SEDIMENTOLOGICAL ANALYSIS UTILIZING THE CIRCUMFERENTIAL BOREHOLE ACOUSTIC IMAGE

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ABSTRACT

The latest version of the Circumferential Borehole Imaging Log (CBIL[SM]) device utilizes a focused, rotating acoustic transducer to generate a graphic image of the entire borehole wall. New techniques for acquiring and processing acoustic images permit improved log definition and identification of textural characteristics of rocks. It is now possible to observe primary and secondary sedimentary features, as well as natural and drilling-induced fractures. Thus, openhole logs are correlated with textural attributes of the formation. It is also possible to recognize the predominant directions of postdepositional stresses.

Openhole log data and CBIL images are combined to analyze sedimentology in a four-well study of carbonate rocks and interbedded sand, silt, clay sequences deposited in a shallow, littoral marine environment. Acoustic images infer:

- ☐ *Type of lithologic contacts*
- ☐ *Primary sedimentary structures (parallel laminations, cross strata, irregular strata, and strata morphology)*
- ☐ *Secondary sedimentary structures generated by carbonate rock dissolution processes*
- ☐ *Discrimination between natural and induced fractures*
- ☐ *Predominant fracture direction and fracture dimensions*

Textural differences between the members of the carbonate series and the underlying and overlying rocks were clearly determined. Reservoir geometry and potential storage capabilities of the traversed formations were estimated, and a detailed stratigraphic description permitted development of a facies association scheme.

INTRODUCTION

The geological analysis of formations is fully optimized through the use of well images with complete coverage (360°) of the borehole wall. The Circumferential Borehole Imaging Log (CBIL) instrument operates in a pulse-echo mode, sending acoustic (pulse) signals and detecting reflected (echo) signals from the borehole wall. Analysis of the reflected amplitude allows for differentiation of:

- ☐ Lithologic contacts resulting from the acoustic impedance contrast between the borehole fluid and the formation
- ☐ Grain size variation
- ☐ Changes in porosity

A study was conducted in the Neuquen Basin of west-central Argentina to differentiate variations in lithology, recognize sedimentary structures, and analyze the depositional environments (Fig. 1). Four strategically distributed wells that cover the entire stratigraphic sequence were studied. Core data were used to confirm interpretation results from images and to adjust image-processing parameters as necessary.

REGIONAL SETTING

The stratigraphic record is characterized by the development of a thick Later Triassic, Jurassic, Cretaceous, and Early Tertiary sedimentary sequence and emphasizes the Tithonian-Valanginian rocks of the Mendoza Group. The Mendoza Group contains the Tordillo, Vaca Muerta, and Loma Montosa formations (Fig. 2).

Tordillo substrata are continental clastic sediments of eolian and alluvial-fan origin. Vaca Muerta sediments are composed of shale source rock and dark carbonates

II

belonging to marine and mainly marine euxinic shale deposits. The Loma Montosa formation overlies the Vaca Muerta and represents inner platform sediments composed of clastic, carbonate, and evaporitic rocks. The Loma Montosa is considered one of the most important reservoir rocks of the basin. CBIL image interpretation permits identification of different facies development and infers ancient depositional environments by recognition of sedimentary structures and textures.

The methodology applied to image processing and interpretation was divided into two separate protocols, processing and interpretation.

PROCESSING PROTOCOL

Static normalization is an image-normalization technique of histogram equalization performed over the entire depth range. Dynamic range of the signal is divided into 15 different intervals or tones from a defined color palette.

Dynamic normalization includes signal-amplitude normalization and edge enhancement. Amplitude normalization is a technique used to enhance the contrasts and eliminate borehole influences by application of different mathematical transforms (median, reflection loss, and Laplacian operators) over a sliding window. The vertical and horizontal size of the window is determined by considering the magnitude of events that need to be emphasized. It is necessary under certain conditions to apply the first and second derivatives to the signal to analyze previously defined features. Normalized and enhanced images must be used in conjunction with the raw data as a reference to ensure recorded primary contrasts have been correctly honored during interpretation.

INTERPRETATION PROTOCOL

Interpretation methodology is a very complex process of observation, description, interpretation, and implication. Although image definition is extremely high, the amount of information recorded by the tool is enormous, and it may be very time consuming to perform any interpretation if a systematic methodology is not followed. A multistep protocol is therefore highly recommended.

Correlation Images

Image plotting (normalized plot) is performed at compressed scales (1:40) to enable correlation accessibility to other openhole logs and eventual depth matching with dip vector plots.

Lithologic Modelling and Zoning of the Main Deposition Units

The primary lithofacies are identified by computing the mineral components from other openhole logs. The computed lithology results are correlated to the acoustic images to associate log responses to textural attributes and petrophysical properties of the sediments.

Expanded Image Plots (1:10, 1:5, eventually 1:1)

A variety of expanded depth scale plots was used to help detect macroscopic and mesoscopic features and permit better correlation of the images to core data.

Sedimentary Structures Recognition

Sedimentary structured recognition is an analytical process that includes observation of lithologies and textures with subsequent recognition. It considers the many methods involved and is beyond the scope of this paper.

Sedimentary Environment Recognition

Recognition of the depositional setting is accomplished by integrating the lithofacies modelling, depositional sequence analysis, bed-boundary differentiation, interval thickness, and other features that describe the sedimentary environment of the formations.

SEDIMENTARY STRUCTURES RECOGNITION

The CBIL instrument's ability to obtain a total circumferential borehole image and its vertical resolution attributes [±0.5 in. (±13 mm)] make it possible to recognize a wide variety of sedimentary features.

Self-Interpretable Features

When no external control is needed, a unique interpretation of the features is possible.

Ambiguous Features

These features are recognized when well log or core data are needed to ensure interpretation exactness. Acquired experience in CBIL image interpretation of sedimentary features is summarized in Fig. 3. The following observations are a description in a detailed working scale of some of the most relevant sedimentary features recognized in the sedimentary interval studied.

Horizontal Bedding Stratification and Lamination

Amplitude variations from textural or depositional changes between bedding planes are reflected as relatively high, dark, and white contrasted bands that cross all the images in a parallel or subhorizontal orientation (Fig. 4). In particular, those structures are observed in both the Vaca Muerta and Loma Montosa formations. In these sand-shale series, parallel bedding indicates a low-energy environment below the wave or tide influence that was not disturbed by bioturbation. This corresponds to sheet or wide-spread blanket deposits.

Crossbedding

Crossbedding sedimentary structures in carbonates, corresponding to grainstones, are typical of the Loma Montosa formation (Fig. 5). The crossbeds exhibit higher clastic influence because of an increase in transport energy. The structures are observed on CBIL images as dark, thin sinusoidal features (fine-grained clastic material) that cross the higher reflectivity zones (carbonates). The sedimentary structures are of variable genesis, related in this particular case to siliciclastic or carbonate sequences with some type of fluid transport.

Lenticular Bedding

Lenticular structures are seen as bright, elongated spots that appear on the images as lenses of more reflective material (Fig. 6). Lenticular bedding is generated when ripples or sand lenses are discontinuous and isolated not only in a vertical fashion but also in a horizontal direction. Thus, ripples are produced in the form of isolated lenticular bodies on a muddy substratum. In other words, lenticular bedding is produced when incomplete sand ripples are formed and preserved as a result of deposition of the next muddy layer. Histograms make it possible to recognize a lower reflectance preponderance bias (pelites) with respect to higher values that represent psammites. The cross section shows wellbore rugosity, and allows rigorous quality control of the images.

Irregular Stratification

Convoluted laminae represent penecontemporaneous deformation structures and are comprised of disturbed, distorted, or deformed sedimentary layers produced by inorganic agents. Convoluted laminae appear as successive alternate beds of contrasting reflectance that are highly deformed and folded (Fig. 7). Convoluted laminae are associated mainly with a high sedimentation rate of materials having different viscosities and densities.

Bioturbated structures are formed by biogenic activity on the surface or within still, unconsolidated sediments. The organisms cause destruction or regeneration of primary sedimentary structures that were previously formed through inorganic agents. The images appear as irregular, darker, subvertical features that penetrate the formation (Fig. 8). High reflectance loss of the signal corresponds to the presence of clay that fills the burrows.

