STRATIGRAPHY AND PETROLEUM POTENTIAL OF THE ACARAU AND PIAUI-CAMOCIM SUB-BASINS, CEARA BASIN, OFFSHORE NORTHEASTERN BRAZIL

by

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ABSTRACT

The Acarau and Piaui-Camocim sub-basins are subdivisions of the Ceara basin, situated offshore in the northeastern continental margin of Brazil. Two main drilling phases, 1971-1973 and 1981, mark the exploratory activities in these areas. Twelve wells were drilled, but with no commercial production of petroleum. Although shows of hydrocarbons are common in most wells, only four of them yielded very small amounts of hydrocarbons during drill-stem tests (three gas; one oil).

The stratigraphic column represents the gradual infilling of an Atlantic-type marginal basin, highly influenced by tectonics (extensional and transpressional regimes) in the earlier stages and by sea level changes in the later phases. Five major depositional sequences constitute the stratigraphic framework of the studied areas. Sequence I (Early to Late Aptian) was deposited under strictly continental conditions and is represented by alluvial fan, lacustrine and fluvial depositional systems. Sequence II (Middle Aptian to Albian/Cenomanian) is represented by transitional to marine environments (deltas, shorelines, offshore) and characterizes the first invasions of marine waters into the rift-valleys. Sequence

III (Turonian to Santonian) represents marine transgressive sediments deposited under oceanic anoxic conditions. Sequence IV defines a period of high influx of terrigenous sediments, causing the development of a prograding continental margin. Sequence V (Eocene to present) is characterized by very shallow marine depositional environments (fan deltas intertonguing with carbonate platforms).

The most prospective reservoirs are the sandstones of Sequence II. The best source rocks are the anoxic deposits of Sequence III and lacustrine shales of Sequence I. The areas which present the best conditions of association of reservoirs and thermally mature source rocks are the northeastern and northern portions of the Acarau subbasin.

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INTRODUCTION

The Ceara basin is an offshore basin situated in the northeastern continental shelf of Brazil (Figure 1). Its age is Cretaceous/Tertiary, and it is composed of three sub-basins, from east to west: Mundau, Acarau and Piaui-Camocim (Figure 2). The Mundau area is the most explored one, having approximately six times more wells than in the other two areas combined. Several works have dealt with the geological aspects of the Mundau sub-basin (for instance, Souza et al., 1979; Marroquim et al., 1982), and it will not be the focus of this study. The Acarau and Piaui-Camocim sub-basins are very poorly explored and are considered as frontier areas.

The objective of this study is to describe and interpret for the first time the stratigraphy of the Acarau and Piaui-Camocim sub-basins, and to assess their petroleum potential. The first part of this work is the establishment of the stratigraphic column, based mainly on well data (logs, cores and descriptions of cuttings) and some seismic sections. The geological evolution of the basins can then be interpreted. Within this framework depositional systems containing potential reservoirs are recognized. The second part of this work consists of the

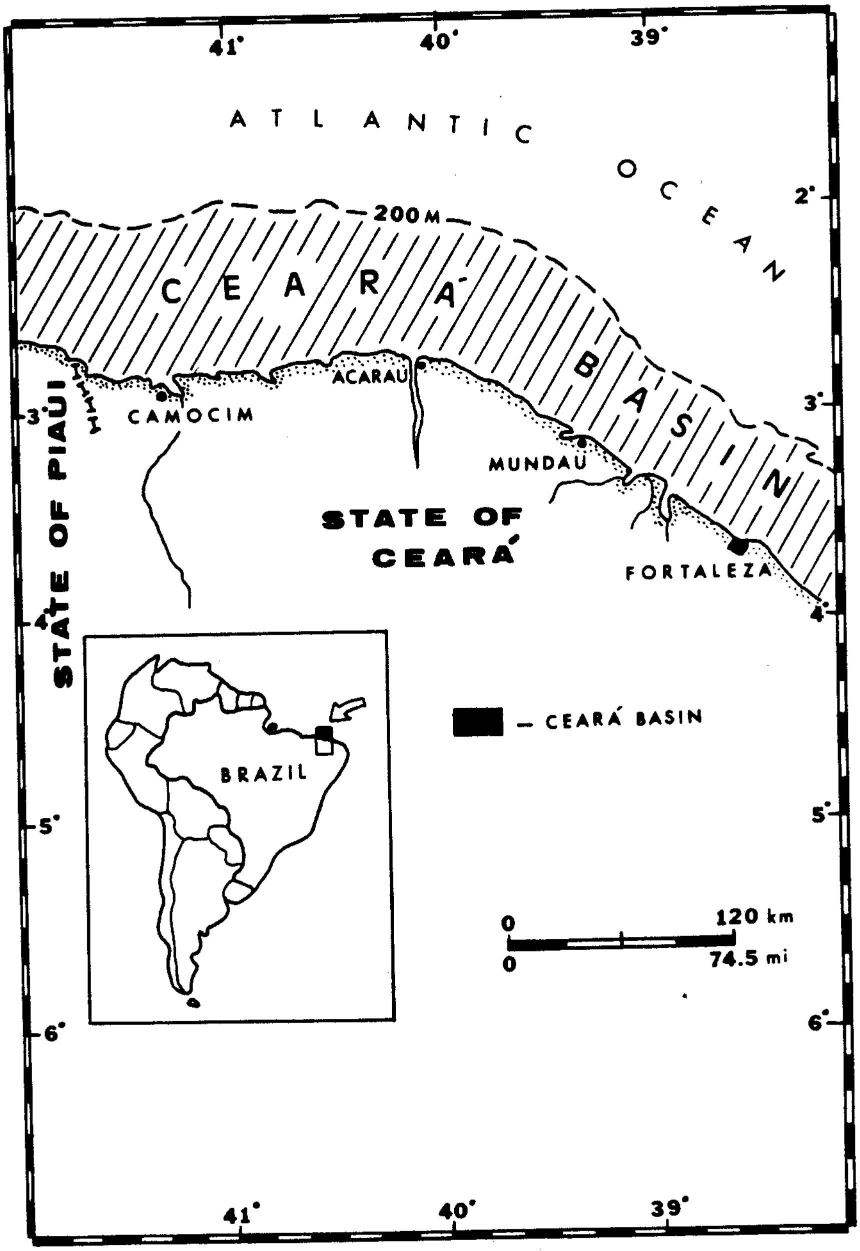


FIGURE 1 - Location map of the Ceara basin, offshore northeastern Brazil (modified from internal file maps of PETROBRAS).

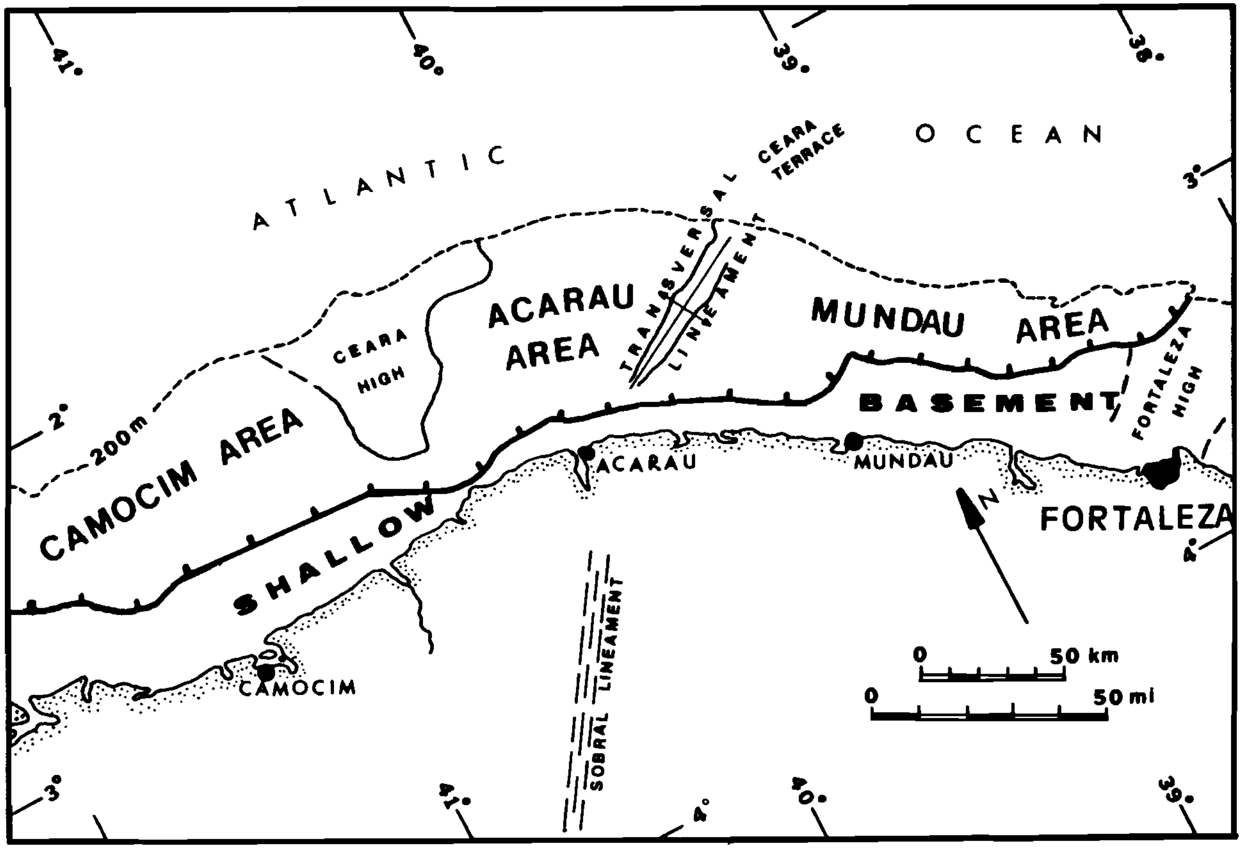


FIGURE 2 - Ceara Basin is composed of three sub-basins: Mundau, Acarau and Piaui-Camocim (modified from internal file maps of PETROBRAS).

interpretation of geochemical analyses of argillaceous rocks recovered from the wells. This interpretation enables the recognition of the main source rock systems, and also the determination of the areal distribution of mature oil-prone source rocks. Integration of the spatial distribution of both reservoir and source rock systems permits the delineation of areas with high potentiality for oil occurrence.

The Ceara Basin is bounded to the north by the 200 meter isobath and to the south by the shallow basement boundary (Figure 2, Plate 1). The 200 meter isobath is taken as the northern limit due to economic and technological reasons, however, the basins extend beyond that. In deeper waters both faulted blocks of Early Cretaceous age and slope sequences of Late Cretaceous and Tertiary age are present. These areas are beyond the scope of this study. Three large-scale structures trending approximately perpendicular to the shoreline subdivide the Ceara basin into three sub-basins. The Fortaleza high is the easternmost of them and separates the Mundau sub-basin from the Potiguar basin (Figure 2). It is a buried seamount composed of volcanic rocks, sometimes called the Ceara guyot, and represents the westward extension of the Fernando de Noronha ridge. The Transversal lineament is a huge horst block which displays large anticlinal structures along its extension. It is the seaward extension of the Sobral lineament, which is a Precambrian transcurrent fault which has been reactivated during the Paleozoic, Mesozoic and, probably, even up to the present. Recent small-scale earthquakes in the state of Ceara are probably related to this wrench fault system. In deeper waters to the northeast this strong horst character is reflected in the ocean bottom physiography by the occurrence of an extensive terrace (Ceara terrace). The Ceara high divides the Acarau and Piaui-Camocim sub-basins. Based on Figure 4 of Miura and Barbosa (1972) and on the data presented by Bryan et al. (1972) the high is considered to be composed of Precambrian crystalline rocks, and perhaps Paleozoic sedimentary rocks. This high, together with the Atlantic high (adjacent to the northwest) (Plate 1), forms a pronounced offshore basement ridge which represents the landward extension of the Romanche fracture zone. The Piaui-Camocim area is sometimes considered a separate basin (Piaui basin) due to its large dimensions. In this study the status of sub-basin is preferred. The dimensions of the two sub-basins studied are approximately 8500 km^2 (Piaui-Camocim) and 4225 km^2 (Acarau).

