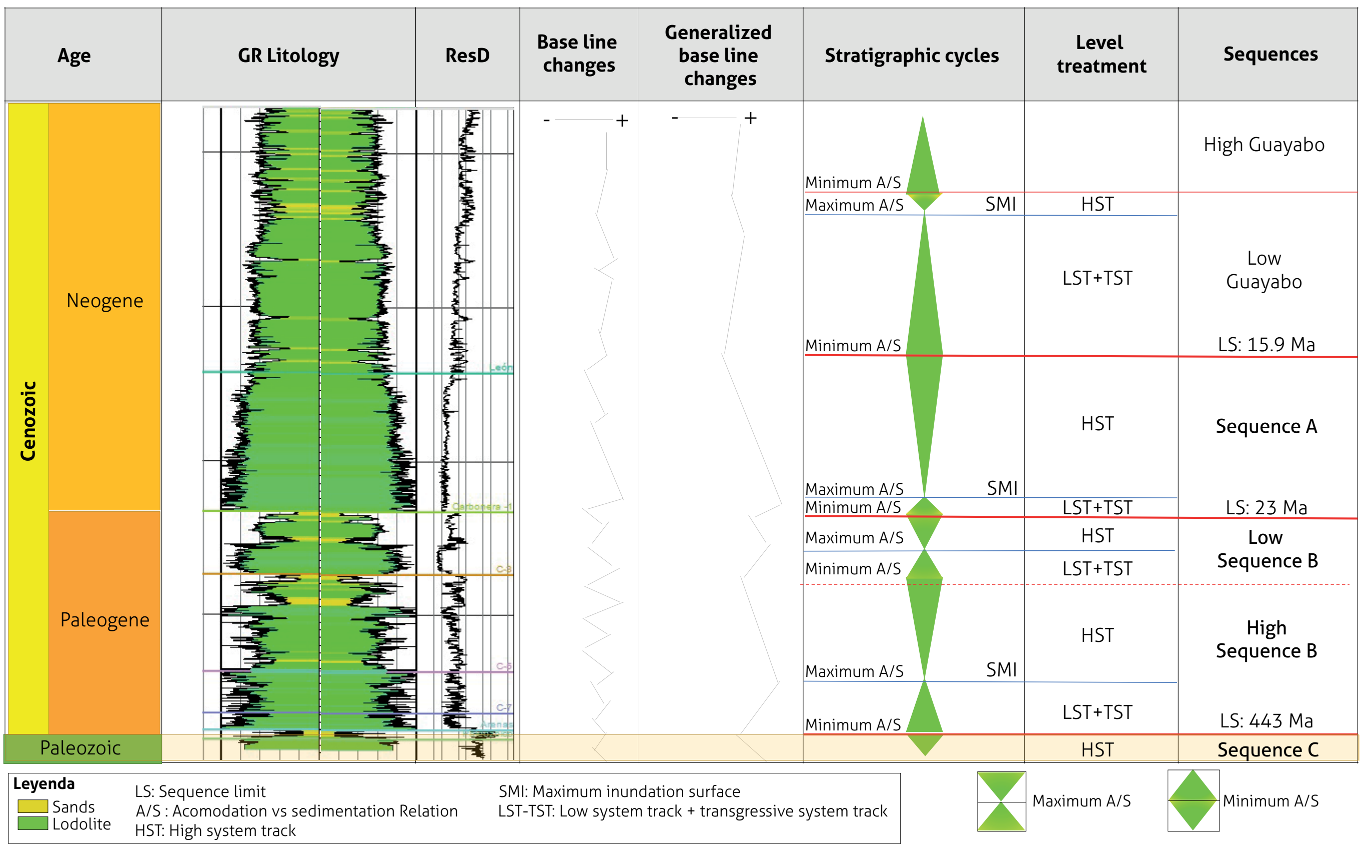


Figure 3. Stratigraphic analysis based on base-level changes for well 3

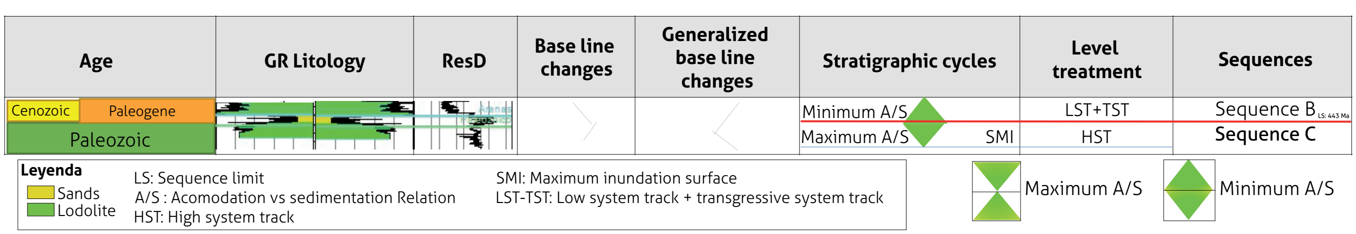


Figure 4. Stratigraphic analysis based on base level changes in the Palaeozoic for well 3