Stylolites

CBIL images of stylolites, represented by obscure, short, vertical lines, are observed as both abrupt and erratic in occurrence and may be sutured or undulated. Stylolites are often observed in compact, cemented carbonate formations, and they frequently occur in the Loma Montosa formation (Fig. 9). These stylolites are the result of a strong dissolution process in the lower and the upper part of the bed. The growth of stylolitic structure is the result of compressive stress.

ENVIRONMENTAL ANALYSIS OF THE IMAGES

An integrative approach utilizing all the available analyzed data was used to suggest environmental settings. The previously described sedimentary structures and mineralogical components were compared to infer the environmental and depositional evolution of the stratigraphic column described previously.

Reconstruction began in the Kimmeridgian (144 M.Y.), with the presence of continental sediments known as the Tordillo formation. These sediments demonstrate very high horizontal and vertical variations and belong to very fine eolian sediments with well-developed foreset bedding (Fig. 10). The sands are predominant in the eastern sector of the study area. The eolian deposits change gradually to fluvial deposits in the western sector, where the correlative unit is represented by conglomerates and coarser sands that correspond to alluvial fan sediments deposited in semiarid conditions as ephemeral channels.

Early Tithonian sediments of the Vaca Muerta formation overlay the Tordillo formation. Marine pelites and calcareous facies are representative. The Vaca Muerta formation is recognized by the alternate presence of contrasting bands (dark and bright subhorizontal features) that result from cyclic variation of the carbonate/shale ratio. The variations produce typical rhythmic patterns of sedimentation clearly observed on CBIL images (Figs. 11 and 12). The multistory deposits are generated mainly by suspension (thick pelites and dark carbonate beds with frequent occurrences of marine organisms) interrupted by thin stratification of coarser material that characterizes the rocks as offshore deposits.

Dramatic variations in eustatic sea level are evidenced in the upper part of the Vaca Muerta formation because of the presence of anhydrite nodules deposited as small beds. These are easily recognized on the acoustic images as rounded, irregular shapes with high reflectance contrast superimposed on the low reflectance host pelite sediment (Figs. 13 and 14).

The transition from offshore to lower shoreface sediments is detected by the presence of hummocky, crossbedded strata coincident with the higher clastic depositional rate, thinner cyclic events, and rare occurrence of fossils (Fig. 15).

Finally, inner carbonate platform facies and clastic and evaporitic sediments known as the Loma Montosa formation are deposited. The main lithofacies are limestone, dolomitic limestones, and some clastic and muddy limestone rocks deposited in a very complex succession. The early deposits are mostly limestone and dolomites that belong to ancient carbonate platforms interbedded with tidal flat sediments.

Reef deposits are also recognized and characterized by planar stratification with highly interlayered shales at the base, changing gradually upward to crossbedded carbonate deposits at the top. Intense biogenic activity may occur and distort primary sedimentation patterns that result in a massive internal structure (Figs. 15 and 16).

The upper part of the Loma Montosa is characterized by a dramatic change in depositional conditions, as evidenced by the abundance of psammopelitic deposits that dominate the carbonates. At the formation base, deformation structures are common (Fig. 17) and small beds having interlayered shales and organic material are found. The upper deposits are predominantly muddy deposits, interrupted by sand lenses that may or may not be connected as a result of slight energy variations. When catastrophic, energy variations are the cause of the storm deposits that appear occasionally in the column as erratic sand bodies [≈ 5 ft (≈ 1.5 m) thick] isolated within thick, muddy sediment. These erratic sand bodies have extraordinary petrophysical properties (porosities > 25% and permeabilities ≈ 1 d) that make them attractive reservoir rocks. The complete stratigraphic sequence is illustrated in Fig. 17.

CONCLUSIONS

A synergistic approach can be made to integrate all available data acquired from a well to evaluate sedimentary reservoir rocks. Complete borehole images of the borehole wall can be made by acoustic pulse-echo methods and provide distinguishable reflectance patterns that compare favorably to visual interpretation of core data. Geological facies can be recognized through the proper use of available log data.

ACKNOWLEDGMENTS

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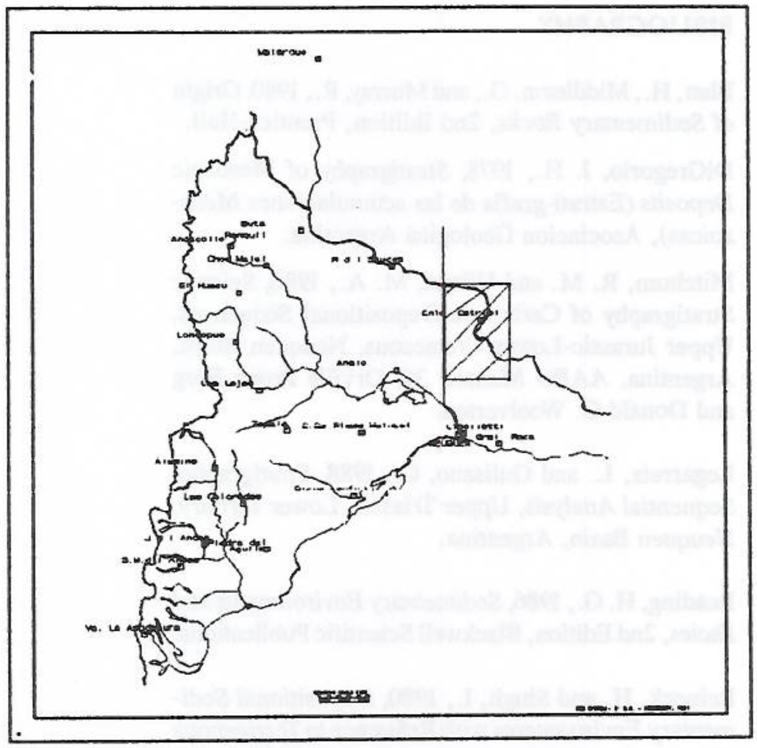
Location Map

Argentina Republic

Neuquen and Rio Negro Provinces



Neuquen Basin Map

Fig. 1 — Area of interest — Catriel – Rio Negro province

MESOZOIC	CRETACEOUS	Valanginian	NEUQUEN MEGASEQUENCE	Mendoza Gr.	Loma Montosa F.
		Berriasian			
	JURASSIC	Tithonian			Vaca Muerta F.
		Kimmeridgian			Tordillo F.