There were two exploratory phases in these two sub-basins. The beginning of exploration in the overall Ceara basin took place in the Acarau and Piaui-Camocim zones with the drilling of 5 wells (CES-1, 2, 3, 4 and PIS-1) between 1971 and 1973. No success was obtained; the wells CES-1, CES-2 and PIS-1 were classified as sub-commercial producers of gas. Exploration shifted to the Mundau sub-basin, where the wells CES-8, CES-19, CES-23, CES-27 and CES-33 found five distinct commercial accumulations of oil. Consequently, exploration was almost entirely concentrated in this area. Meanwhile, two other dry holes were drilled in the Acarau sub-basin in 1975 (CES-5) and 1977 (CES-11). Only after completion of several new seismic lines in the Acarau zone and the delineation of several large domal structures was exploration in the latter area resumed with great intensity. In 1981 five wells were drilled, all of them dry holes. Three of these five wells had abundant oil shows. Geochemical analyses indicated that mature oil-prone source beds are present in the area. Sandstones are very common in the entire sections drilled. Widespread unconformities are present to provide traps. The absence of economic accumulations of oil is attributed to absence of porosity and permeability in the sandstones. These facts prompted search for stratigraphic-type accumulations of hydrocarbons; in such a program a correct understanding of the nature and distribution of the depositional environments of both the reservoirs and source rocks are of fundamental importance, and thus this study was undertaken.

I - DATA BASE, METHODS AND APPROACH

The material used in this study is summarized in Table 1. Data from twelve wells drilled by Petrobras in the Acarau (nine wells) and Piaui-Camocim (three wells) areas were extensively used, as well as some seismic sections. The data base includes tens of thousands of meters of electrical logs run by Schlumberger, descriptions of thousands of cuttings samples made by several wellsite geologists of Petrobras, twelve cores (described and interpreted by the author), thin sections (studied by the author), hundreds of micropaleontological and geochemical analyses performed by geologists of the Paleontology and Geochemistry laboratories of Petrobras; and synthetic seismograms also supplied by Petrobras. All the interpretations presented in this work, resulting from the analysis and integration of the above cited data base, are the exclusive responsibility of the author.

This research was divided into three stages. The first part (Chapter III) consisted of the description and environmental interpretation of available cores, analysis of the descriptions of the cuttings, and the lithological interpretation of the sedimentary section of each well (based on the responses of the electrical logs and the

TABLE 1 - Material used in this study: T.D. - terminal depth, Rt - total interval of resistivity log, GR - total interval of gamma ray log, BHC - total interval of sonic log, FDC - total interval of density log, DIP - total interval of dipmeter log, DST - number of drill stem testings, CUT. - number of cutting samples, CORES - total interval cored, THIN SEC. - number of thin sections, Ø + K - number of porosity and permeability analyses, PALE. - paleontological analyses, F - foraminifer, P - palynology, N - nannofossils, O - ostracodes, GEOCHEM. - number of samples analyzed for geochemistry, SEIS. SEC. - number of seismic sections.

BASIN	WELL	T.D. (m)	RT (m)	GR (m)	BHC (m)	FDC (m)	DIP (m)	DST	CUT.	CORES (m)	THIN SEC.	Ø • K	PALE.	GEO-CHEM.	SEIS. SEC.
ACARAU	1-CES-2	3769	3442	3248	3249	2014	2978	6	1137	—	3	—	P,F,N	76	
	1-CES-4	3160	2890	2887	2887	—	2651	—	1030	—	3	—	P,F,N	69	
	1-CES-5	3847	2919	3543	2915	1225	2916	1	1030	15.0	7	2	P,F	96	
	1-CES-11	2418	1950	2250	1948	1950	1950	—	752	18.0	6	1	P	25	
	1-CES-48	3201	2425	2888	2416	2269	1008	—	870	28.5	11	2	P,F,N	33	
	1-CES-50	2726	2014	2432	2005	2014	412	—	737	5.0	7	1	P,F	44	
	1-CES-52	4035	3313	3799	3304	2237	2080	1	1111	2.0	5	—	P,F,O	67	
	1-CES-55	3037	2668	2667	2658	2669	2438	1	948	7.9	9	4	P,F,O	39	
	1-CES-56	3354	2870	3190	2862	2872	1957	—	857	—	4	—	P,F		
PIAUI - CAMOCIM	1-CES-1	2978	2539	2539	2539	—	1469	1	787	—	1	—	P,F,N	3	
	1-CES-3	3676	3424	3417	2881	—	2881	—	974	—	3	—	P	7	
	1-PIS-1	3857	3466	3559	3559	1402	1313	1	1115	—	4	—	P	111	
	TOTAL	40058	33920	36419	33223	18652	24053	11	11348	76.4	63	10	—	570	8

descriptions of cuttings). The environmental interpretation of the lithologic columns was performed using the analyses of the cores, presence of characteristic lithologies and fossils, micropaleontological analyses, and the patterns displayed on the electrical logs. Some wells were tied to seismic sections and the patterns of reflections were also used to help determine depositional environments. Micropaleontological analyses determined the age of the sedimentary rocks and also helped in the determination of unconformities. Unconformities were mainly determined by paleontological data (indications of hiatus). Secondarily, changes in the electric logs (mainly dipmeter) and lithological/environmental evidence were also used either to confirm or to infer the presence of unconformities.

The second part (Chapters IV and V) consisted of the integration of the results obtained in the first part in order to establish the stratigraphic column (Chapter IV) and the geological evolution (Chapter V) of the studied basins. Several cross-sections and isopach maps were constructed. Seismic sections were also used to perform correlations. Strips of seismic sections at the locations of some wells are shown in order to display the seismic responses of the depositional sequences determined.

The third part (Chapter VI) was the characterization of the principal source rock systems present in the basins, by means of the geochemical data. Their stratigraphic position, areal distribution and maturation stages were determined. The integration of the spatial distribution of reservoir rocks and source rocks led to the delineation of areas most favorable for petroleum exploration.

II - A SUMMARY OF THE GEOLOGICAL EVOLUTION OF THE BRAZILIAN MARGINAL BASINS

The systematic geologic investigation of the Brazilian sedimentary basins began in 1954, following the creation of Petroleo Brasileiro S.A. - PETROBRAS. In 1968 the exploration of the offshore basins was initiated. Much data have been accumulated during these fifteen years of exploration. As a result several regional syntheses were done, and they led to a much better understanding of these basins. This knowledge permitted: (1) the comparison with other similar producing basins of the world (for instance, the offshore basins of West Africa), (2) an appraisal of the petroleum potential of the less known offshore basins, and (3) determination of the role played by these basins and their structures in a global-scale geology (plate tectonics).

The landmark of these studies is the work done by Asmus and Porto (1972) in which the authors developed the genetic classification of Brazilian sedimentary basins according to plate tectonics concepts. Several major syntheses of the knowledge which was gradually being obtained followed. Only some of them will be cited, in which the interested reader can find extensive bibliographic references for more specific subjects concerning the Brazilian marginal basins. They are: Asmus and Ponte (1973), Campos et al. (1974), Ponte and Asmus (1976, 1978), Ponte et al. (1978), and Brown and Fisher (1977). The following summary is mostly based on the works by Asmus (1981) and Ojeda (1982), which constitute the most recent references on Brazilian marginal basins.

The origin of the Brazilian marginal basins is intimately related to the opening of the South Atlantic Ocean. Their evolution and consequently their stratigraphy reflect the step by step separation of the South American and African continents. This continental separation began in the Jurassic, when thermal activities of regional scale took place heralding that the quiescence of the vast Brazilian craton would be disturbed by a major tectonic event. Thermal doming in two vast areas occurred. The largest dome was situated approximately at the present locations of the Santos and Campos basins, while the second was located in a region that encompasses the present Pernambuco/Paraiba basin (Figure 3). The Early Cretaceous was marked by intense tectonic activity, mainly in the form of normal faulting and intense volcanic activity. The most extensive flood basalts of the world (the basalts of the Parana Basin) were extruded between 130 and

105 million years ago. Subsidence of the crust began and the compartmentation of the marginal basins took place. During the Aptian the marine waters first invaded the rift-valleys, and where restriction occurred extensive beds of evaporites were deposited. Finally during the Albian normal marine circulation was established, and the sediments deposited during this time and up to the present are predominantly marine. Figure 3 shows the localization of the Brazilian marginal basins. Figure 4 shows schematically their geologic evolution.

It has been long observed that the sedimentation and the characteristics of the sediments deposited in the Mesozoic basins related to the opening of the South Atlantic ocean could be arranged into a small number of discrete stratigraphic super-units. Each super-unit is defined by sediments representing a group of related depositional environments which existed during certain stages of the separation of the continents, after which they are named. Asmus and Porto (1972) recognized the rift-valley, the evaporitic and the open marine sequences. This three-fold division was used in subsequent works. Asmus (1981) introduced a fourth interval including the sediments deposited around the Jurassic thermal domes very well preserved in the onshore basins and present in the deepest parts of

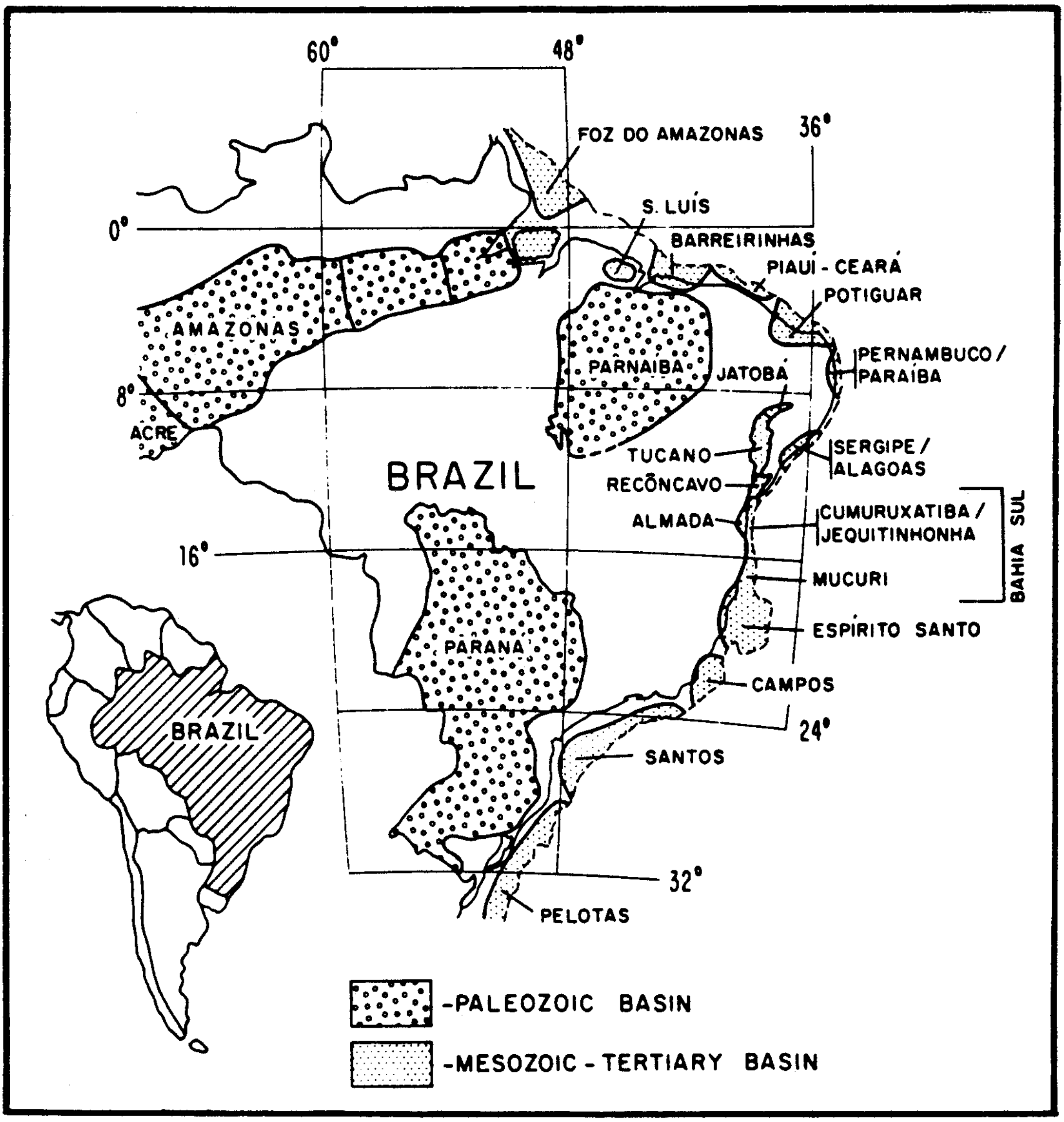


FIGURE 3 - Index map of the Brazilian marginal basins (from Ojeda, 1982).

