CONEXPO ARPEL'92

RECOGNIZING SEDIMENTARY STRUCTURES, FACIES AND RELATED FACIES THROUGH COMPLETE BOREHOLE IMAGES.

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RESUMEN

El Circumferential Borehole Imaging Log (CBIL^{sm}) emplea un transductor acústico rotativo para generar una imagen completa de la pared del pozo. El desarrollo de nuevas técnicas de adquisición y procesamiento de las imágenes acústicas permite una mejora en la definición del perfil. Actualmente es posible inferir características sedimentarias tales como: tipos de estratificación, estructuras sedimentarias primarias y secundarias, depósitos multiepisódicos y sequencias. Una metodología integral, denominada protocolos, se propone como una guía para tener en cuenta durante el procesamiento e interpretación de las imágenes. Además, se presentan distintos ejemplos que ponen de manifiesto las ventajas que tienen estas herramientas y sus aplicaciones geológicas.

ABSTRACT

The Circumferential Borehole Imaging Log (CBIL^{sm}) device utilizes a focused rotating acoustic transducer to generate a graphic image of the entire borehole wall. The development of new techniques for acquiring and processing acoustic images permits improved log definition. It is now possible to infer sedimentary attributes like: types of stratification, primary and secondary structures, multistorey deposits and sequences. As a guide, a complete methodology, called protocols, is proposed to take into account during processing and interpretation of the images. Besides, a variety of field examples are presented showing the advantages of this kind of tools and related applications in geology.

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INTRODUCTION

The geological analysis of formations is fully optimized through the usage of well images with complete coverage (360°) of the borehole wall. The CBIL[sm] operates in a pulse-echo mode, sending acoustic (pulse) signals and detecting reflected (echo) signals from the borehole wall (1). Analysis of the reflected amplitude allows differentiation of:

- texture
- porosity
- mass properties

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

REGIONAL SETTING

The study area is located in the Neuquén Basin of west-central Argentina (Fig. 1). The stratigraphic record is characterized for the development of a thick Late Triassic, Jurassic, Cretaceous, and Early Tertiary sedimentary sequence, and emphasizes the Tithonian-Valanginian rocks of the Mendoza Group (2). The Mendoza Group contains the Tordillo, Vaca Muerta and Loma Montosa formations (Fig. 2).

Tordillo substratum are continental clastic sediments of eolian and alluvial fan origin (3). Vaca Muerta sediments are composed of shale source rock and dark carbonates belonging to marine and mainly marine euxinic shale deposits (3). The Loma Montosa Formation overlies the Vaca Muerta and represents inner platform sediments composed of clastic, carbonate and evaporitic rocks (3). The Loma Montosa is considered one of the most important reservoir rocks of the basin. CBIL[sm] image interpretation permits identification of different facies development and infers ancient depositional environments by recognition of sedimentary structures and textures (4).

METHODOLOGY

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 through histogram equalization over the entire range of depth. 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 defined considering the magnitude of events 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 insure that the recorded primary contrasts have been correctly honored during interpretation.

INTERPRETATION PROTOCOL

Interpretation 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 multi-step protocol is therefore highly recommended.

Correlation Images

Image plotting (normalized plot) is performed at compressed scales (1:40) to enable correlation accessibility to other open-hole logs, and eventually to depth match with dip vector plots.

Lithologic Modelling and Zoning of the Main Deposition Units

Identification of the primary lithofacies is determined by computing the mineral components using the other open-hole 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 were used to help detect macroscopic and mesoscopic features, and also to permit better correlation of the images to core data.

Sedimentary Structures Recognition

Sedimentary structure recognition is an analytical process that includes observation of lithologies and textures with subsequent recognition. The CBIL^{sm} permits recognition of a variety of attributes from the sedimentary rocks, such as texture, porosity and in general mass properties (5). In this sense, and due to the high vertical resolution (less than a cm) it is possible to infer sedimentary attributes like:

- ❑ types of stratification.
- ❑ internal primary structures, erosionals, deformationals, chemicals and biogenetics.

And from a stratigraphy point of view:

- ❑ multistorey deposits
- ❑ sequences

The CBIL^{sm} images show the complete borehole wall projected over a plane and for that reason some sedimentary attributes will appear distorted relation with the appearance in an outcrop or a sliced core. The magnitude of this effect is maximized in highly dipping features while in subhorizontal ones appear with no major distortion. Table 1 summarizes general guidelines for interpretation showing the process involved but not intending to cover all the possible sedimentary structures.