Fig. 2 — The Mendoza Group of formations

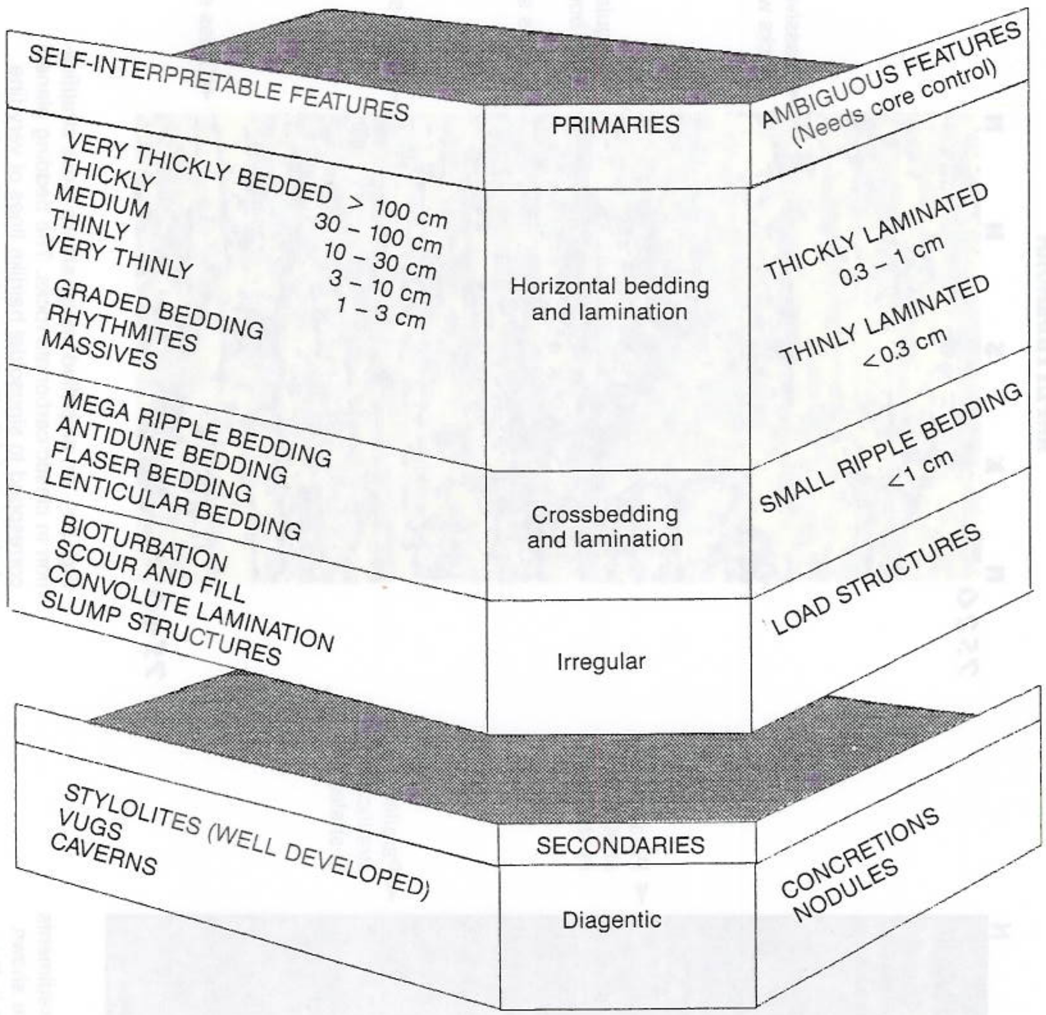


Fig. 3 — CBIL recognition of sedimentary structures

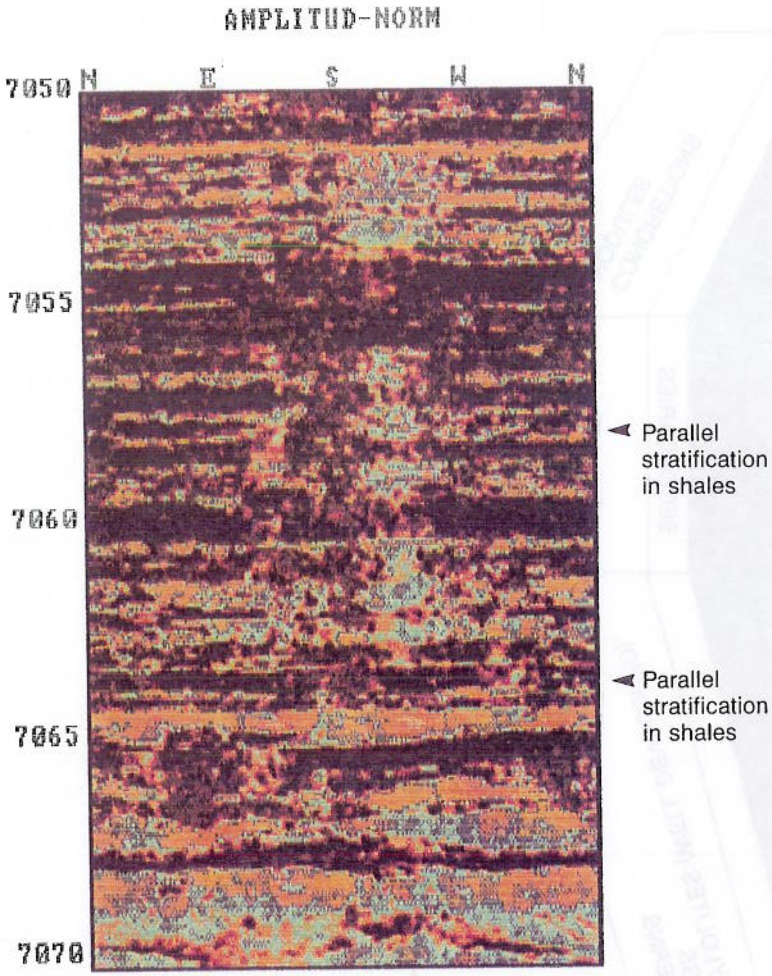


Fig. 4 — Very fine interstratified pelitic sediments with organic material and carbonates are shown. The parallel stratification, corresponding to low-energy deposits, is clearly denoted in the geometry of the bedding planes.

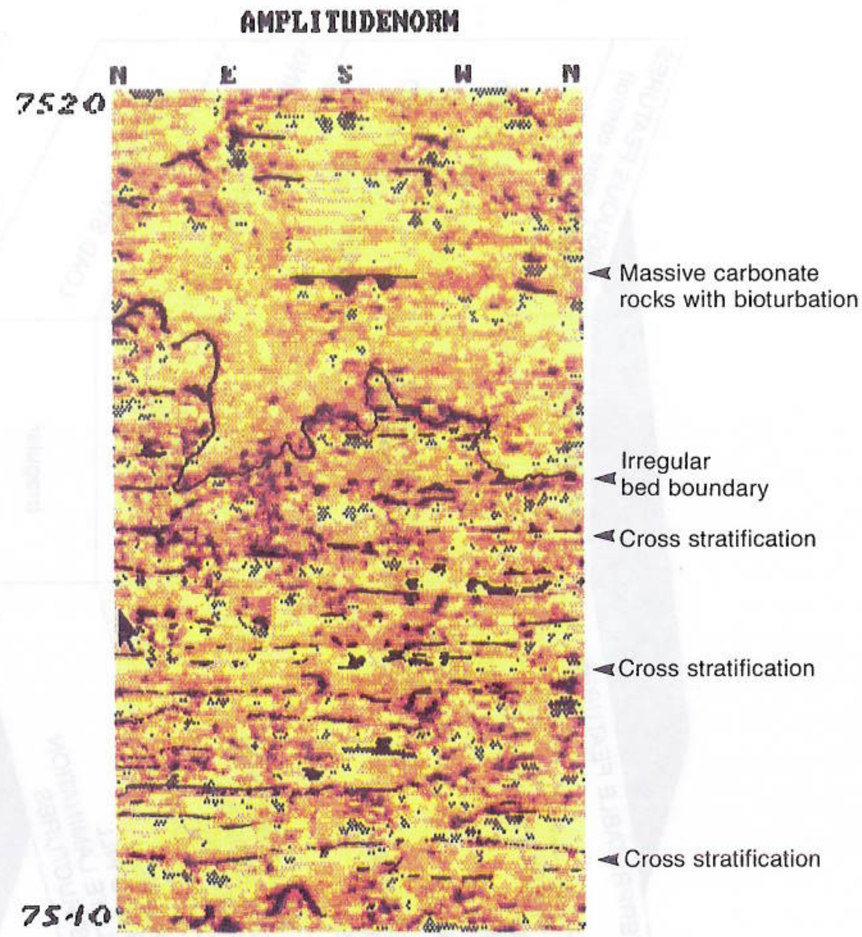


Fig. 5 — An amplified image shows cross stratification in clastic carbonate rocks. The bedding planes correspond to sinusoidal hairlike lines of very fine shaly material limited by subhorizontal surfaces. These structures are related to reworked carbonates, transported with some type of fluid agent.