FIGURE 4 - Schematic geological evolution of the Brazilian marginal basins. See text for summarized discussion.

A - PRE-RIFT ARCH STAGE

B - RIFTING STAGE

C - PROTO-OCEANIC STAGE

D - OPEN MARINE STAGE (Lower carbonate sub-sequence)

E - OPEN MARINE STAGE (Upper clastic sub-sequence)

LEGEND

— direction of main drainage

— direction of minor drainages

S.A.P. — South American plate

A.P. — African plate

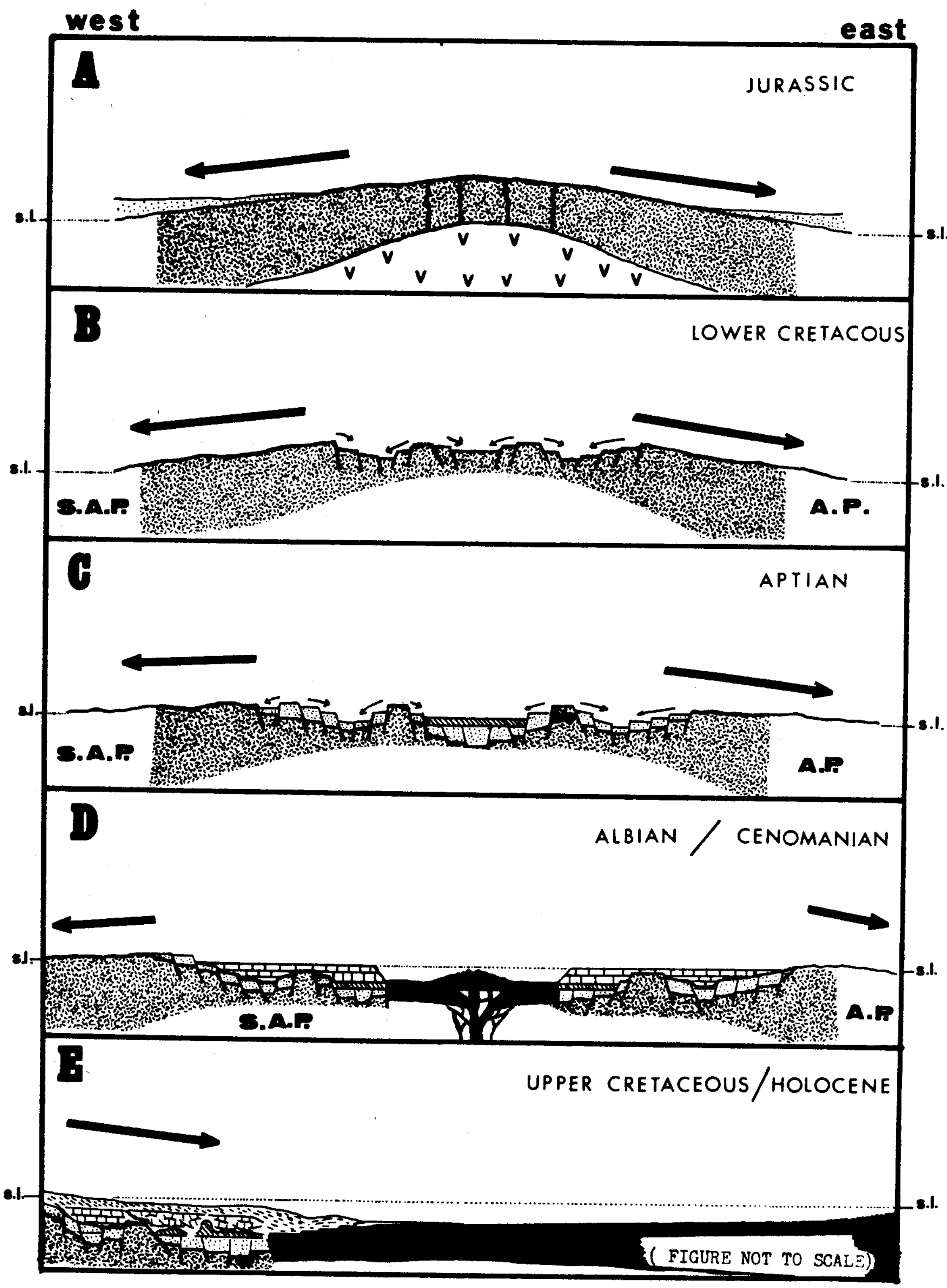
— clastic sediments

— continental crust

— evaporites

— oceanic crust

— carbonates


west
east
A
JURASSIC
s.l.
s.l.
B
LOWER CRETACOUS
s.l.
s.l.
S.A.P.
A.P.
C
APTIAN
s.l.
s.l.
S.A.P.
A.P.
D
ALBIAN / CENOMANIAN
s.l.
s.l.
S.A.P.
A.P.
E
UPPER CRETACEOUS/HOLOCENE
s.l.
s.l.
(FIGURE NOT TO SCALE)

some offshore basins. Each of these four sedimentary sequences can be related to a specific geologic environment or stage of the continental separation, and, according to Asmus (1981), they are:

(1) PRE-RIFT STAGE or CONTINENTAL SEQUENCE (Figure 4A) - clastic sediments of Late Jurassic age deposited in fluvial (braided), lacustrine and eolian environments, in peripheral basins situated around the two major domes cited above. Tectonic quiescence prevailed during this time.

(2) RIFTING STAGE or LACUSTRINE SEQUENCE (Figure 4B) - during the Early Cretaceous intense tectonic activity occurred mainly as normal faulting. Numerous rift-valleys were formed and they were the sites of extensive lake development. Lacustrine deltas and turbiditic deposits developed into these lakes. The age of the rifting was not uniform along the Brazilian continental margin. It was older (Neocomian) in the eastern margin and younger (Aptian) in the northern equatorial basins (e.g.: Ceara basin).

(3) PROTO-OCEANIC STAGE or GULF SEQUENCE (Figure 4C) - composed of evaporites and clastic sediments of transitional character, deposited during Alagoas age (Brazilian stage roughly equivalent to the Aptian). During this time the first marine waters invaded the rift-valleys. In the eastern marginal basins (from Santos to Sergipe/Alagoas) extensive beds of evaporites were formed. Ojeda (1982) recognized two distinct evaporite cycles. The occurrence of evaporites in this eastern area was due to restriction caused by the Pernambuco/Paraiba uplift in the north and by the volcanic Rio Grande-Walvis ridge in the south. Intermittent bypassing of marine waters through this southernmost barrier provided the necessary recharge to evaporitic basins (see Figure 3). It is interesting to notice that restriction increases from south to north. In the Santos basin evaporites are solely anhydrite, halite appears in the intermediate basins, and in the Sergipe/ Alagoas basin we had the deposition of potassium and even magnesium salts. In the northern equatorial basins (from Potiguar to Amapa) large-scale restricted conditions did not occur, and this sequence is represented by clastic sediments of transitional environments (for instance, deltas, barrier bars, tidal flats). Some isolated evaporites can be found in the Ceara and in some onshore basins.

(4) OPEN MARINE STAGE or MARINE SEQUENCE - includes Albian/Cenomanian carbonates (LOWER CARBONATE SUB-SEQUENCE, Figure 4D) deposited in shallow platforms and clastic sediments of Turonian to Holocene (UPPER CLASTIC SUB-SEQUENCE, Figure 4E) deposited during several transgression/regression events that affected the continental margin. Main depositional environments are slope, continental rise and shallow platform. In some basins the carbonate sub-sequence is practically non-existent (e.g.: Ceara basin). Among the four sequences this last one has the greatest areal extent and also the greatest volume of sediments.

It is necessary to emphasize the fact that the above scheme was constructed based mainly on the eastern margin basins, which are related to the opening of the South Atlantic. However, the northern equatorial basins (including the Ceara basin) have their evolution linked to the opening of the North Atlantic. Consequently, differences in the structural and stratigraphic framework exist and should be emphasized:

(i) The ages of rifting are different. According to Asmus (1981) in the equatorial segment faulting could have been initiated as early as Triassic, but most faults were active into the Aptian/Albian, or locally into Late Cretaceous. During these times the eastern margin was essentially quiescent.

(ii) The absence of large scale barriers, such as the Rio Grande-Walvis ridge, prevented the occurrence of restricted conditions. Consequently no extensive evaporite beds were deposited (with few local exceptions). The Aptian sequence is represented by transitional clastic sequences or, sometimes, even open marine sequences. Open marine conditions were established earlier in the equatorial basins during a period when tectonic activity was still going on.

(iii) The relative movement of separation between the South American and African plates in the equatorial segment was of transcurrent character in the initial stages instead of orthogonal as in the eastern margin. This led to the occurrence of transpressional regimes during the Santonian, originating compressional structures in the Piaui-Camocim and Acarau areas.

III - SUMMARY OF THE STRATIGRAPHY OF THE WELLS

In this chapter the stratigraphy and interpretation of depositional environments is summarized for each well. For each well a composite of electrical logs, interpreted lithologies and interpreted depositional environments is presented (Plates 2-13). Four types of electrical logs are usually displayed, being from left to right: gamma ray, resistivity, sonic and density. The density log is present only in certain intervals or is not present at all (CES-1, CES-3). Although the dipmeter log was widely used in the interpretation it is not shown in the composite logs. However, when the dipmeter patterns are fundamental for the interpretation of an unconformity or a fault they are shown in a separate figure. The column between the gamma ray and the resistivity logs is used to portray the interpreted lithologies. Sandstones, limestones and igneous rocks are indicated with their classical symbols (see Appendix A). Blank space indicates argillaceous rocks. The nomenclature of argillaceous rocks employed is the one presented by Folk (1974, Table 2). In the available spaces of the composite logs ages, depositional environments, unconformities, important lithological characteristics and fossils, shows of hydrocarbons, and fining- and coarsening-upward patterns are noted. Depths used in these logs are related to the kelly bushing (KB) of the rotary table.

Each well is divided into several intervals reflecting different depositional environments. Related depositional environments are grouped into larger order "sequences" such as continental, transitional or marine. For instance, an association of fluvial, lacustrine and alluvial fan depositional environments forms a continental sequence. An association of delta, barrier bar, marsh, lagoon and tidal flat depositional systems represents a transitional sequence. Carbonate platform, slope and continental shelf depositional systems compose marine sequences.

In this chapter the several intervals representing different depositional environments and their groupings into sequences are presented and very briefly discussed for each well. Descriptions of cores, which are fundamental for environmental interpretation, are also here presented. At the end of each well a table summarizes the vertical piling of the different depositional sequences. Depths in these tables are related to sea level. These tables form the foundation for the establishment of the stratigraphic column of the studied basins (Chapter IV).

The first nine wells discussed are located in the Acarau sub-basin, and the last three ones in the Piaui-Camocim sub-basin (see Plate 1). The order of presentation of the wells of the Acarau area is from the continent to the sea. The reader will notice the gradual appearance and thickening of certain sequences as the presentation moves seaward. The sedimentary column is much more complete and thick in wells situated in more offshore positions.