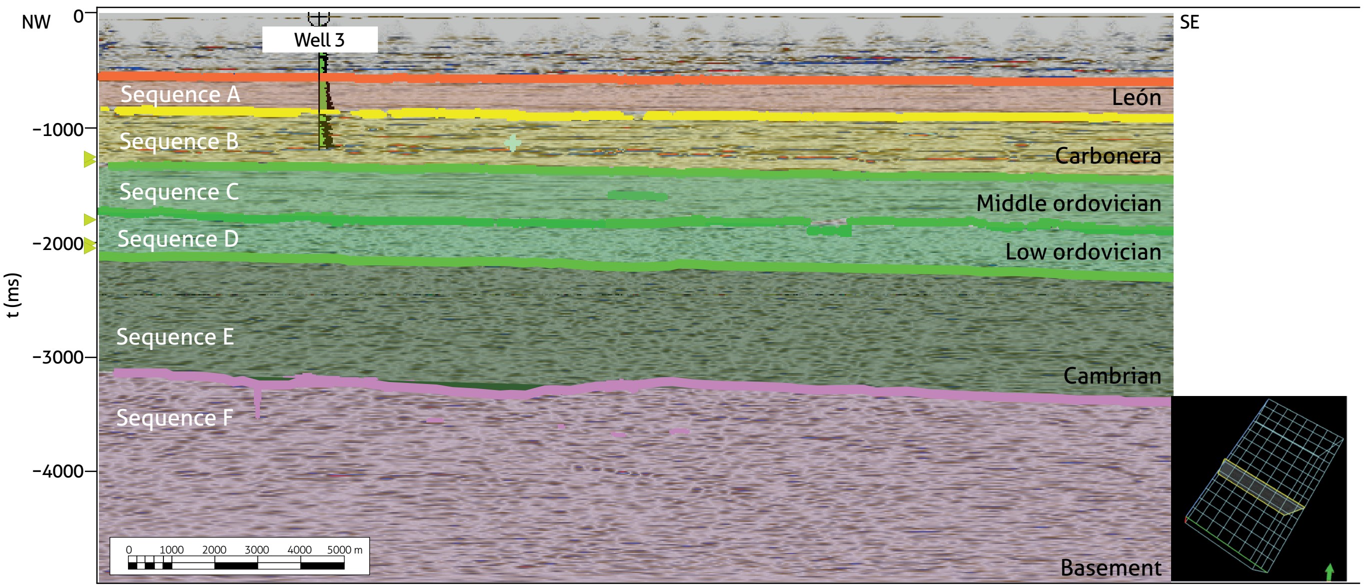


Figure 5. Sequences established for the study area (*Inline*: 650)

the event is limited towards the base, with a surface of maximum flooding, and towards the top, with a surface of unconformity. Figure 4 shows prograding patterns corresponding to a high-level treatment (HST) that according to the electrofacial analysis, is associated mainly with a shallow marine environment. On this marker, an event corresponding to a low-level treatment (LST) is recorded; the event shows retrograde patterns and an increase in the A/S ratio, with the top limited by a surface of maximum flooding, corresponding to a treatment transgressive level (TST).

4.2. Seismo-stratigraphy

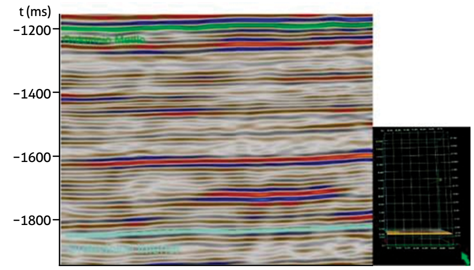
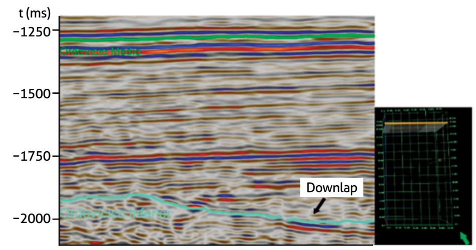
Six horizons corresponding to six seismic sequences were identified for the study area, as shown in Figure 5. Of these six sequences, for the Palaeozoic, three seismic sequences corresponding to the Middle Ordovician, Lower Ordovician, and Cambrian were found along with the basement (sequences C, D, E and F, respectively). For the age correlations in the seismic data, the palynological data from the final reports of well 3 (Appendix 3.2.), which were drilled up to the top of sequence C, were used; the lower sequences were defined based on interpretation.