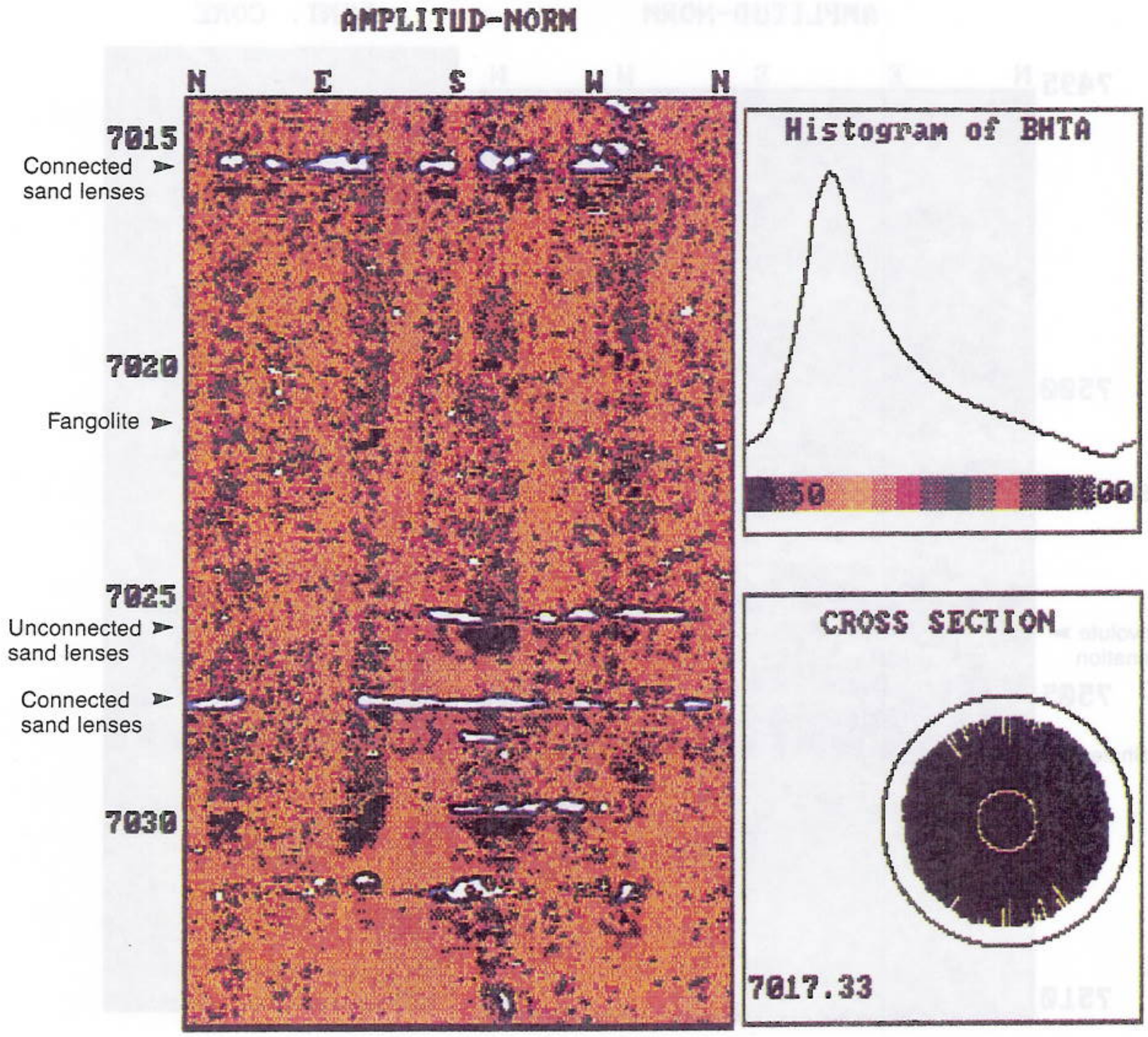


Fig. 6 — Multiple sand lenses (bright shapes), deposited into a muddy sequence (darker low-reflectance zones) are shown. It is possible to recognize if they are connected or not. Those characteristics are evidence of the energy of the depositional environment that helps preserve finer material rather than coarser material. These structures could be generated under tidal conditions.

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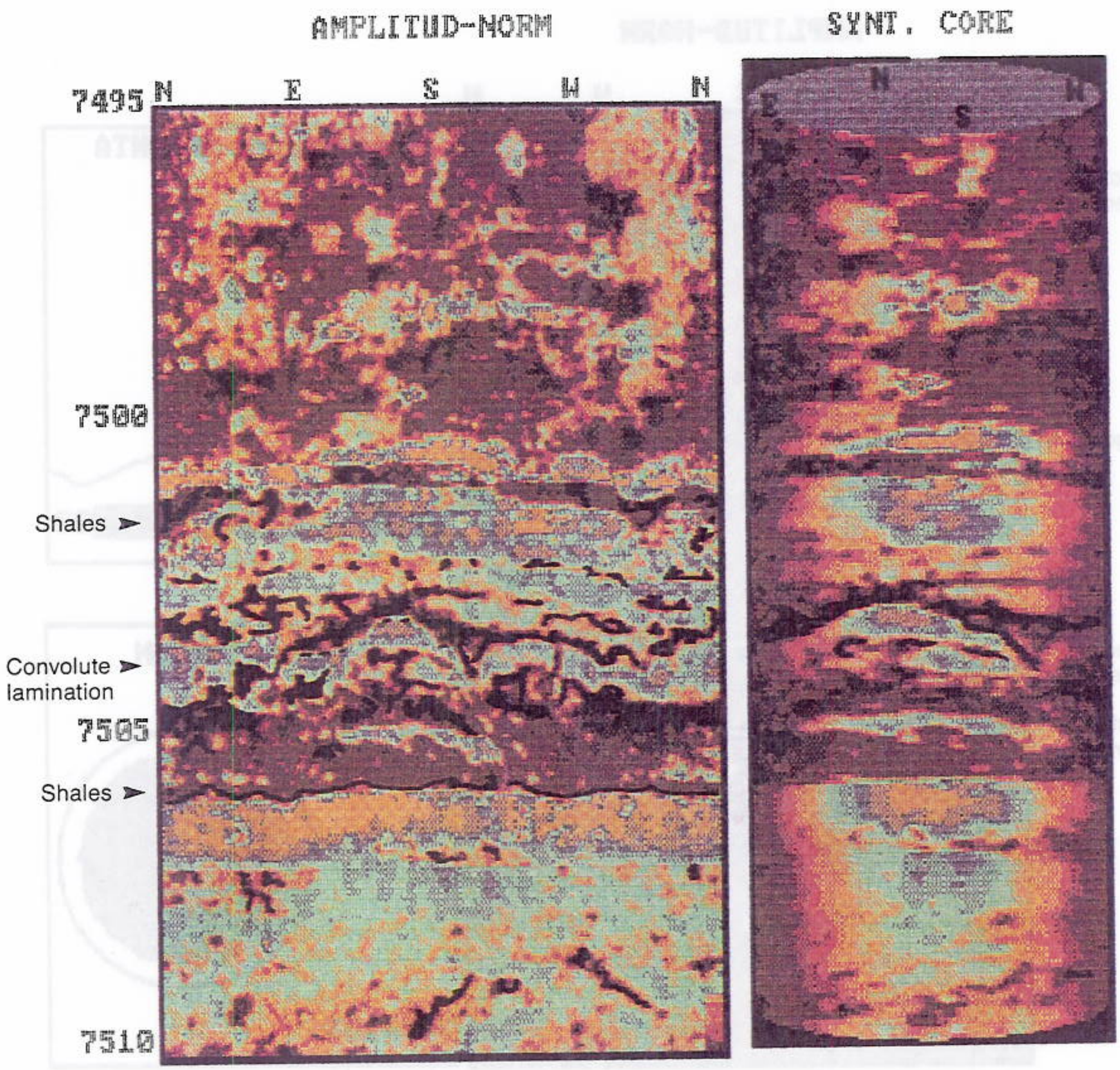

Fig. 7 — Example of convoluted laminations with clearly defined strong deformation and microfolds. These structures may occur in intertidal deposits that are mainly subaqueous. They are typical of very fine sediments, such as fine sands, silts, and micritic limestones, as a result of local strength over hydroplastic sediments, which are folded and convoluted.