CES-4 (Plate 2)

3152-2575 m - interval composed of intercalations of sandstones and argillaceous rocks (predominant). Coals occur near 3100 m. Continental conditions are indicated by paleontology (absence of foraminifera and dinoflagelates). It is interpreted to represent a fluvial meandering system.

2575-2260 m - argillaceous rocks predominate. It is a highly radioactive interval. Geochemical data indicate preservation of cellular vegetal organic material. Continental conditions are indicated by paleontology. It is interpreted to represent lacustrine deposits.

2260-2133 m - interval composed of intercalated sandstones and argillaceous rocks. Paleontology indicates continental conditions, and no detailed environmental interpretation was possible.

These three intervals together form a continental sequence.

2133-610 m - the appearance of several thin beds of limestone, besides the predominant sandstones and argillaceous rocks, indicates changing environmental conditions. Several beds of shells (probably coquinas) occur concentrated in certain stratigraphic levels, associated with coals and shows of gas. Interpreted depositional environments include lagoons, marshes, shoreline and deltas. This interval represents a transitional sequence. The well crossed a normal fault at 1800 m (Figure 5), indicating that rifting was still going on during the first invasions of marine waters.

610-347 m - argillaceous rocks predominate. Paleontology indicates shallow marine fauna. A muddy offshore depositional environment is interpreted. This interval represents a marine sequence.

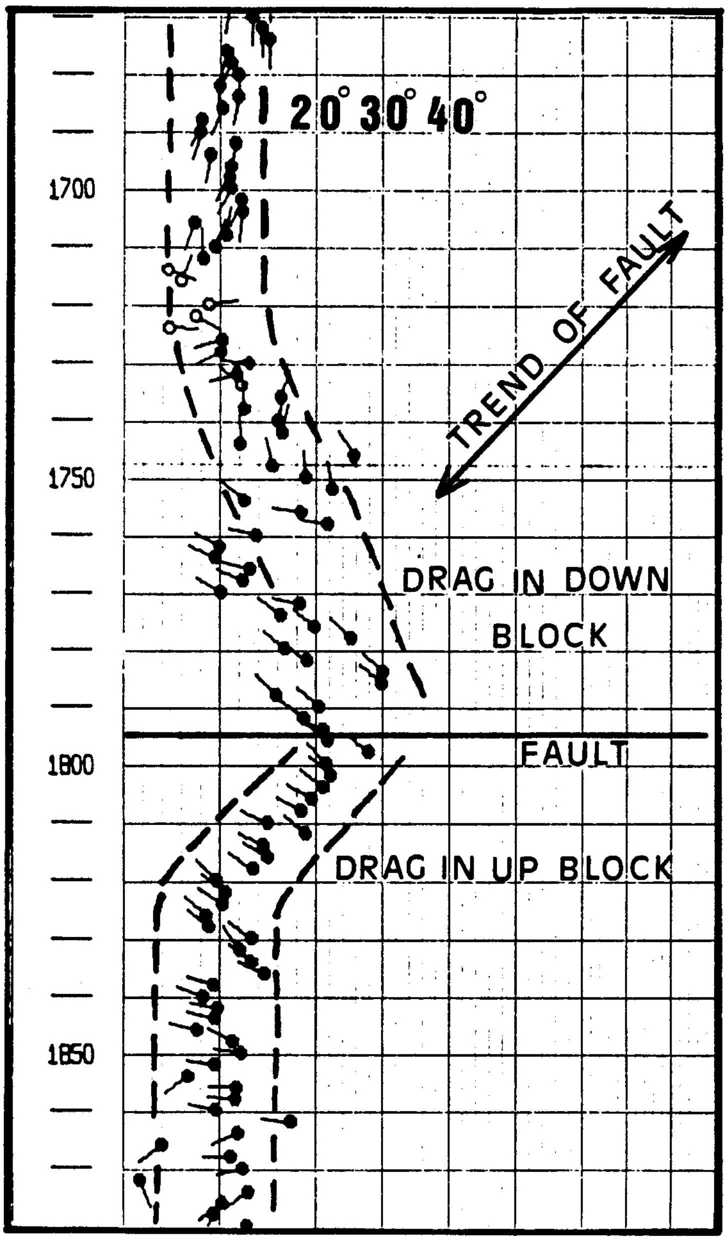


FIGURE 5 - Dipmeter log displaying normal fault at 1800 meters, CES-4.

An unconformity occurs at 347 m, defined by paleontological and seismic criteria and log characteristics. Tertiary sedimentary rocks overlie Albian ones.

347-sea bottom - coarse-grained sands predominate, with minor intercalations of calcarenites. Shallow marine conditions are indicated by paleontology. These deposits are interpreted as resulting from deposition of fan deltas within a shallow shelf dominated by carbonate deposition (intertonguing of both environments).

Table 2 summarizes the depositional sequences, unconformities and ages occurring in this well.

CES-11 (Plate 3)

2418-2375 m - medium-grained, thick bedded (up to 10 m) sandstones predominate. Continental conditions are indicated by paleontology. It is interpreted to represent a fluvial system, probably braided.

2375-1855 m - interval composed of intercalated sandstones and argillaceous rocks. Coals occur near 2340 m. Paleontology indicates continental environments. Core #1 recovered sandstones interpreted to represent levee and

AGE		DEPTH M	DEPOSITIONAL SEQUENCES	
TERTIARY		325	MARINE SHALLOW	
ALBIAN		588	MARINE SHALLOW	
APTIAN	LATE		TRANSITIONAL	DELTA
	MIDDLE (?)	2111	CONTINENTAL	LAKE / FLUVIAL
		3130		

TABLE 2 - Generalized stratigraphic column of the CES-4. Depths are related to sea level.

crevasse splay deposits, and argillaceous rocks interpreted to represent floodplain facies (Figure 6). A fluvial meandering system is assigned to this interval.

1855-1550 m - argillaceous rocks predominate. Continental conditions are indicated by paleontology. Log characteristics are very similar to those of interval 2575-2260 m in the CES-4. The interval is interpreted as lacustrine deposits.

1550-1400 m - interval composed of intercalated sandstones and argillaceous rocks. Paleontology indicates continental conditions. A marginal lacustrine environment is suggested to these deposits, without further detailed interpretations.

These three intervals compose a continental sequence.

1400-990 m - interval composed of sandstones, argillaceous rocks and thin beds (1-2 m) of limestones. This interval is very similar to the interval 2133-610 m of the CES-4, except for the coquinas and coals which are here absent. It is interpreted as deltaic deposits.

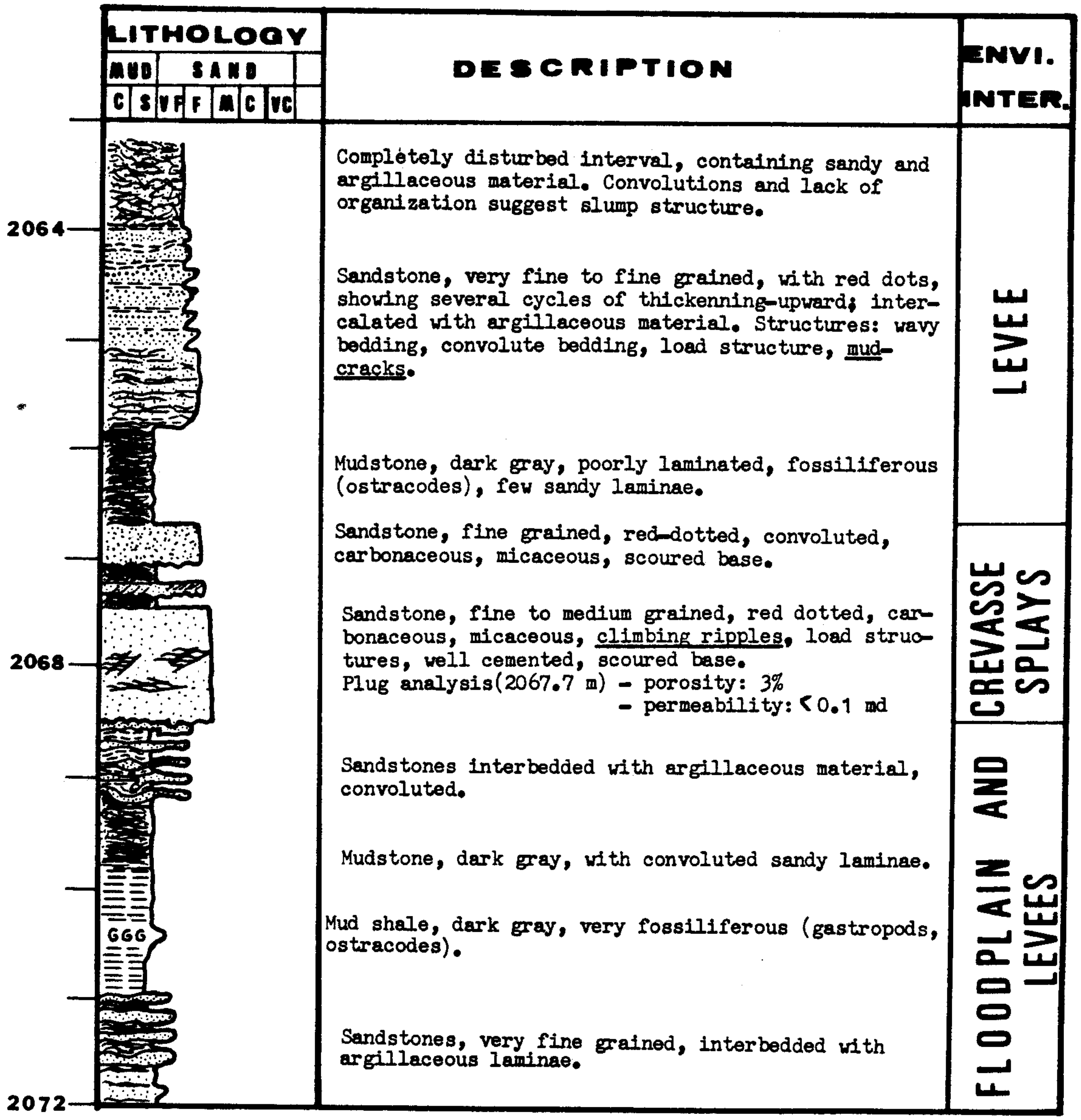


FIGURE 6 - Lithological description and environmental interpretation of core #1, well CES-11. Depths in meters.