The methodology is based upon the discrimination of:

- configuration or geometry
- the scale and magnitude of the feature
- lithology

From this, it is possible to distinguish, for instance: geometry of the boundary, repetitive changes in color and texture and features form the interior of the beds. These are the first level elements of decision in the analysis of any event. Subsequently, aspects such as lithology, contrast, forms and relationships are taken into account allowing the identification of a unique sedimentary event.

SEDIMENTARY FEATURES

From another point of view, it is reasonable to consider the sedimentary features as self-interpretable or ambiguous (4). Acquired experience in CBIL^{sm} image interpretation of sedimentary features is summarized in figure 3.

Ambiguous Features

This occurs when well log or core data is needed to ensure interpretation exactness.

Self-Interpretable Features

This is possible whenever no external control is needed for the interpretation so that a unique interpretation of the feature results.

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 variation due to textural or depositional changes between bedding planes that are reflected as relatively high, dark and white contrasted bands that cross all the images in a parallel or subhorizontal orientation are shown (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 (6).

Cross Bedding

Cross bedding sedimentary structures in carbonates, corresponding to grainstones are typical of the Loma Montosa Formation The cross beds exhibit higher clastic influence due to an increase in transport energy. The structures are observed on CBIL^{sm} images as dark thin sinusoidal features (fine-grained clastic material) that cross the higher reflectivity zones (carbonates).

The sedimentary structures are of variable genesis, being related in this particular case to siliclastic or carbonate sequences with some type of fluid transport (7).

Lenticular Bedding

Lenticular structures are seen as bright, elongated spots that appear on the images as lenses of more reflective material. 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 (7). 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.

Irregular Stratification

Convoluted laminae represent penecontomporaneous deformation structures and are comprised of disturbed, distorted or deformed sedimentary layers produced by inorganic agents (7). Convoluted laminae appear as successive alternate beds of contrasting reflectance that are highly deformed and folded. Convoluted laminae are associated mainly with a high a rate of sedimentation of different viscosity and density materials (8).

Bioturbated structures are formed by biogenic activity on the surface or within still, unconsolidated sediments (9). The organisms cause destruction or regeneration of primary sedimentary structures that were previously formed through inorganic agents (7). The images appear as irregular, darker, subvertical features that penetrate the formation (Fig. 5). High reflectance loss of the signal corresponds to the presence of clay that fills the burrows.

Styolites

CBIL^{sm} images of styolites are represented by obscure, short, vertical lines are observed that are both abrupt and erratic in occurrence and may be sutured or undulated (7). Styolites are often observed in compact, cemented carbonate formations, and often occur in the Loma Montosa formation. These styolites are the result of a strong dissolution process no only in the lower but also the upper part of the bed. The growth of styolitic structure is due to the compressive stress.

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.

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 in order to infer the environmental and depositional evolution of the stratigraphic column described above.

Reconstruction began in the Kinmeridgian (144 my), 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. 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 semi-arid conditions as ephemeral channels.

Early Tithonian sediments of the Vaca Muerta Formation overly 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 sub-horizontal features) that result from cyclic variation of the carbonate/shale ratio. The variations produce typical rhythmic patterns of sedimentation clearly observed on CBIL℠ images (Fig. 4. The multistorey 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 due to the presence of anhydrite nodules deposited as small beds that are easily recognized on the acoustic images as rounded, irregular shapes with high reflectance contrast superimposed on the low reflectance host pelite sediment (Fig. 4).

The transition between the offshore to lower shoreface sediments is detected by the presence of some hummocky, cross-bedded strata coincident with the higher clastic depositional rate, thinner cyclic events, and rare occurrence of fossils (Fig. 4).

Finally, inner carbonate platform facies and also 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 interdigitated with tidal flat sediments.

Bar deposits are also recognized and characterized by planar stratification with highly interlayed shales at the base, changing gradually upward to cross-bedded carbonate deposits at the top. Intense biogenic activity may occur distorting primary sedimentation patterns that result in a massive internal structure.

The upper part of the Loma Montosa is characterized by a dramatic change in depositional conditions as evidenced by the abundance of psamopelitic deposits that dominate over the carbonates. At the formation base deformation structures are common, and development of 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 occurrence of storm deposits that appear occasionally in the column as erratic sand bodies (≈ 1.5 m thick) isolated within thick, muddy sediment. These erratic sand bodies have extraordinary petrophysical properties (porosities > 25% and permeabilities ≈ 1 darcy) making them attractive reservoir rocks. The complete stratigraphic sequence is illustrated (Fig. 5).