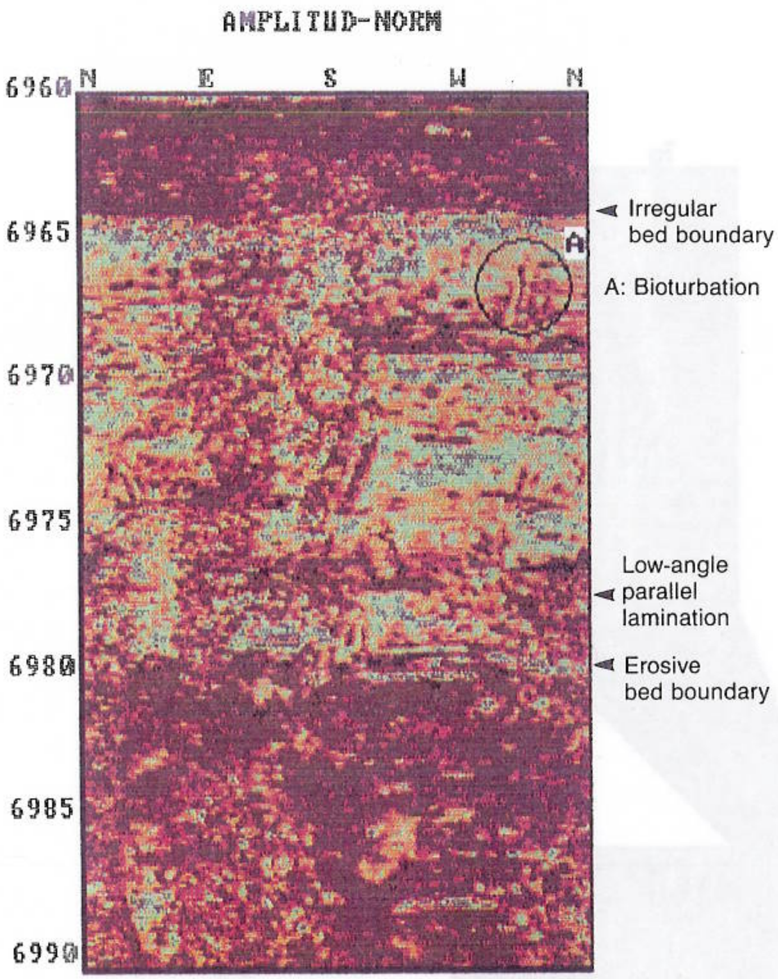

Fig. 8 — Example of a storm sand body with bioturbation. Its basel contact is erosive and irregular. Parallel stratification is developed and it ends with a sharp bed boundary at the top. Thick, muddy sediments lay over the sand bodies and also beneath them.

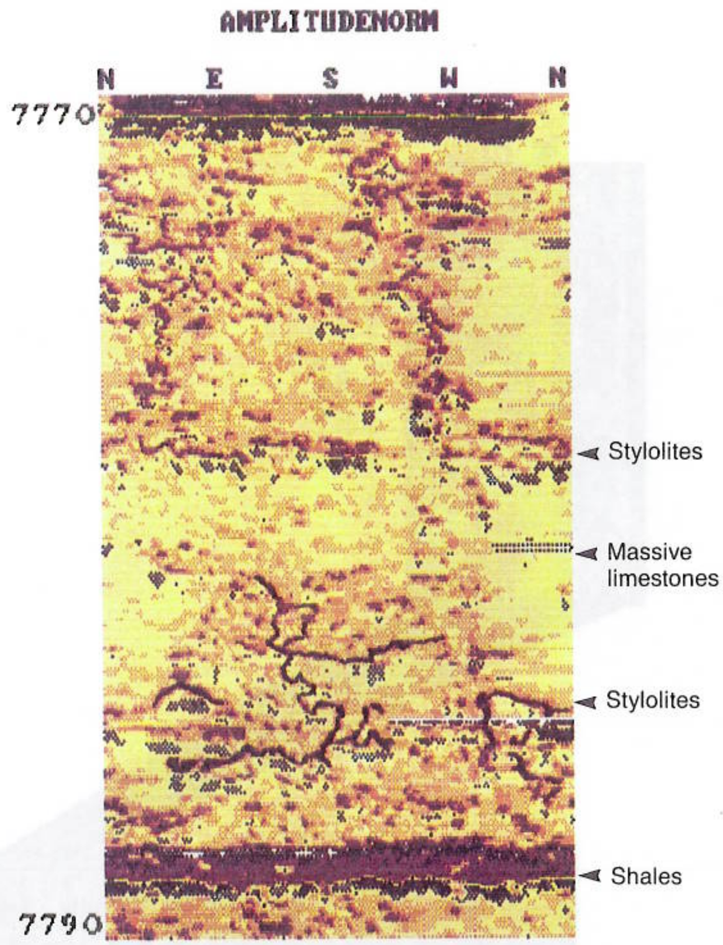

Fig. 9 — Stylolitic structures in carbonates, charaterized by irregular, darker hairlike features (low reflectance) superimposed over high-reflectance carbonates. The width may be exaggerated by the effect of drilling mud and the real dimensions are probably emphasized.

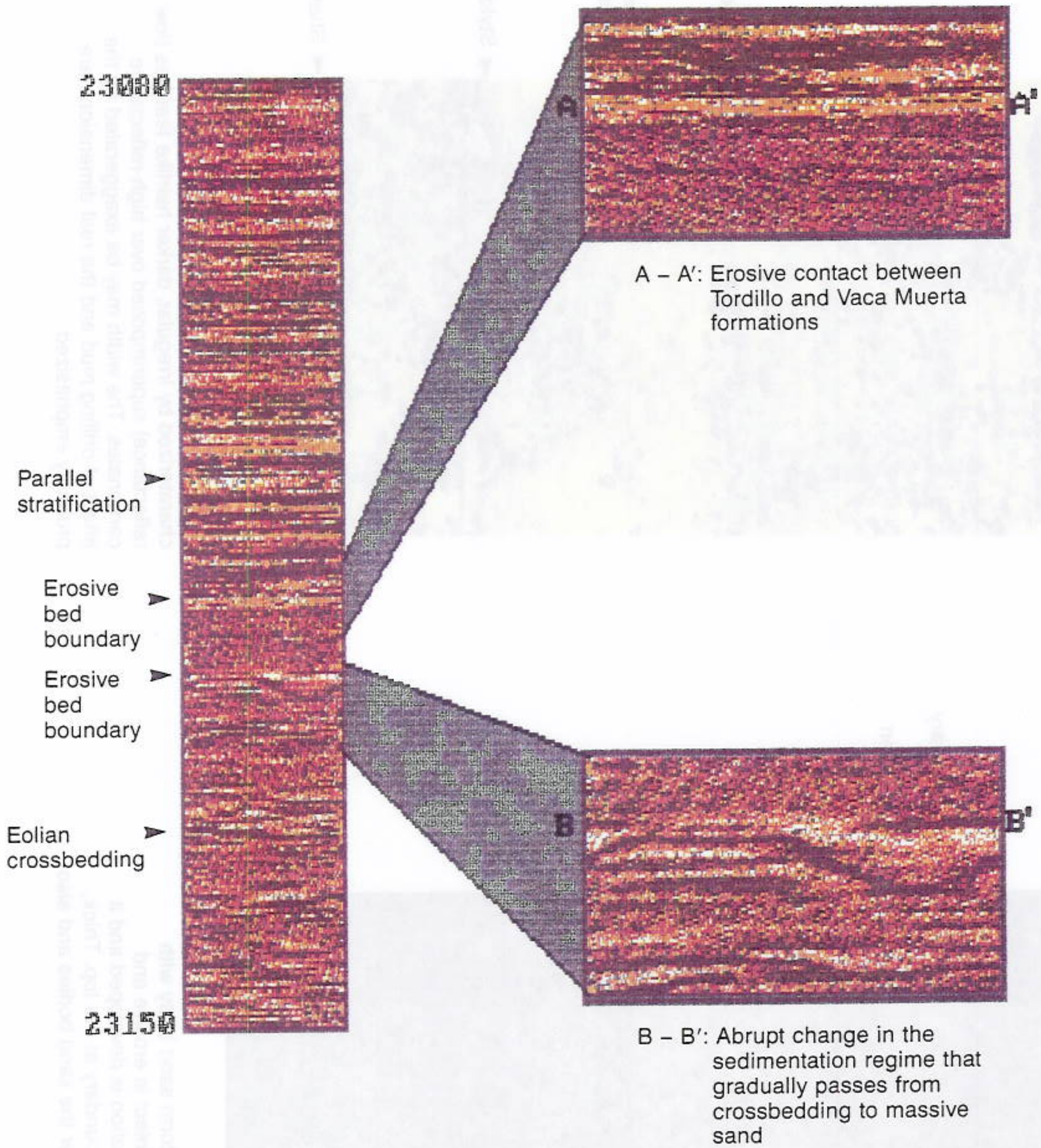

Fig. 10 — Eolian sandstone deposits from Tordillo formation are shown in the lower part and are overlayed by the marine shaly carbonates of the Vaca Muerta formation.