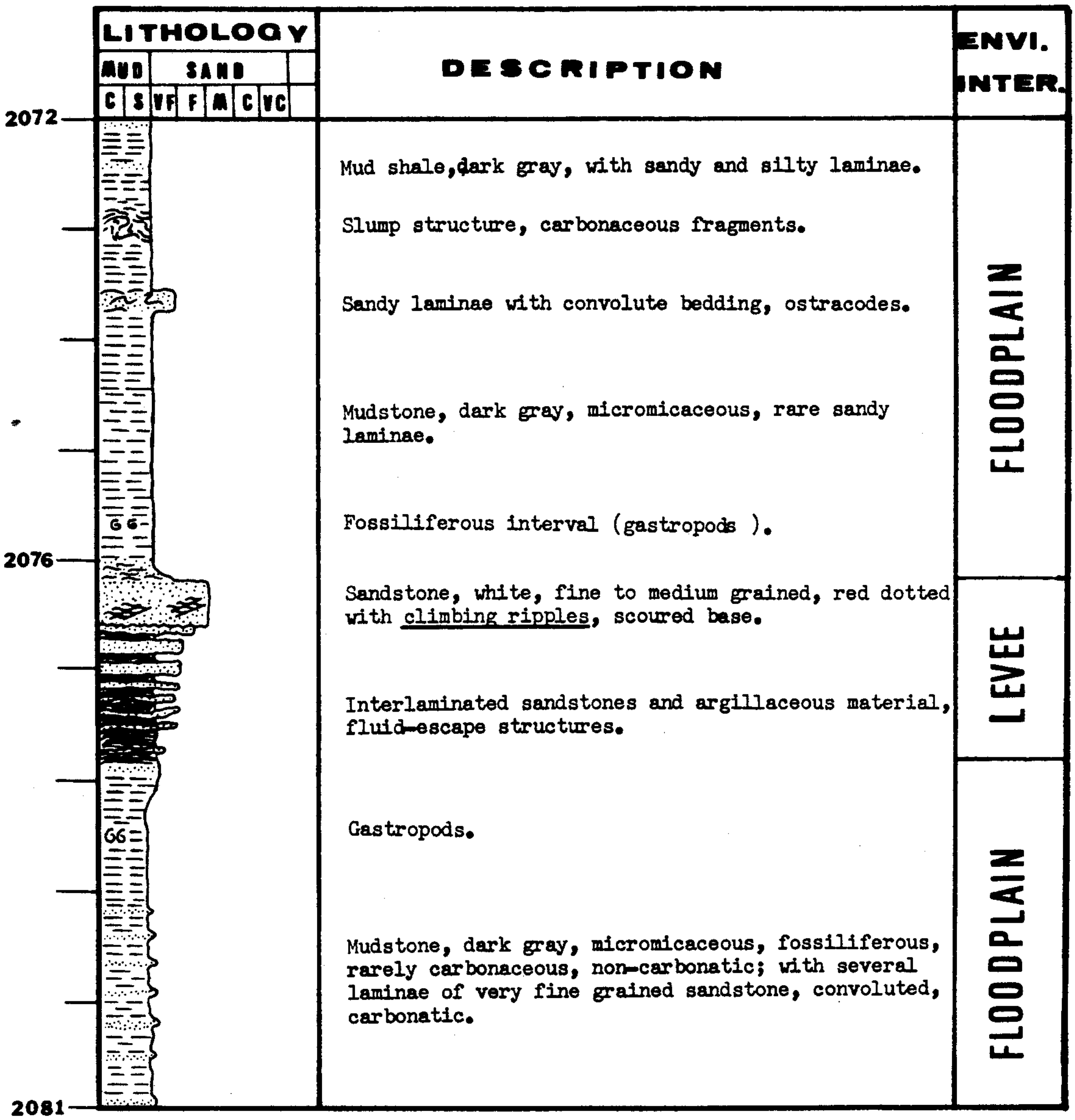


FIGURE 6 (continuation) - Lithological description and environmental interpretation of core #1, well CES-11. Depths in meters.

990-890 m - argillaceous rocks predominate, with several beds of coquinas of unidentified shells. These lithologies are interpreted to represent a lagoonal environment.

890-820 m - argillaceous rocks predominate without coquinas. This interval is interpreted as interdeltaic marine bay deposits.

820-750 m - interval composed of intercalations of sandstones, carbonaceous mud-shales and thin beds of limestones. It is interpreted as deltaic deposits.

These four intervals comprise a transitional sequence.

750-290 m - interval composed of argillaceous rocks (predominant) intercalated with sandstones. Paleontology indicates marine conditions. These lithologies are interpreted to represent prodelta or offshore environments; thus this interval corresponds to a marine sequence.

An unconformity is defined by paleontology at 290 m. Tertiary sedimentary rocks lie over Aptian ones.

290-sea bottom - very coarse-grained, loose sands predominate, with minor calcarenites near 150 m. Paleontology indicates shallow marine environments. Fan deltas are the interpreted depositional environment.

Table 3 summarizes the depositional sequences, unconformities and ages occurring in this well.

CES-2 (Plate 4)

3769-2715 m - interval composed of intercalated argillaceous rocks (predominant) and sandstones. Continental conditions are indicated by paleontology; and a fluvial meandering system is interpreted as the depositional environment.

2715-2290 m - argillaceous rocks predominate. The basal clay-shales (2715-2590 m) are highly radioactive, and present good source rock characteristics (Figure 26). Paleontology indicates continental conditions. A lacustrine depositional environment is here interpreted.

These two intervals comprise a continental sequence.

AGE		DEPTH M	DEPOSITIONAL SEQUENCES	
TERTIARY		253	MARINE	SHALLOW
APTIAN	UPPER	713	MARINE	SHALLOW
	MIDDLE	1363	TRANSITIONAL	DELTA
	EARLY (?)	2381	CONTINENTAL	LAKE / FLUVIAL

TABLE 3 - Generalized stratigraphic column of the CES-11. Depths are related to sea level.

2290-910 m - interval composed of alternations of sandstones, argillaceous rocks and thin beds of limestone. Few beds of coquinas occur in this interval. These lithologies are interpreted to represent a transitional sequence. The following depositional environments have been interpreted: Lagoon (2290-2080 m), delta (2080-1270 m), interdeltaic marine bay (2080-1170 m). The uppermost part of this interval is suggested to represent shallow marine conditions.

910-745 m - this interval is confined between two unconformities defined by: (1) sharp breaks at the base and the top of the interval in both gamma ray and sonic logs, (2) an abrupt change in lithologies and environmental conditions occur through the basal unconformity (deep marine over transitional or shallow marine), and (3) Late Cenomanian sediments overlie Albian ones at the base. It is composed predominantly of argillaceous rocks with numerous intercalations of thin beds of limestones. Brown colors are characteristic of these lithologies. Paleontology indicates moderate to deep marine environments. An outer shelf to upper slope environment is here ascribed to this marine sequence.

745-500 m - mudstones are the predominant lithologies, with minor beds of sandstones. Paleontology indicates moderately deep marine conditions. This interval is interpreted to represent outer shelf to upper slope environments. It constitutes another marine sequence.

500-sea bottom - coarse-grained, loose sands predominate. Calcarenites occur above 100 m. Paleontology indicates shallow marine environments and Tertiary age. Fan deltas are the interpreted depositional environment of this marine sequence.

Table 4 summarizes the depositional sequences, unconformities and ages occurring in this well.

CES-55 (Plate 5)

3040-2490 m - interval composed of intercalations of sandstones and argillaceous rocks. Paleontology indicates continental conditions. Some shaly beds contain algal-type organic matter. A mixed fluvio-lacustrine environment is interpreted for these deposits.

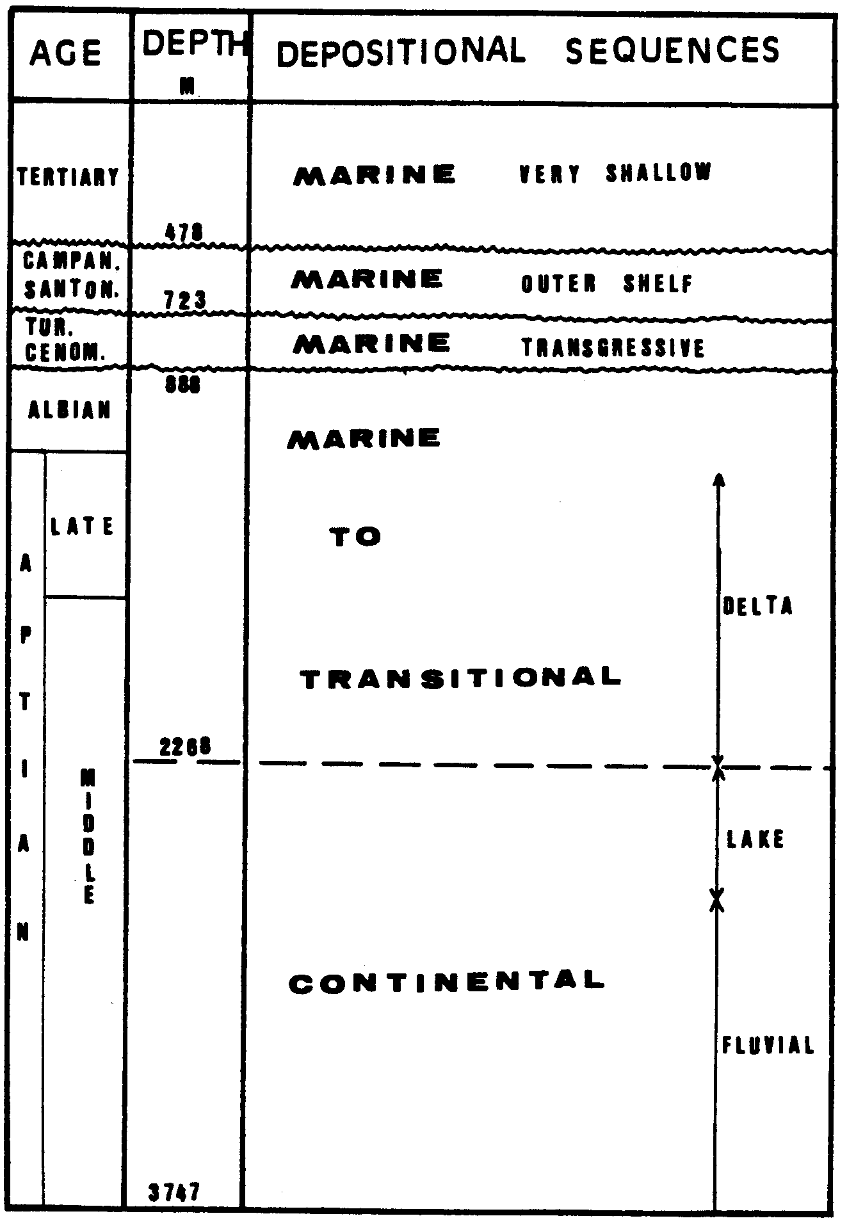


TABLE 4 - Generalized stratigraphic column of the CES-2. Depths are related to sea level.

2490-2200 m - argillaceous rocks are the predominant lithologies. Continental conditions are indicated by paleontology. These lithologies present good source rock characteristics (see Figure 27). This interval represents lacustrine deposits.

2200-1660 m - lithologically is very similar to the interval 3040-2490 m. Paleontological data indicate an association of fluvio-lacustrine ostracodes.

These three intervals form a continental sequence.

1660-1340 m - interval composed of intercalations of sandstones and argillaceous rocks. Thin beds of limestones also occur. Paleontology indicates an association of marine ostracodes. Cores #1 and #2 recovered sandstones full of oil, interpreted as deltaic crevasse splays; and argillaceous rocks interpreted as swamps and interlobe marine bay deposits (Figure 7). A deltaic environment is suggested to this interval (transitional sequence).

1340-1210 m - interval composed of alternations of argillaceous rocks and limestones. Brownish colors are common. Paleontology indicates deep marine conditions.