The interpretations of seismic sequences C, D, E and F are shown, organized from youngest to oldest. Different behaviours were found in the reflectors to the north and south of the seismic block; for this reason, detailed descriptions are provided for sequences C, D and E.

4.2.1. Seismic sequence C

Seismic sequence C, presented in Table 1, corresponds to Palaeozoic formations whose base horizon is 470 Ma and whose top is 443 Ma. That is, it corresponds to Medium to Late Ordovician units according to the biostratigraphic dating of well 3. In addition, the thicknesses are preserved throughout the study area.

Table 1. Results of the seismic facies analysis for sequence C

Sequence	Seismofacies	Internal configuration	Example
Sequence C	CC/ P to subparallel	The reflectors are parallel, continuous and have moderately high amplitudes and frequencies.	 Seismic facies corresponding to the southern part of the study area (*Inline*: 72481).
	CD/W	The reflectors are wavy and interrupted with moderate amplitudes and high frequencies.	 Seismic facies corresponding to the northern part of the study area (*Inline*: 1019251).

C: concordant; D: *downlap*; W: wavy

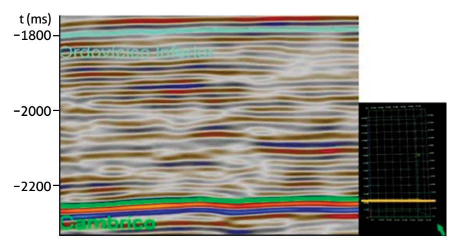
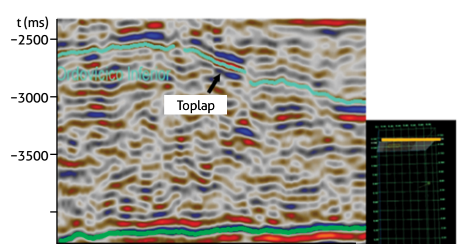
4.2.2. Seismic sequence D

Seismic sequence D, presented in Table 2, was associated with Palaeozoic formations whose base horizon is at 488 Ma and its top at 471 Ma, that is, with Early Ordovician units. The reflectors of this sequence are characterized by preserving thicknesses throughout the seismic block.

4.2.3. Seismic sequence E

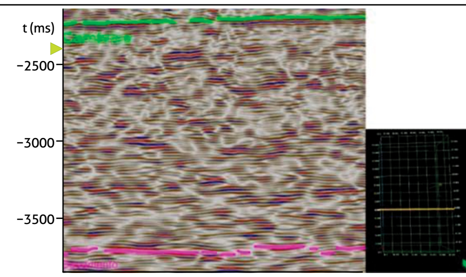
Seismic sequence E, presented in Table 3, was related to Palaeozoic formations whose base horizon is at 542 Ma and top is at 488.3 Ma; that is, to Cambrian units. It presents reflectors with subparallel, wavy, interrupted, contorted and chaotic configurations.

Table 2. Results of the seismic facies analysis for sequence D

Sequence	Seismofacies	Internal configuration	Example
Sequence D	CC/P to subparallel	The reflectors are continuous and have moderately strong amplitudes and high frequencies.	 Seismic facies corresponding to the southwestern part of the study area (*Inline*: 148736).
	Top-C/W	The reflectors have moderately high amplitudes and frequencies, with chaotic and contorted undulations.	 Seismic facies corresponding to the northwestern part of the study area (*Inline*: 979991).

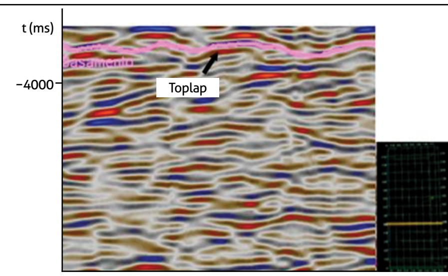
C: concordant; D: *downlap*; W: wavy; Top: *toplap*.

Table 3. Results of the seismic facies analysis for sequence E

Sequence	Seismofacies	Internal configuration	Example
Sequence E	CC/W	The reflectors are presented in a subparallel, contorted and chaotic form with moderately low amplitudes and medium frequencies.	 Seismic facies corresponding to the centre of the study area (*Inline*: 449226).

C: concordant; W: wavy.

Table 4. Results of the seismic facies analysis for sequence F

Sequence	Seismofacies	Internal configuration	Example
Sequence F	TC/chaotic	The reflectors are presented in a subparallel, chaotic and noncoherent way.	 Seismic facies corresponding to the centre of the study area (*Inline* -520951).