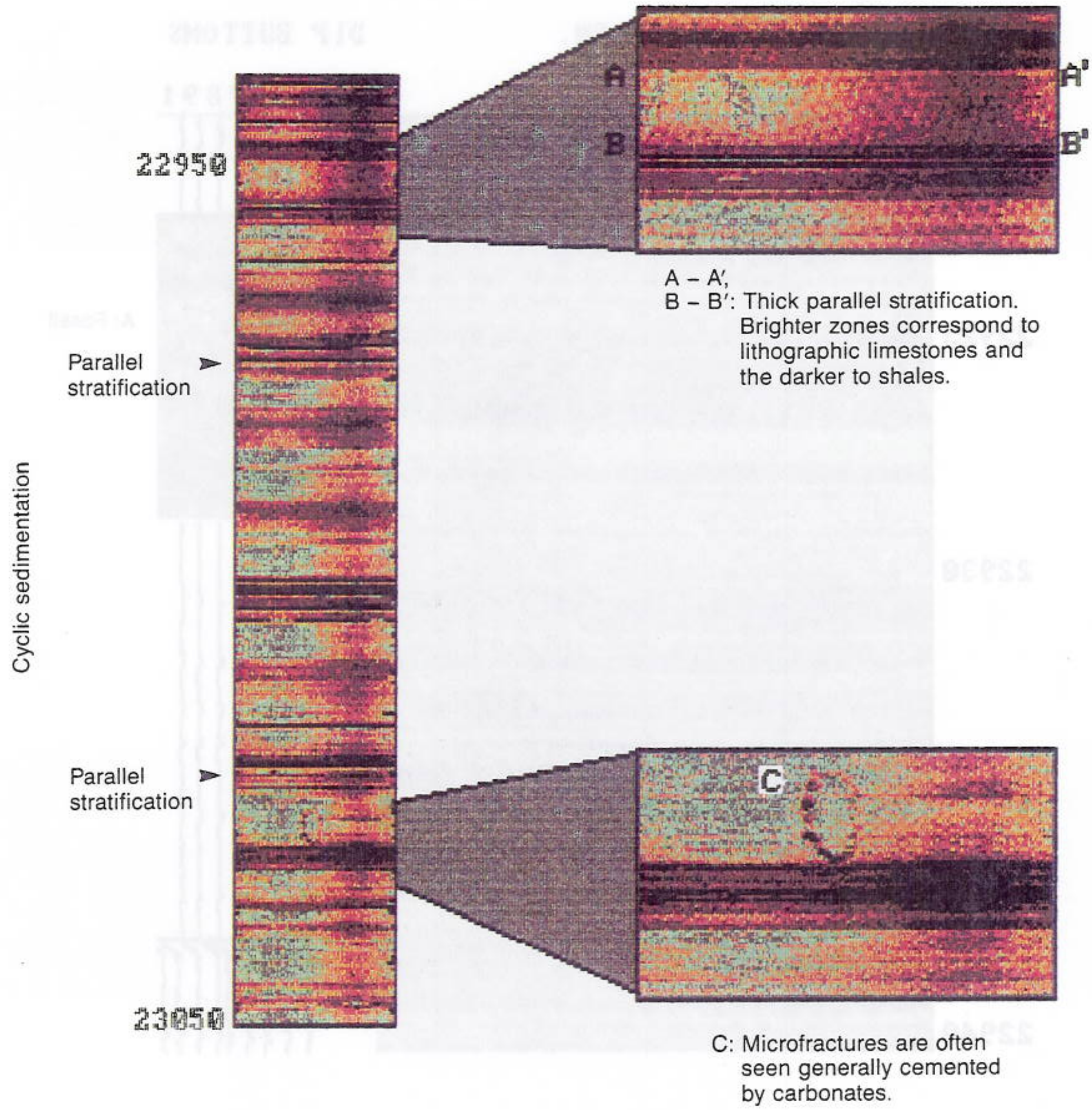

Fig. 11 — Cyclic sedimentation of the Vaca Muerta formation, characterized by dark shales and carbonates deposited under low-energy marine conditions. Variations in carbonate percentages make the tones change.