CONCLUSIONS

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. Moreover, applying the processing and interpretation protocols is possible to recognize several attributes from the sedimentary rocks that were quite forbidden using the traditional methods. Geological facies can be recognized through the proper use of available log data also.

ACKNOWLEDGMENTS

The authors wish to thank Western Atlas Argentina for permission to publish this paper. We also wish to thank the oil companies for allowing us to present the illustrative data. Thanks is also owed to several colleagues who offered editorial criticism to improve the text.

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Fig. 1

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

Fig. 2

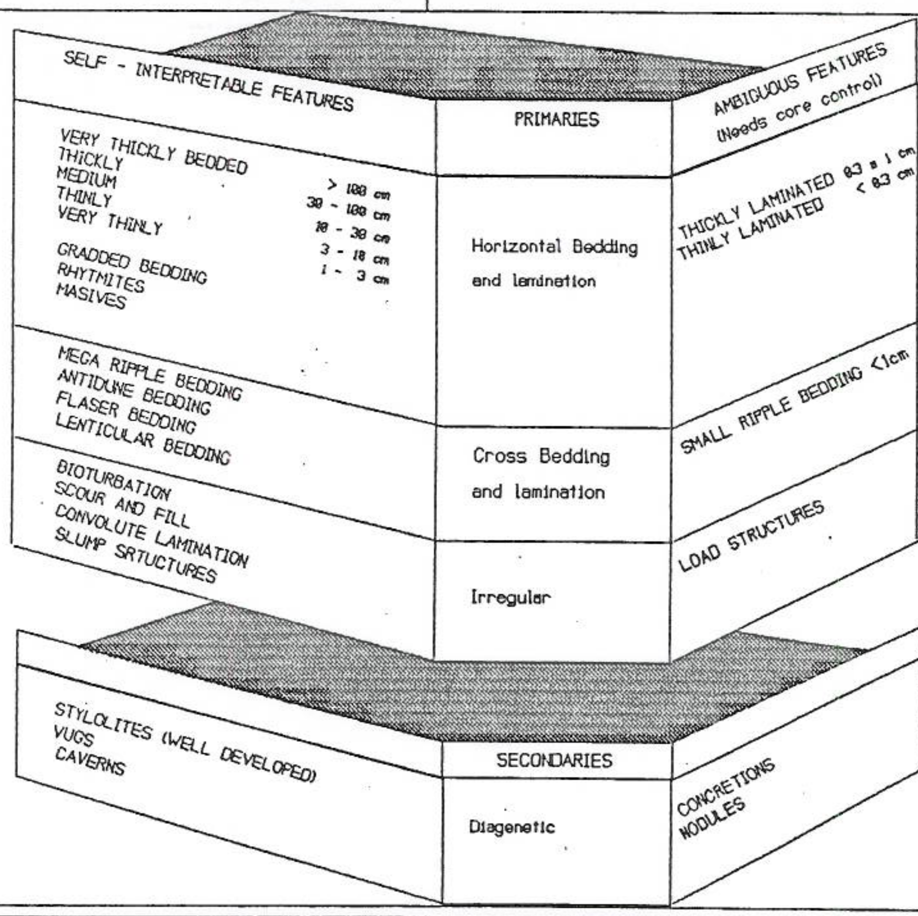

Fig. 3

Table 1.

General guidelines for image interpretation inferring the process involved.

Targets	Boundaries Geometry	Straight				Planar Stratif.
		Concave				Major Channel
		Solitaire Sinusoid				Minor Channel
		Repetitive Sinusoides				Dipping. Seq.
		Irregular				Scour Marks
						Flute Marks
						Load Structures
						Symmetric Wavy
						Asymmetric Wavy
	Repetitive Changes in Tone & Texture	Without changes in lithology	Clastic Cycle	Planar		Interestrat.
				Sinus.	Continuous	Mixed Wavy
					Disc > Sh	Lenticular
					Disc < Sh	Flaser
			Carbonate Cycle	> Sh		Muddy
				< Sh		Grainy
		With changes in lithology	Multistorey Cycle	Planar		Amalgamation
				Sinus.	Continuous	Wavy
					Discont.	Lenses
Features	Features from the interior of the beds	Open	In phase with the ss.	Clastic	Coarse	Horizontal Lam.
					Fine	Parallel Lam.
				Carbonates		Stromatolites
				Evaporites		Thin Bedded
			Unconformed	Clastics	Long Sinusoids	Cross Bedd. ss.
					Short Sinusoids	Cros. Bedd. lam
					Conformed base sinusoid	HCS
					Concave, in phase and columnar	Load and dish structures
				Carb		Stromatolites
			Subvert. and Obliques	Clastics < ϕ and > Sh		Cracks
				Carbonates / Clastics		Bioturbation
			Folded	Evaporites		Enterolitic
				Carbonates / Clastics		Convolute
		Close	More reflective than background	Clastics		Grains
				Carbonates		Pisolites and Oncolites
				Evaporites		Nodules
			Less reflective than the background	Clastics		Intraclasts, Fossils, Absent grains
				Carbonates		Fossils, Vugular or Cavernosa Porosity
				Evaporites		Vugular, Porosity, Differential Dissolution
		Amorphi	Carbonates (with change in ϕ)			Dolomitization
			Clastics (with change in ϕ)			Mud Cake