4.2.4. Sequence F

Sequence F, presented in Table 4, was related to formations whose top horizon is at 542 Ma and base age is < 542 Ma, i.e., Precambrian units associated with the basement. This sequence presents reflectors with low amplitudes and a chaotic configuration, without continuity and with little coherence. Their endings in the lower part are concordant, and in the upper part, they can be interpreted as truncations.

4.3. Interpretation of faults

The interpretation of faults was performed for the entire seismic block. Figure 6 shows the fault corresponding to *Inline* 650 with simple amplitude processing (ABS), which consists of the calculation of the absolute value of the trace and is used to highlight structural events.

Figure 6 also shows a system of inverse faults, predominant in the Palaeozoic, with some reaching Cenozoic formations. The faults present have dips in the north-western and south-eastern directions and extend to Precambrian ages. For sequence C, these reverse faults predominate in the northern zone of the seismic cube, while in sequences D and E, they are identified towards the central and southern zones of the seismic cube (Annex 3.1.).

4.4. Seismic attributes

The seismic attributes were applied with the objective of knowing the distribution of the stratigraphic and structural elements for the study area (Chen and Sidney, 1997; Tanner, 2001). In general, they allowed the identification of lithologies, channels and faults (Table 5).

These attributes were calculated on the interpreted seismic horizons, which correspond to the caps of seismic sequences C, D and E and can be visualized as maps. The results are shown in Figures 7, 8 and 9.

The RMS coherence and amplitude attributes for this study allowed us to identify stratigraphic elements, lithologies and channels. On the other hand, the attributes of spectral decomposition and variance facilitated the interpretation of some channels, sinuosity and faults only for sequence C, since for deeper sequences, structural elements were not clearly recognized. In this way, a difference in behaviour was recorded between the north-eastern and southwestern zones of the seismic block for sequences C and D; therefore, a distinction was made for these sequences in these zones. The results of these interpretations are presented in Table 5.