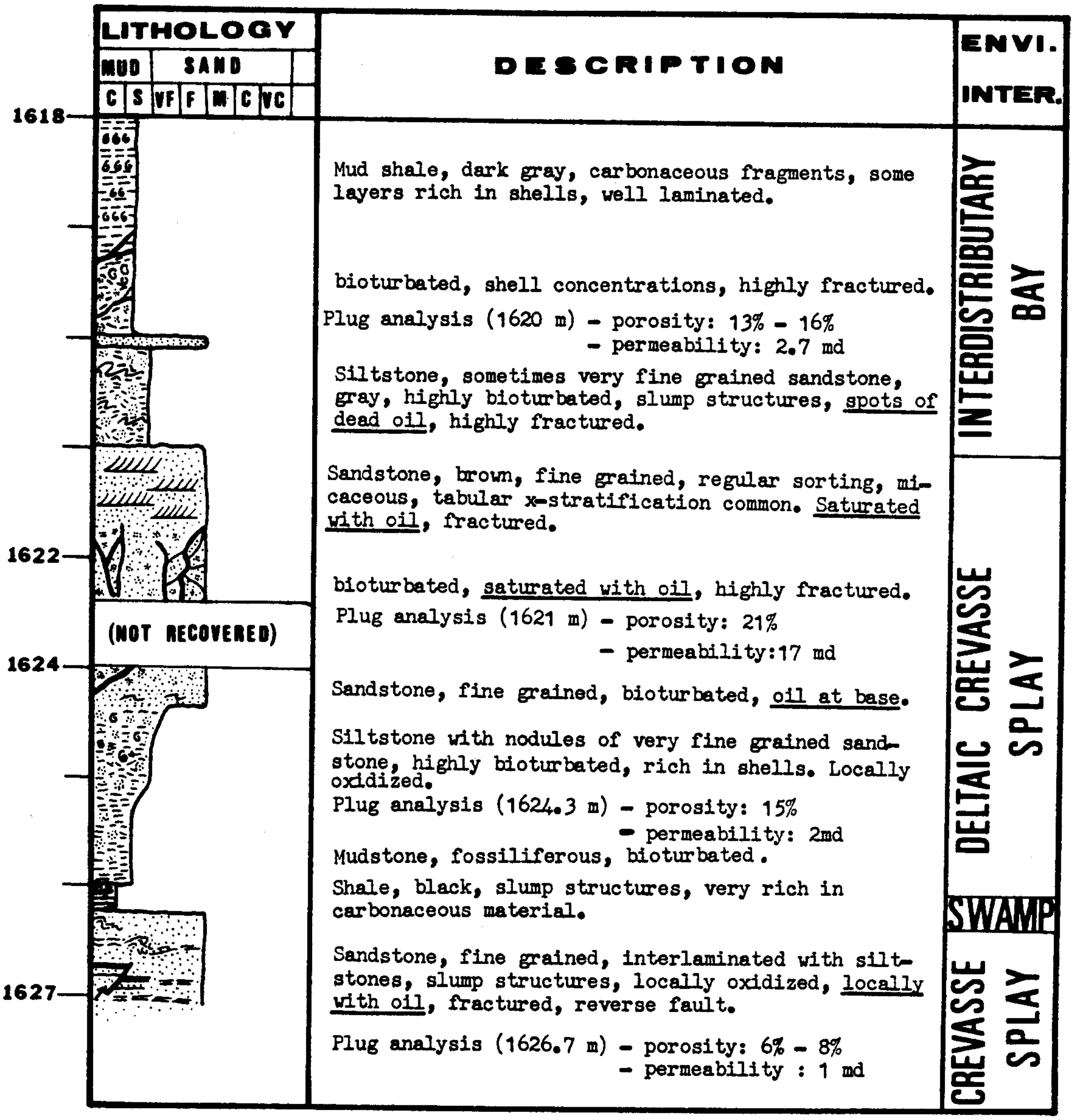


FIGURE 7 - Lithological description and environmental interpretation of cores #1 and #2, well CES-55. Depths in meters.

This interval corresponds to the zone of the foraminifer *Hedbergella delrioensis*, which is very important in correlations of these marine sequence throughout the Acarau basin (see discussions in Chapter VI). Good source rock properties are characteristic (Figure 27). There are several evidences indicating that these deposits represent a transgressive marine sequence (see discussions in Chapters IV, V, VI). It is characteristically bounded by two unconformities, very well displayed in the dipmeter log (see Figure 8).

1210-835 m - argillaceous rocks predominate. Clusters of sandstone beds occur at certain level. Bathyal environments are indicated by paleontology. This interval is interpreted to represent continental slope with sandy submarine fans, and comprises another marine sequence. Its top corresponds to the Cretaceous/Tertiary unconformity.

835-sea bottom - interval composed of three lithofacies: argillaceous (lower part), sands (middle part), calcarenites (upper part). Paleontology indicate shallow marine environments. The envisaged depositional environment for this interval is one of fan deltas deposited in a shallow marine platform, which sometimes was muddy and sometimes limy.

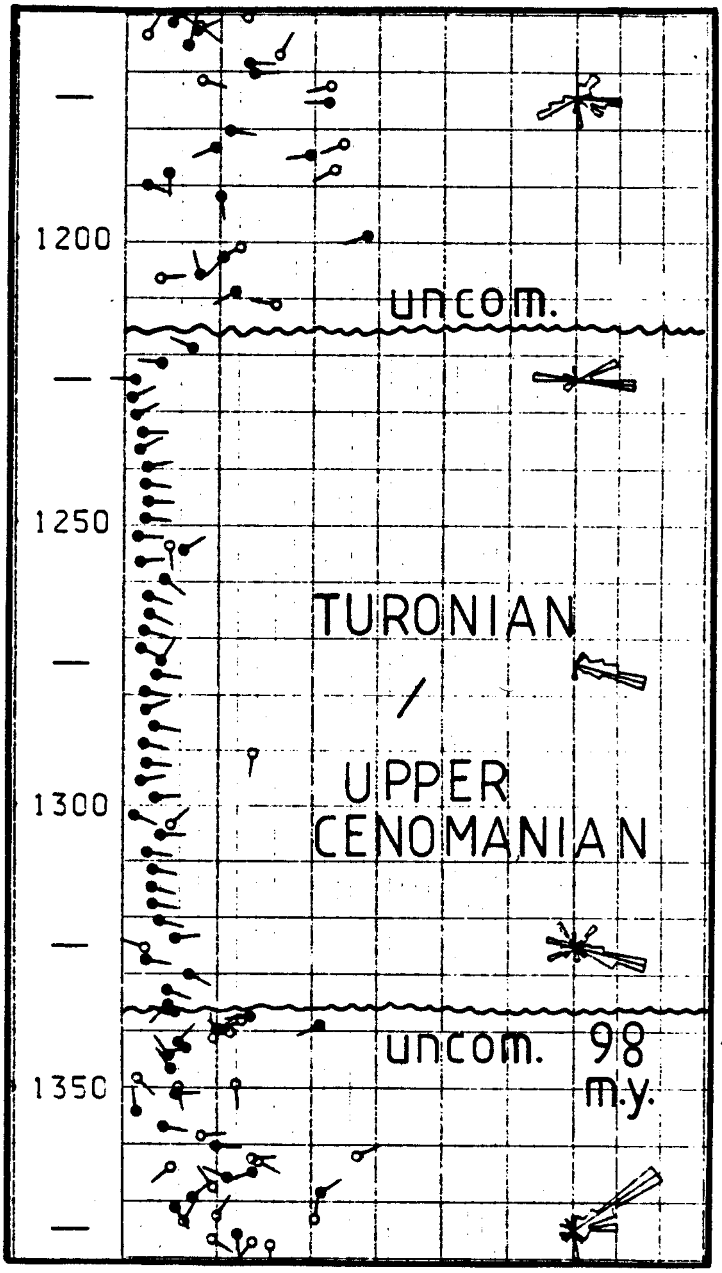


FIGURE 8 - Typical pattern of the dipmeter log in the Turonian anoxic deposits, CES-55.

Table 5 summarizes the depositional sequences, unconformities and ages occurring in this well.

CES-52 (Plate 6)

4007-2270 m - interval composed of alternations of sandstones and argillaceous rocks. Paleontology indicates continental conditions. The following depositional environments are interpreted: fluvio-lacustrine (4007-3010 m), lacustrine (3010-2960 m) (with good source rock properties, Figure 28), and fluvial meandering (2960-2270 m).

2270-1780 m - lithologically is very similar to the underlying interval, but it is very rich in thick-bedded (thicker than 20 m) sandstones. A fluvial braided depositional environment is here assigned.

These intervals comprise a continental sequence.

1780-1330 m - argillaceous rocks predominate. Several intercalations of sandstones occur. Paleontologically it is characterized by the presence of gastropods, pelecypods, benthonic and planktonic forams. The following depositional environments are interpreted:

AGE		DEPTH M	DEPOSITIONAL SEQUENCES	
TERTIARY			MARINE VERY SHALLOW	
LATE CRETACEOUS		811	MARINE REGRESSIVE, BATHYAL	
TUR. CENOM.		1186	MARINE TRANSGRESSIVE	
ALBIAN		1316	MARINE TO TRANSITIONAL	DELTA
APTIAN	VERY LATE	1731	CONTINENTAL	FLUVIAL
				LAKE
	LATE			FLUVIAL
		3016		

TABLE 5 - Generalized stratigraphic column of the CES-55. Depths are related to sea level.

deltaic (1780-1600 m) and prodelta/muddy offshore (1600-1330 m) (see Figure 9). This interval represents a transitional to marine sequence.

1330-1240 m - interval composed of intercalations of mud-shales and limestones, of brownish color. The presence of the foraminifer *Hedbergella delrioensis* and the very good source rock properties of the interval (see Figure 28) characterize this interval as the "Turonian anoxic deposits" (informal designation used in this work) (see discussions in Chapters IV and VI), deposited during a transgressive phase.

1240-810 m - argillaceous rocks predominate, but some thick (20-25 m) beds of sandstone occur in the lower half of the interval. Paleontological data indicate these beds to be correlative to the interval 1210-835 m of the CES-55. They represent Late Cretaceous deep marine (bathyal) deposits.

810-sea bottom - lithologically it is very similar to the interval 835-sea bottom of the CES-55. Paleontological data indicate very shallow marine conditions. The depositional environment is similar to the one interpreted for the CES-55.

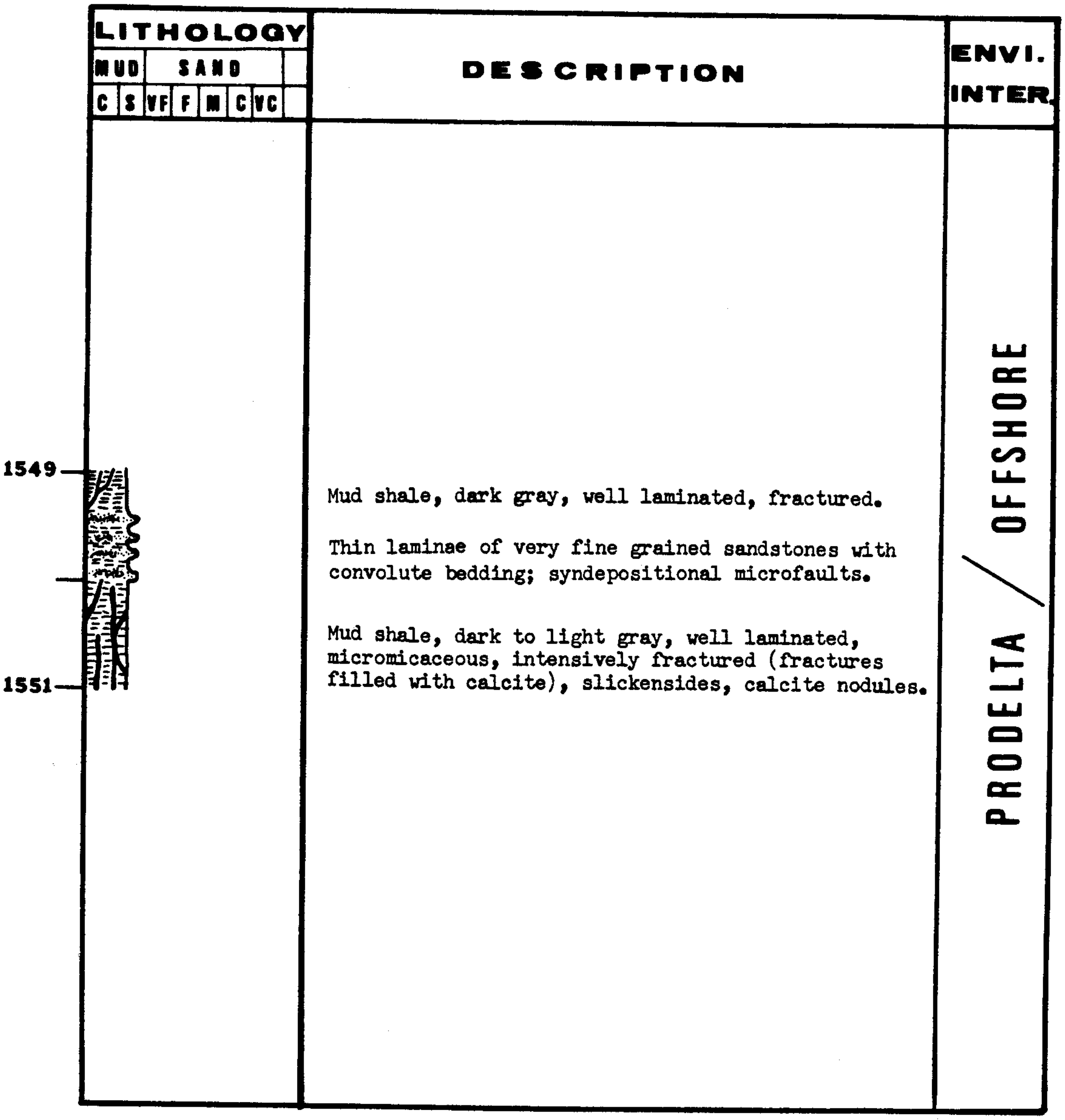


FIGURE 9 - Lithological description and environmental interpretation of core #1, CES-52. Depth in meters.