References:

Sh= shale content

ss= stratification

ϕ = porosity

HCS= hummocky cross stratification

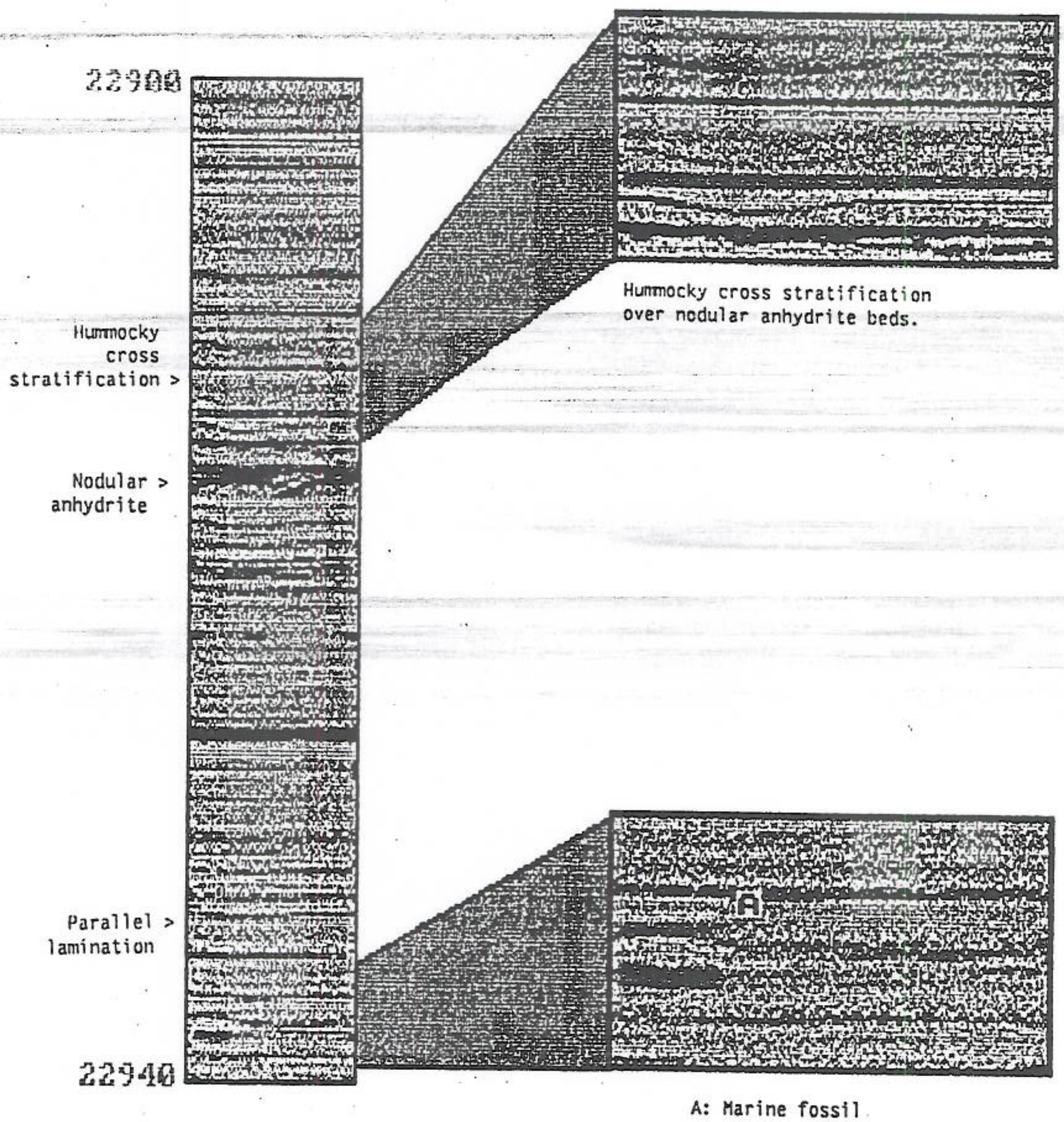

Fig. 4

Top of the Vaca Muerta Formation showing the gradually shallow deposits with fossils and parallel bedding reaching minimum depth with the anhydrite precipitates. Hummocky cross bedded terms are the tidal flats deposits characteristic. The total depositional