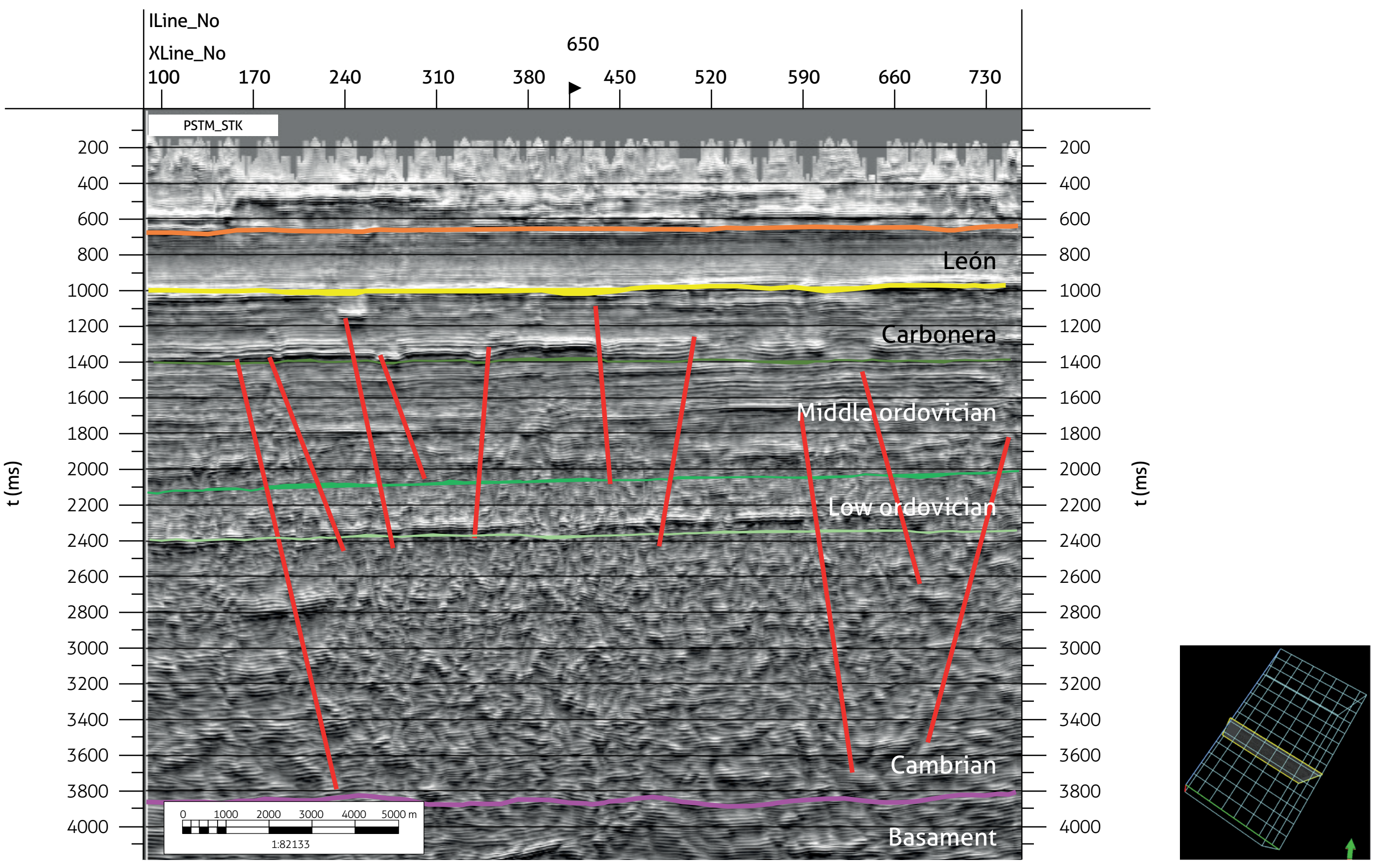


Figure 6. Interpretation of faults (red lines) along Inline 650 of the seismic block

Sequence C

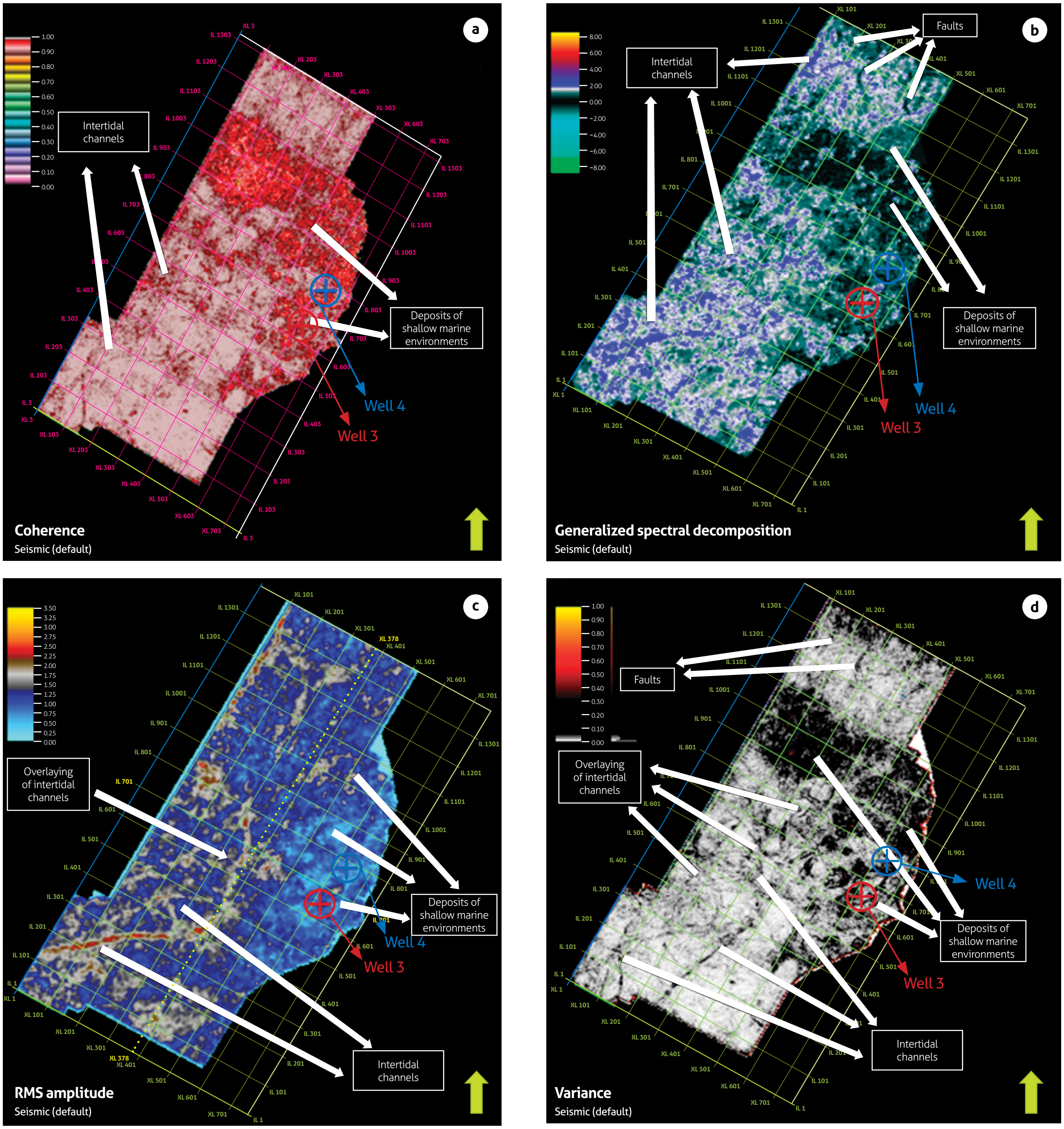


Figure 7. Attributes of a) coherence, b) spectral decomposition, c) RMS amplitude and d) variance for the top of sequence C (Middle Ordovician horizon)