Table 6 summarizes the depositional sequences, unconformities and ages occurring in this well.

CES-56 (Plate 7)

3354-2690 m - interval composed of alternations of sandstones and argillaceous rocks. Continental environments are indicated by paleontology. The following depositional environments are recognized: fluvial meandering (3354-3150 m), lacustrine (3150-2940 m) and fluvio-lacustrine (2940-2690 m). This continental sequence is very similar to those described in previous wells (with the exception of the CES-52), where a basal fluvial meandering system is followed by lacustrine deposits, which in turn are topped by mixed fluvio-lacustrine deposits.

2690-2090 m - intercalated sandstones and argillaceous rocks predominate. Thin beds of calcarenites are frequent. Paleontology indicates influence of marine waters (occurrence of dinoflagelates). The following depositional environments are recognized: delta (2690-2350 m), prodelta/offshore (2350-2090 m). This interval represents a depositional sequence which is transitional at the base and probably changes to marine

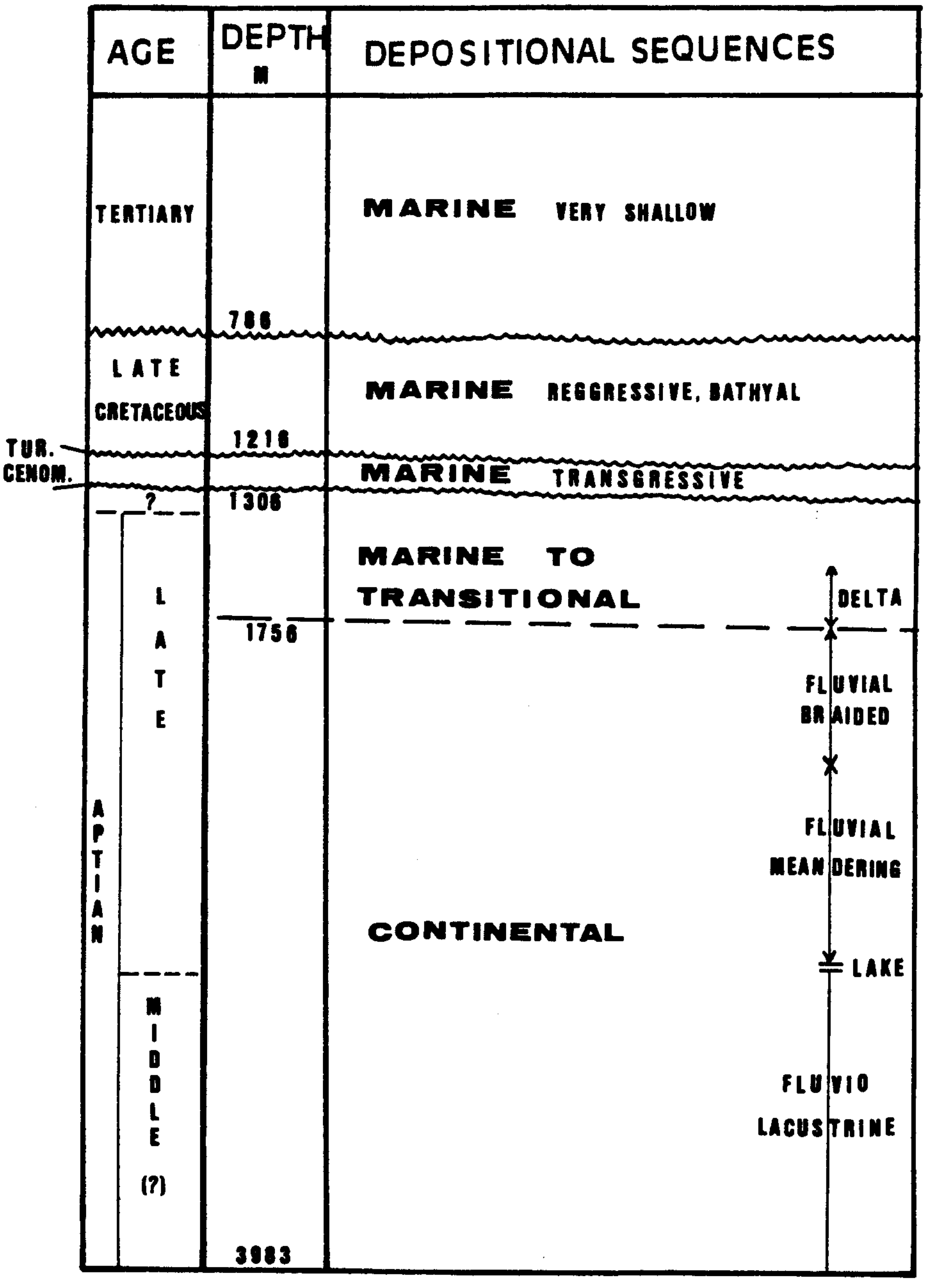


TABLE 6 - Generalized stratigraphic column of the CES-52. Depths are related to sea level.

to the top. A local unconformity occurs at 2090 m defined by the absence of Early Albian sedimentary rocks and the dipmeter log (180° change in the dips of the beds above and below this level). This unconformity is probably of local character, since it was not found in the other wells. It is interpreted to represent recurrent movement of fault blocks during Early Albian, causing a spectacular angular unconformity between Late Albian (dipping to north) and Aptian (dipping to south) beds. This unconformity is an evidence to the fact that tectonic activity was still going on during, at least, the Early Albian.

2090-1860 m - marls, shales and calcarenites are the predominant lithologies. Paleontology indicates bathyal conditions. The interpreted depositional environments of this marine sequence are upper continental slope (base) and outer shelf (top).

1860-1690 m - shales, marls, limestones are predominant, and they are strongly brown colored. The presence of the foraminifer Hedbergella delrioensis and the lithological properties characterize these deposits as the Turonian anoxic beds. Two unconformities bound this sequence, defined by paleontology.

1690-1100 m - argillaceous rocks predominate. Paleontological data indicate bathyal conditions. This marine sequence represent continental slope deposits. The top of this sequence is an unconformity, where Middle Eocene rocks overlie Middle Paleocene ones.

1110-sea bottom - interval composed of intercalations of sands and calcarenites. These Tertiary shallow marine deposits are very similar throughout the studied areas. This marine sequence represents fan delta sandstones intertongued with shallow shelf carbonates.

Table 7 summarizes the depositional sequences, unconformities and ages occurring in this well.

CES-50 (Plate 8)

2736-2070 m - interval composed predominantly of kaolinitic sandstones. Bed thicknesses are high (up to 30 m). Continental conditions are indicated by paleontology. It is interpreted to represent deposits of a fluvial braided system. This interval constitutes the continental sequence of this well; and it is very different from the others described before. Fluvial braided deposits in such offshore wells, without similar

AGE	DEPTH M	DEPOSITIONAL SEQUENCES	
PRESENT TO OLIG. MIDDLE EOCENE	1084	MARINE VERY SHALLOW	
MIDDLE PALEOCENE LATE CAMPAN.	1164	MARINE REGRESSIVE, BATHYAL	
TURONIAN	1844	MARINE TRANSGRESSIVE	
LATE ALBIAN	2064	MARINE UPPER CONTINENTAL SLOPE	LOCAL UNCOM.
APTIAN	2664	MARINE TO TRANSITIONAL	DELTA
	3328	CONTINENTAL	FLUVIO LACUSTRINE LAKE FLUVIAL

TABLE 7 - Generalized stratigraphic column of the CES-56. Depths are related to sea level.

counterparts in the more proximal wells (CES-5, 11, 4, 2 and 55) indicate sediment sources situated either in the African portion of the rift-valley or in the Ceara High.

2070-1800 m - lithologically it is very similar to the underlying interval, slightly richer in argillaceous rocks. Paleontology indicates influence of marine waters (occurrence of foraminifers). This interval is interpreted to represent the underlying fluvial system suddenly subjected to marine conditions; thus a fan delta depositional environment is assigned. It represents a transitional sequence.

1800-1690 m - argillaceous rocks predominate, with minor sandstones and calcilutites. Paleontology indicates shallow marine environments. Prodelta or muddy offshore environments are interpreted for this marine sequence.

1690-1315 m - interval composed of intercalations of thin beds (1-2 m) of argillaceous rocks and calcilutites. Brownish colors are predominant. A very well defined fining-upward pattern is observed in the gamma ray log (Plate 8). The presence of the foraminifer <u>Hedbergella delrioensis</u> and the good source rock properties (see

Figure 29) characterize the Turonian anoxic deposits. It is bounded by two unconformities.

1315-925 m - interval composed of alternations of thick beds of sandstones and argillaceous rocks. Core #1 recovered sandstones and conglomeratic sandstones interpreted to represent a sandy continental shelf facies (Figure 10), as described by Porter (1976). This marine sequence represents outer continental shelf deposits.

925-sea bottom - interval composed of alternations of thick beds of calcarenites (predominant) and coarse-grained sandstones and sands. Fan deltas intertonguing with shelf limestones are the interpreted depositional environments.

Table 8 summarizes the depositional sequences, unconformities and ages present in this well.

CES-5 (Plate 9)

3847-2880 m - interval composed of intercalations of sandstones and argillaceous rocks. Continental conditions are indicated by paleontology. Core #2 recovered sandstones representative of a freshwater channel margin