section evolution is shown in Fig. 11, which represents the lower terms of the formation.

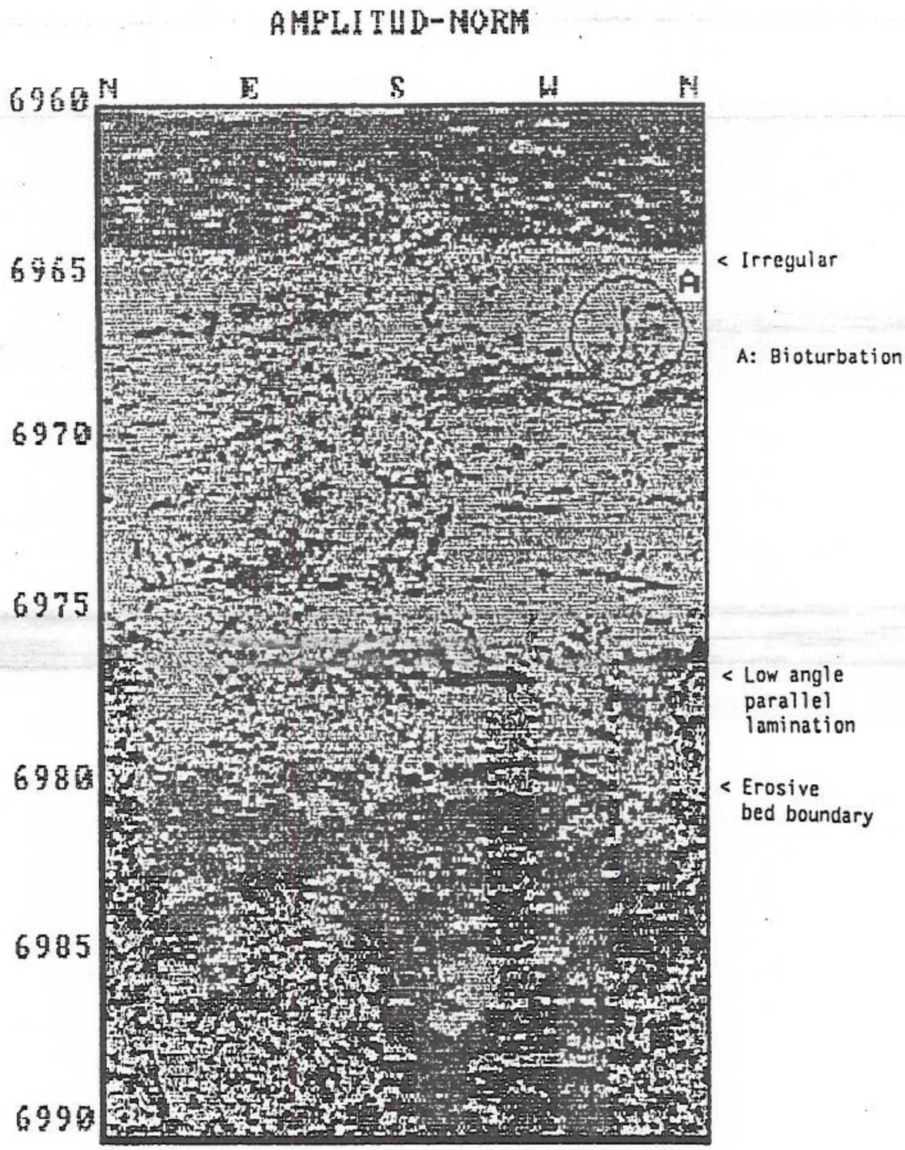

Fig. 5

Example of a storm sand body with bioturbation. Its basal contact is erosive and irregular. Parallel stratification is developed and it ends with a sharp bed boundary at the top. Important thickness of muddy sediments lay over the sand bodies and also beneath them.