In the lower part of the figure, the wells in the seismic cube are shown. Well 3 provided the biostratigraphic data corresponding to the Palaeozoic, with reference to the seismostratigraphic units of well 1 with Line 1 (left) and well 3 with *Inline* 650 (right).

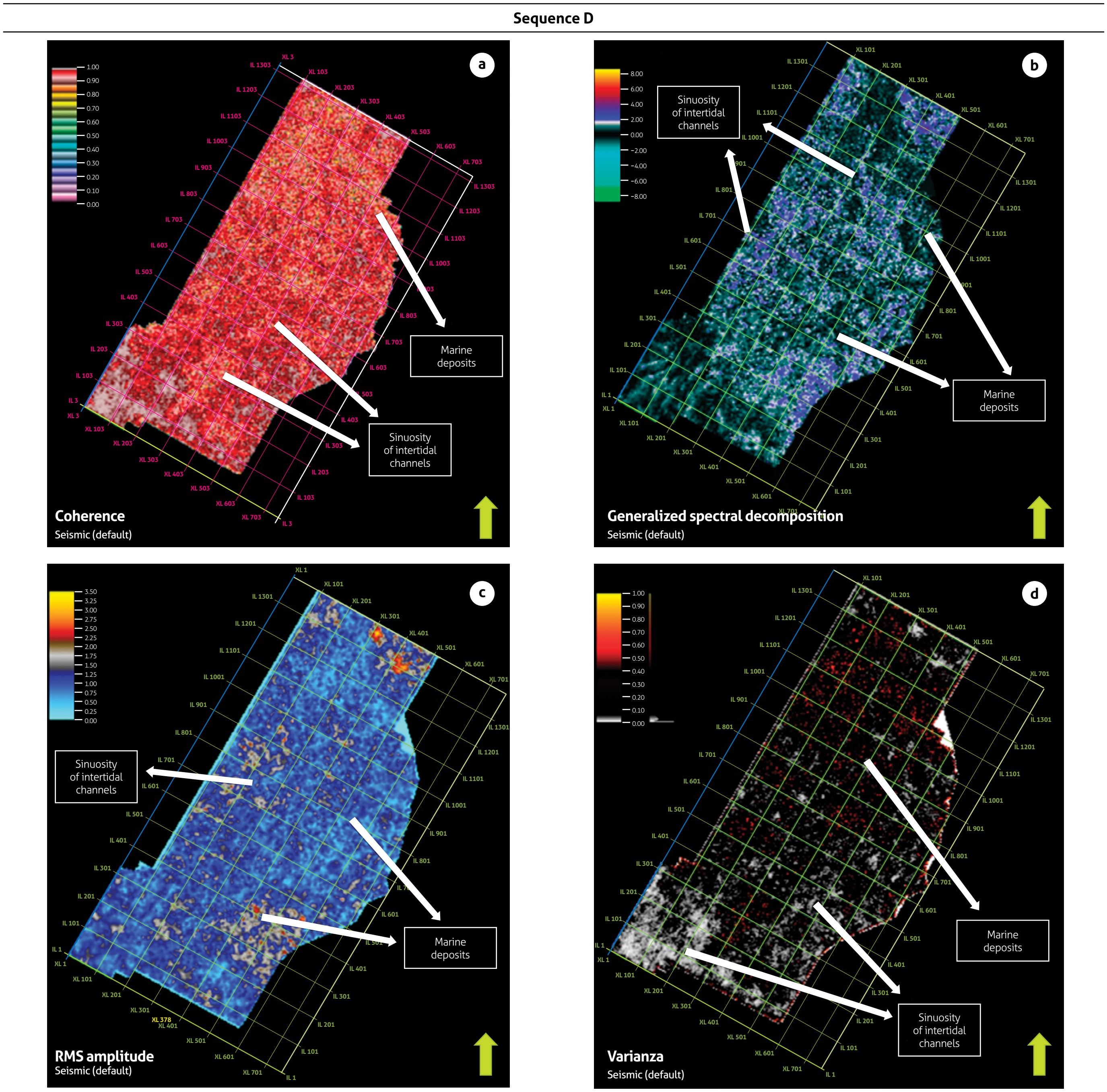


Figure 8. Attributes of a) coherence, b) spectral decomposition, c) RMS amplitude and d) variance applied to the top of sequence D (Lower Ordovician horizon).