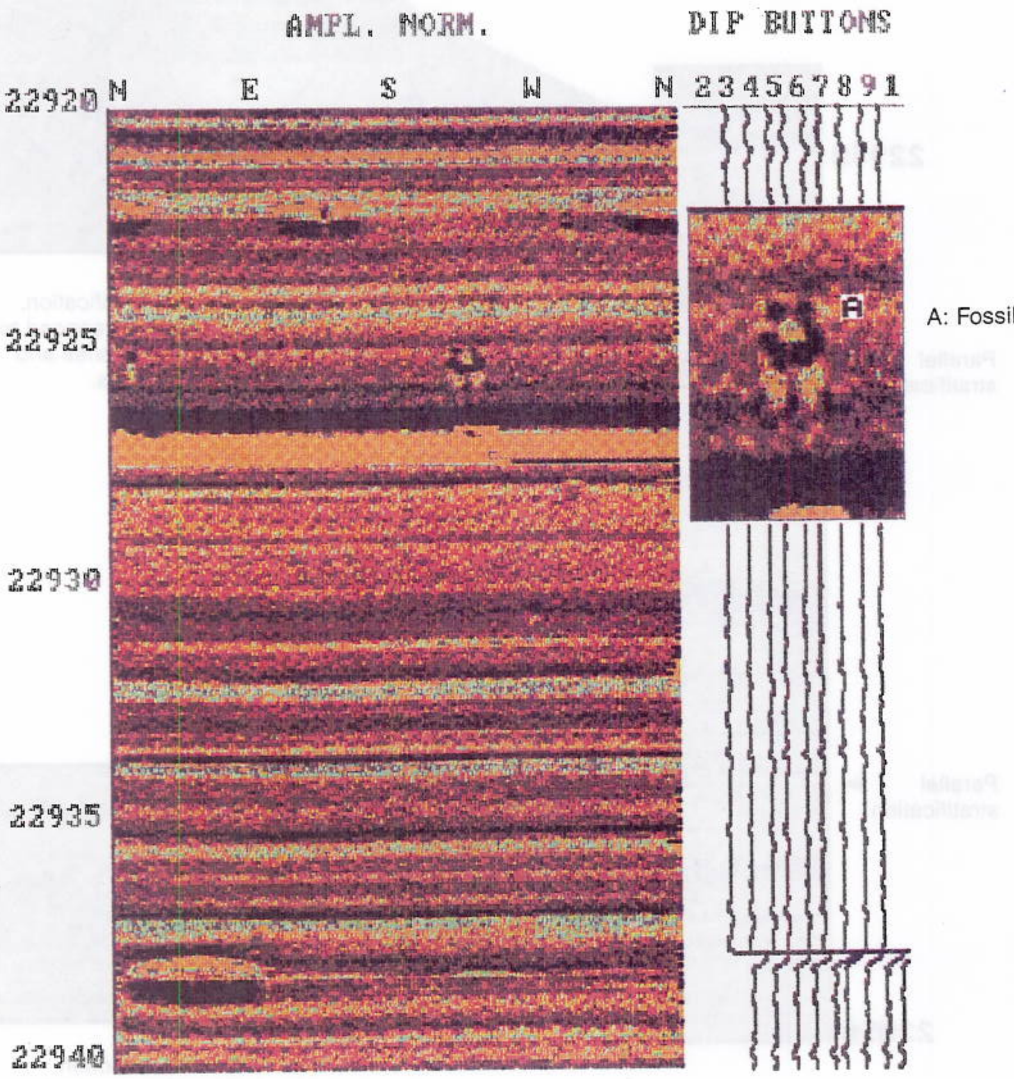

Fig. 12 — Parallel stratification with marine fossils in shales

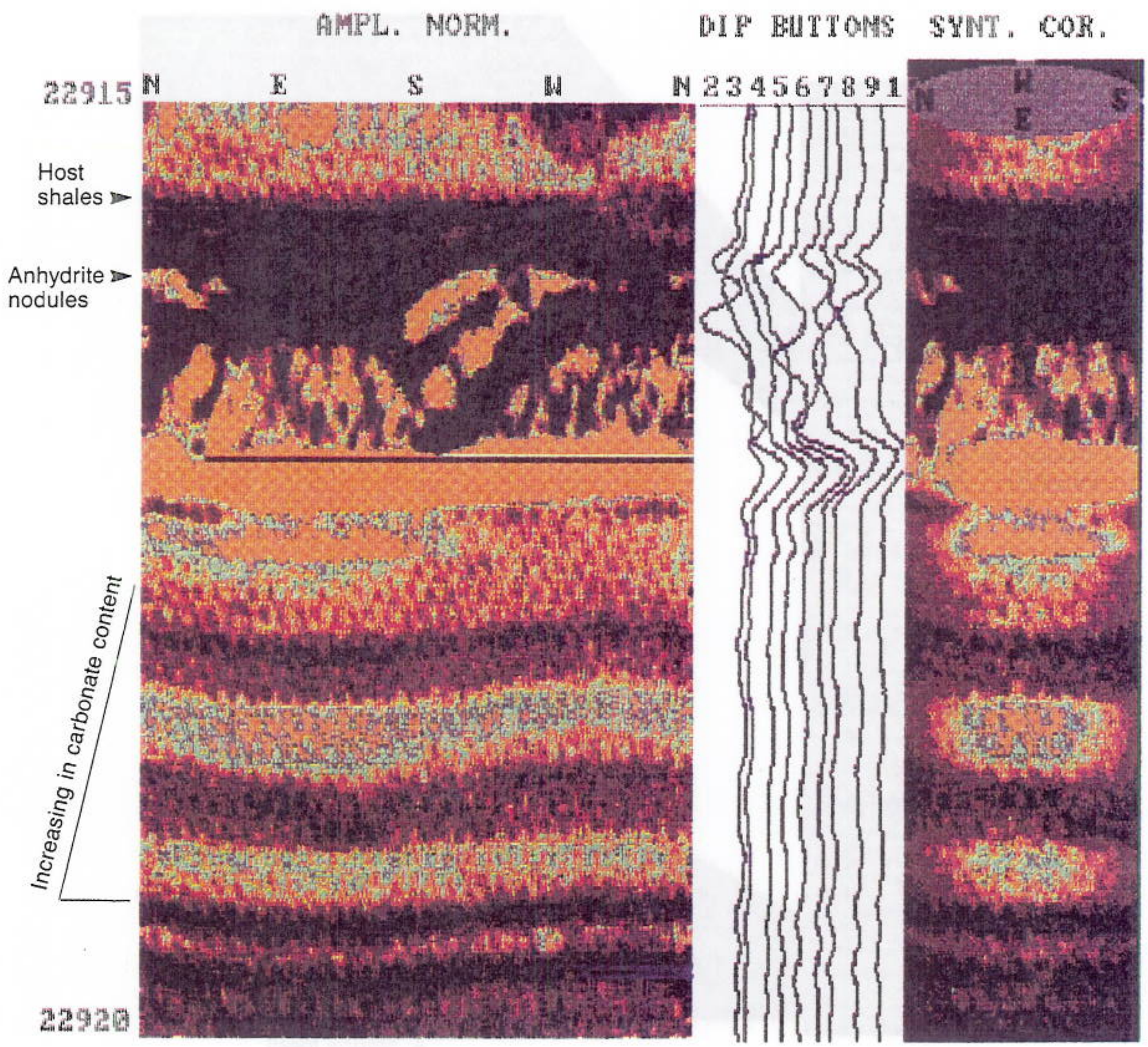

Fig. 13 — Example of nodular anhydrite, hosted in shales over the calcareous rocks of the Vaca Muerta formation. The contrast between the anhydrite nodules and the shales is clearly seen in the synthetic traces.

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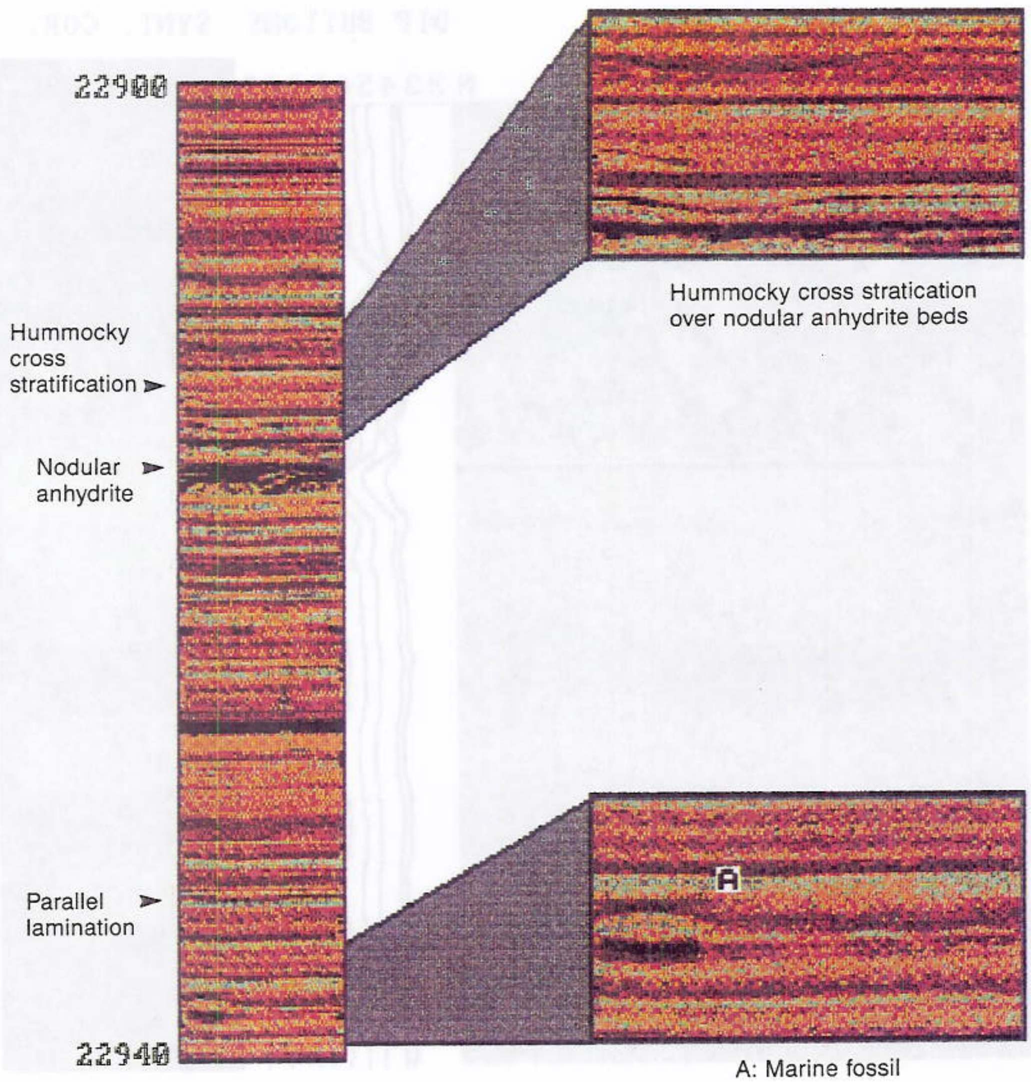

Fig. 14 — Top of the Vaca Muerta formation showing the supertidal deposits with fossils and parallel bedding reaching minimum depth with the anhydrite deposits towards the top. Hummocky crossbedded deposits are characteristic of tidal. The total depositional section evolution is shown in Fig. 11, which represents the lower deposits of the formation.