Sequence E

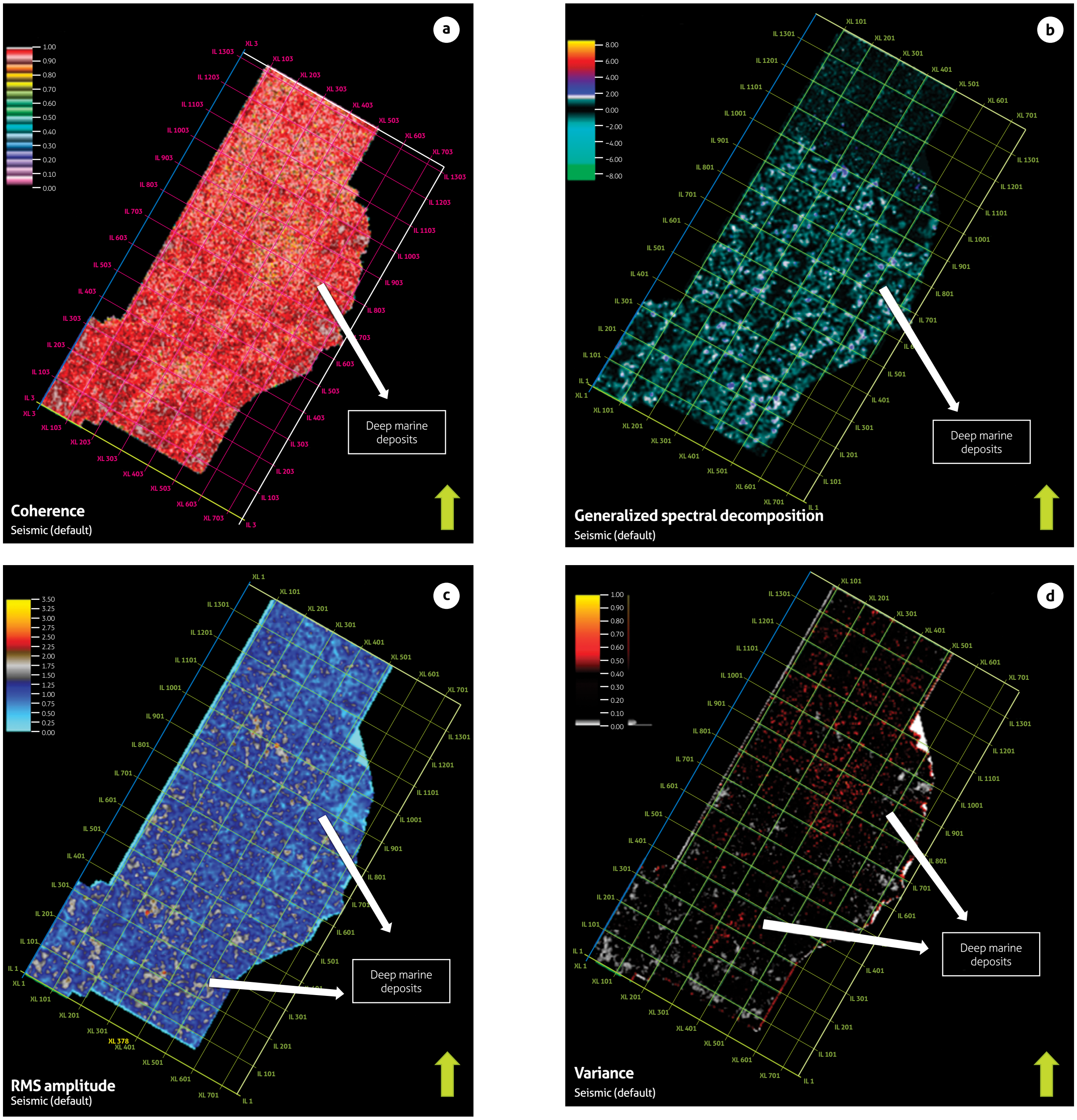


Figure 9. Attributes of a) coherence, b) spectral decomposition, c) RMS amplitude and d) variance applied to the top of the sequence E (lower Ordovician horizon).

Table 5. Results and interpretation of the seismic attributes applied

Sequence \ Seismic attribute		Coherence	Spectral decomposition	Amplitude RMS	Variance	Interpretation
Sequence C	NW	High similarity.	Low frequencies with the presence of segments with moderate to high frequencies.	Low energy, porosities and amplitudes.	Low correlations with segments of moderate correlations.	**Deposits** of clayey and muddy lithologies. **Failures.**
	SE	Moderate to low wavy morphologies.	High frequencies in the wave morphology.	High energies, porosities and amplitudes in the wave morphology.	Low correlations with the presence of high correlations that demarcate the wave bodies.	Sedimentation of muddy lithologies with sand intercalations. **Channels.**
Sequence D	NW	High similarity.	Low frequencies with the presence of segments with moderate frequencies.	Low energies, porosities and amplitudes.	High correlations.	**Deposits** of clayey and muddy lithologies.
	SE	Moderate values of similarity.	Moderate to low frequencies for wavy patterns.	Moderate to low energies, porosities and amplitudes.	Moderate to high correlations.	**Sinuosities** of clayey and muddy lithologies.
Sequence E		High similarities.	Low frequencies.	Low energy, porosities and amplitudes.	High correlations.	**Deposits** of clayey and muddy lithologies.

5. Discussion

Inverse faults in the north-eastern to southwestern direction predominate in the northern zone of the seismic block for sequence C and throughout the block for sequences D and E. These structural elements are related to the events reported in the literature, which indicate a *rifting* at the end of the Proterozoic and early Cambrian, which produced a partial collapse with normal faults that were reactivated in the Palaeozoic due to compressive events (Cediel, 2019) that generated a failure inversion. These were extended to more superficial sequences because they are areas of structural weakness.

For sequence C, which is associated with the Middle Ordovician according to palynological data, the stratigraphy of sequences showed a drop in sea level due to the presence of muddy lithologies with sands. On the other hand, the analysis of seismic facies determined different behaviours in the reflectors in the north-eastern and southwestern areas could be related to the locations of the faults found in the seismic block. Finally, the seismic attributes provided information on the distribution of lithologies, where muddy and sandy sediments associated with the intertidal channels were identified. These characteristics would seem typical of a shallow marine sedimentation environment (Serra, 1984).

For sequence D, which was interpreted in this project as Lower Ordovician based on the analysis of seismic facies, different behaviours were recorded in the north-eastern and southwestern areas of the seismic block, which are associated with faults in these areas. The seismic attributes of this sequence indicated mostly muddy lithological distributions with small sand lenses towards the centre of the block associated with apparent sinuosity of intertidal channels in a shallow marine environment. Lithologies were recognized from the characteristics provided by the seismic attributes mentioned in Table 5.

For sequence E, which was interpreted in this project as Cambrian, the analysis of seismic facies recognized a similar behaviour for the entire seismic block, which may be due to the decreased presence of faults compared to more superficial sequences or the decrease in the vertical resolution at depth, which could prevent the clear visualization of elements (Sheriff, 1997). On the other hand, the seismic attributes indicate high lithological similarities associated with sludge. This interpretation and the drop in sea level towards the Middle Ordovician corresponding to sequence C indicate for sequence E a shallow marine sedimentation environment that is slightly deep (Serra, 1984).

6. Conclusions

The analysis of sequential stratigraphy based on information from wells and 2D and 3D seismic data facilitated an understanding of the stratigraphic and structural elements of the study area for the Palaeozoic interval. Therefore, it was possible to interpret a shallow marine depositional environment that was somewhat deep in the Cambrian and a shallower marine environment in the Lower Ordovician. These results provide innovative geological information for this period in the study area.

The analysis of seismic facies for seismostratigraphic sequences C, D, E and F showed differences in behaviours between the northeastern and southwestern zones of sequences C and D.

The seismic attributes applied to the 3D seismic information (coherence, RMS amplitude, spectral decomposition and variance) turned out to be a very useful tool to find the distribution of lithologies and faults and associate them with geological events. In the Cambrian, mudstones and claystones from slightly deep and shallow marine environments predominate;

in the Lower to Middle Ordovician, there was a transition in which intertidal channels of muddy and clayey lithologies were presented with fine sandy bodies related to shallower marine environments towards the southwest.

Based on these attributes, maps of geoforms were obtained (Appendix 3.3.) This facilitated the understanding of the distribution of lithological deposits in the study area. However, the interpretation of the attributes was not as detailed for seismic-stratigraphic sequences D and E as it was for the other sequences because the seismic resolution at these depths did not facilitate the recognition of all structural and stratigraphic elements.

Further geophysical studies, such as reach greater depths, provide more direct information, achieve greater analytical detail, and reduce the uncertainty about the composition of seism-stratigraphic sequences D and E.

This study provides innovative geophysical information in the study area, which has some potential for hydrocarbon exploration; since the study is focused on the Palaeozoic era and was conducted within a historically hydrocarbon-rich basin, geoforms were found that had not been identified.

7. Supplementary data

Supplementary data for this article can be found online at https://doi.org/10.32685/0120-1425/bol.geol.49.1.2022.557

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