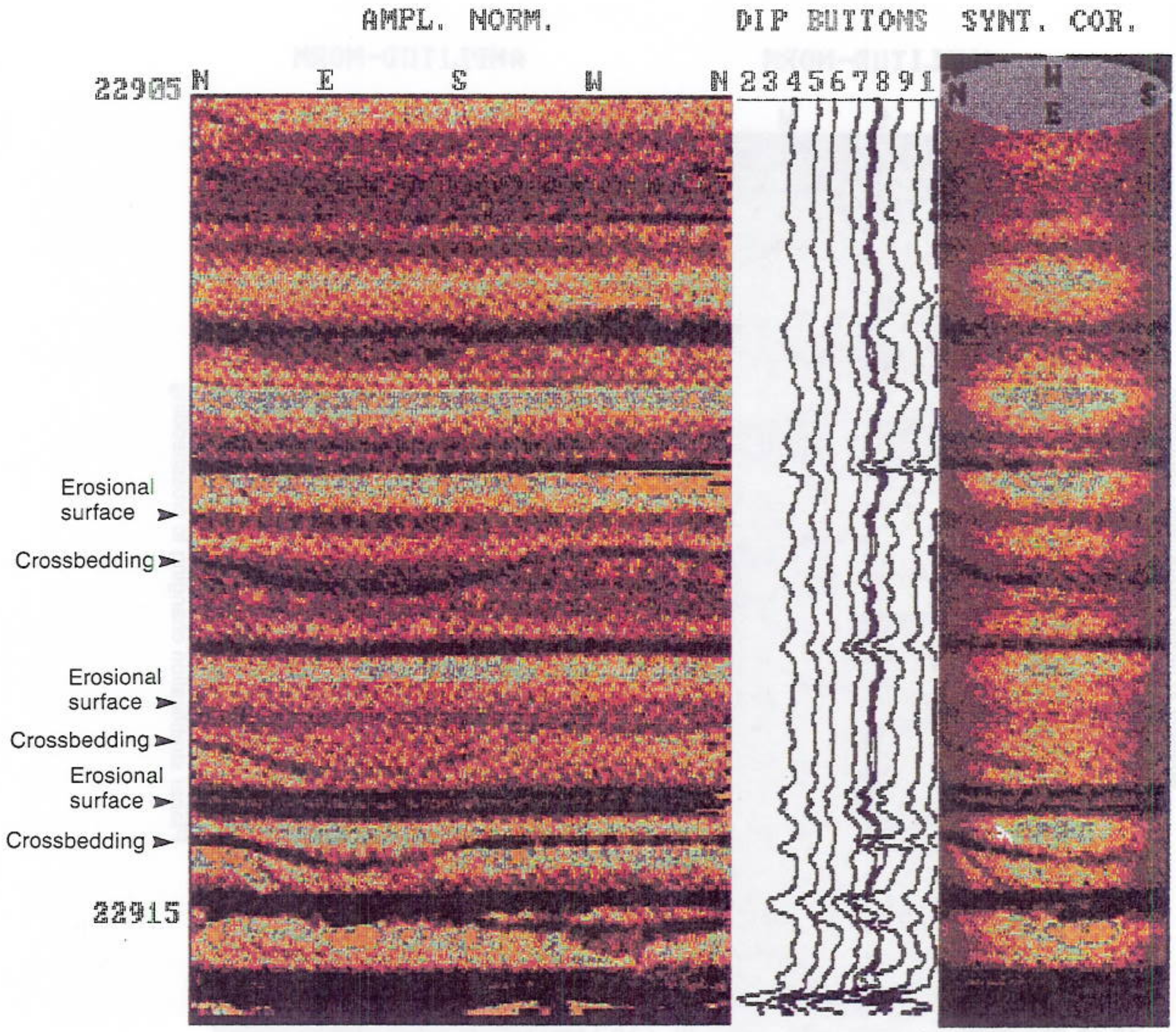

Fig. 15 — An example showing hummocky cross stratification. This structure shows several wavy crossbeds cut with erosional surfaces. They are common in tidal flat deposits.

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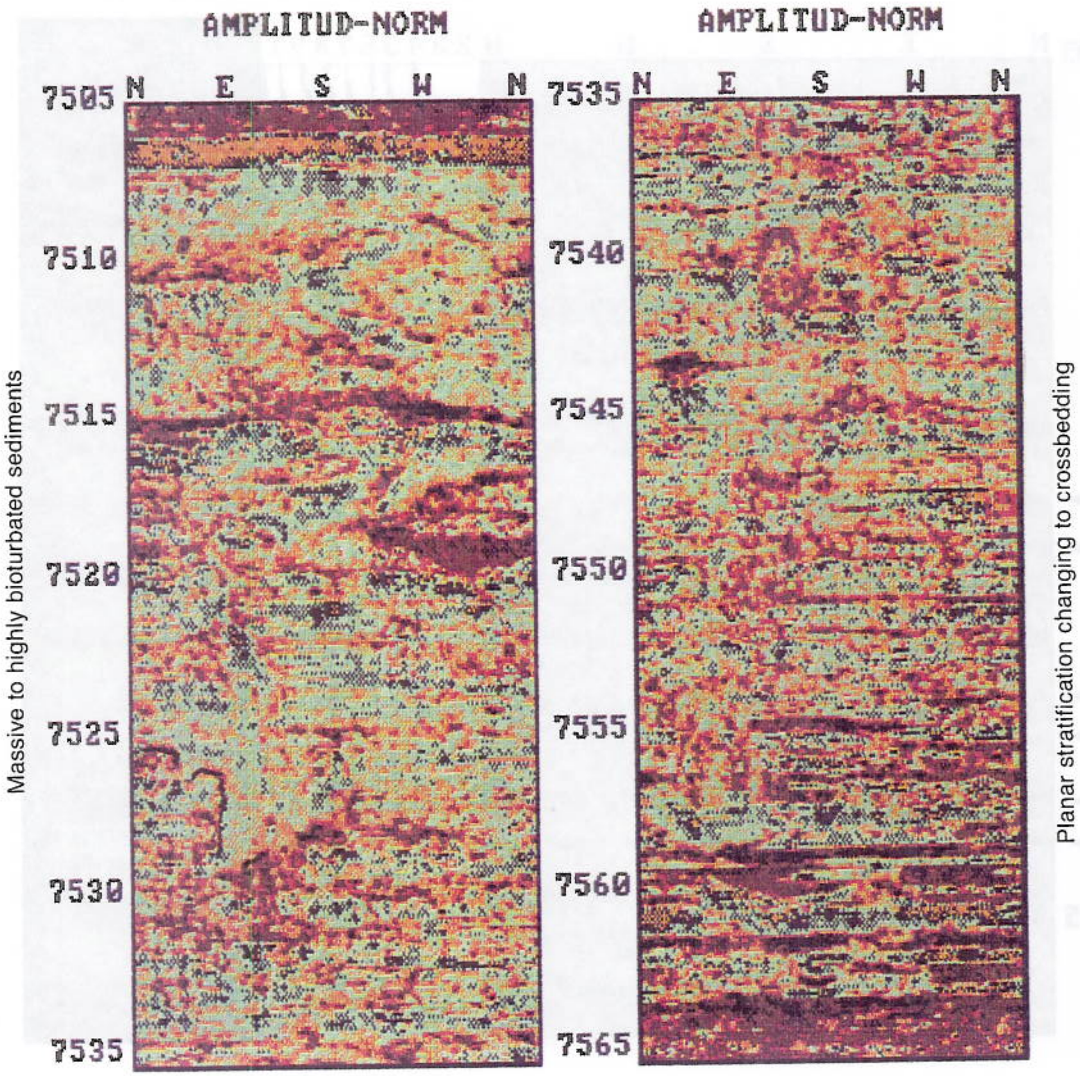

Fig. 16 — Total development of the Loma Montosa formation reed sequence. Planar stratification at the base is gradually changing to crossbedding at the top, where biogenic activity produces diffused structures.