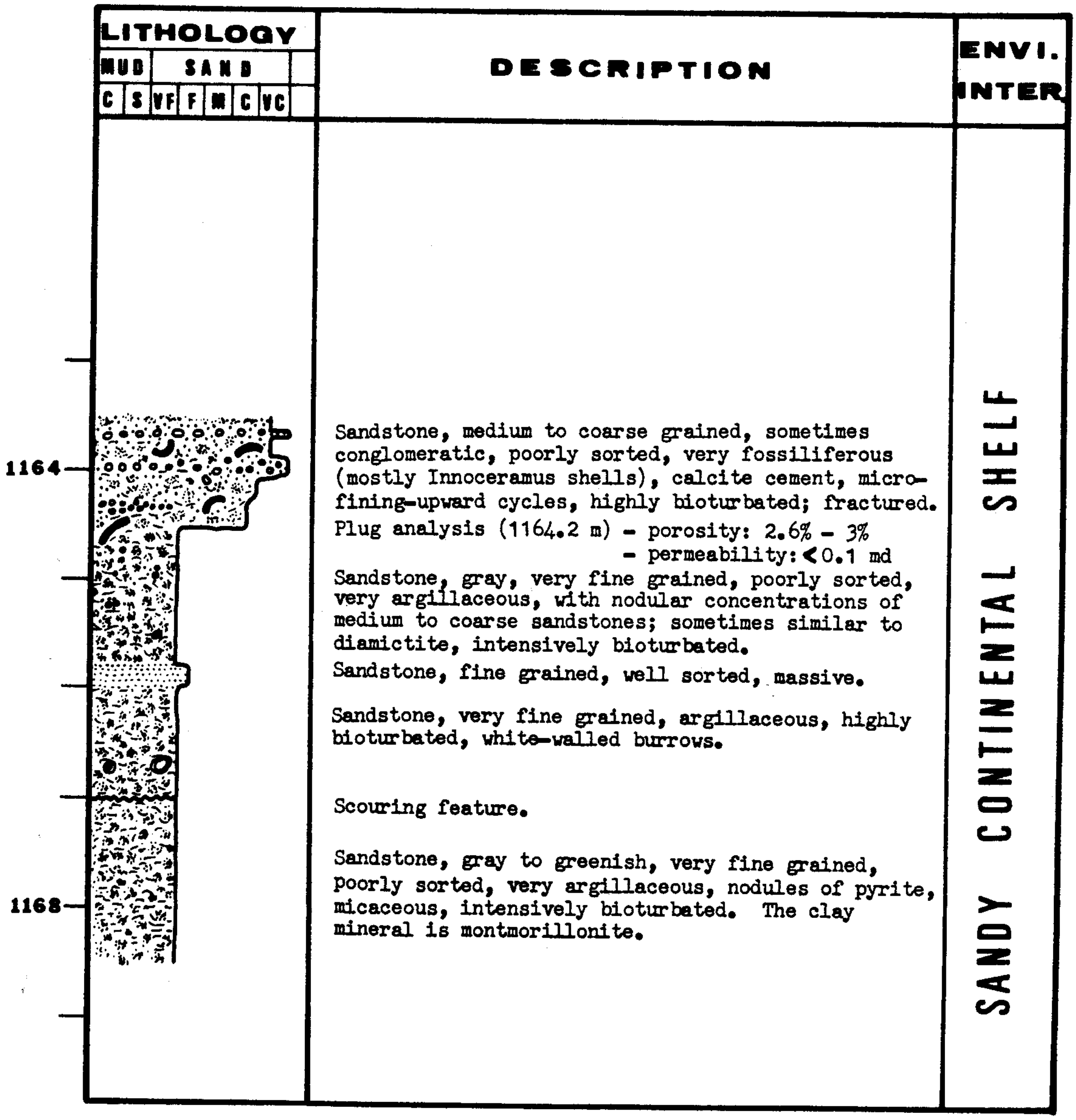


FIGURE 10 - Lithological description and environmental interpretation of core #1, well CES-50. Depths in meters.

AGE	DEPTH M	DEPOSITIONAL SEQUENCES	
PRESENT TO LATE OLIG.	901	MARINE VERY SHALLOW	
MAAST.	1291	MARINE OUTER SHELF	
TURONIAN	1666	MARINE TRANSGRESSIVE	
LATE APTIAN	1776	MARINE SHALLOW	
	2046	TRANSITIONAL	FAN DELTA
	2712	CONTINENTAL	FLUVIAL BRAIDED

TABLE 8 - Generalized stratigraphic column of the CES-50. Depths are related to sea level.

(Figure 11). A fluvial meandering system is interpreted to this interval.

2880-2730 m - argillaceous rocks predominate. The interval is well defined on the sonic and gamma ray logs (higher radioactivity). Continental conditions are indicated by paleontology. A lacustrine system is interpreted to this interval.

These two intervals form the continental sequence of this well.

2730-1800 m - interval composed of intercalations of sandstones and argillaceous rocks. Limestones and coals are frequent. Coquinas occur 2130 m. Core #1 recovered sandstones representative of shoreface and tidal channel environments; and argillaceous rocks representing lagoon and marsh facies (Figure 12). This interval represents a transitional sequence.

1800-1190 m - argillaceous rocks predominate. Paleontology indicates shallow marine conditions.

1190-960 m - interval composed of argillaceous rocks and sandstones, with minor calcarenites. Brownish colors are frequent. The presence of the foraminifer

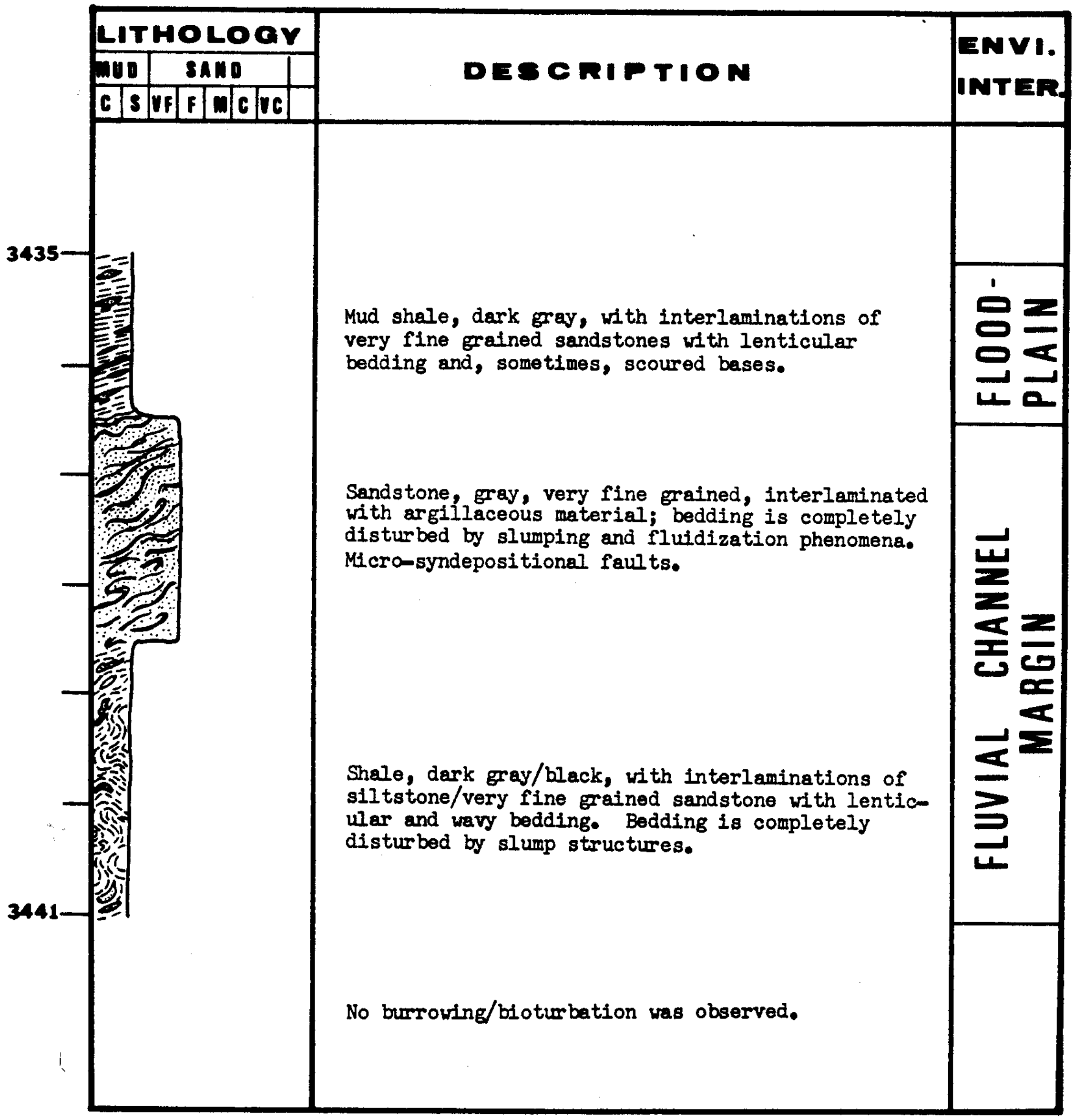


FIGURE 11 - Lithological description and environmental interpretation of core #2, well CES-5. Depths in meters.

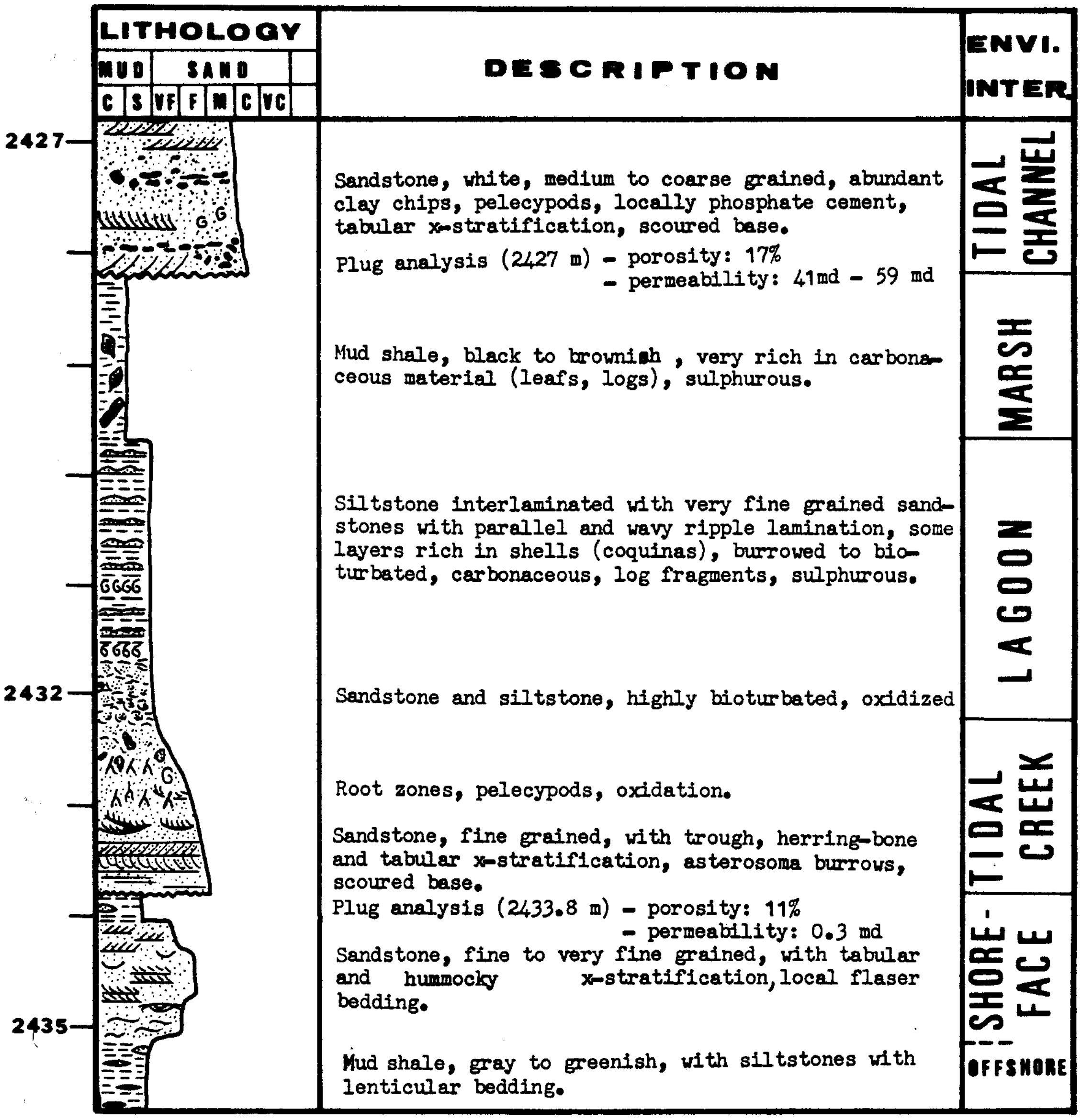


FIGURE 12 - Lithological description and environmental interpretation of core #1, well CES-5. Depths in meters.

Hedbergella delrioensis characterize the presence of the Turonian anoxic deposits.

960-920 m - argillaceous rocks predominate. It represents the Late Cretaceous marine bathyal deposits (based on correlation with previous wells).

920-sea bottom - interval composed predominantly of coarse-grained loose sands, with minor calcarenites. It is lithologically very similar to the Tertiary shallow marine deposits of the previous wells; and the depositional environments are probably the same.

Table 9 summarizes the depositional sequences, unconformities and ages occurring in this well.

CES-48 (Plate 10)

3200-1880 m - argillaceous rocks and sandstones predominate, with limestones and marls at the very top. Paleontology indicates shallow marine environments. Cores #5, #4 and #3 recovered sedimentary rocks indicative of deposition in anoxic or slightly anoxic depressions within the continental shelf (Figures 13 and 14). This interval is interpreted as being representative of deposition in a continental shelf where anoxic depressions

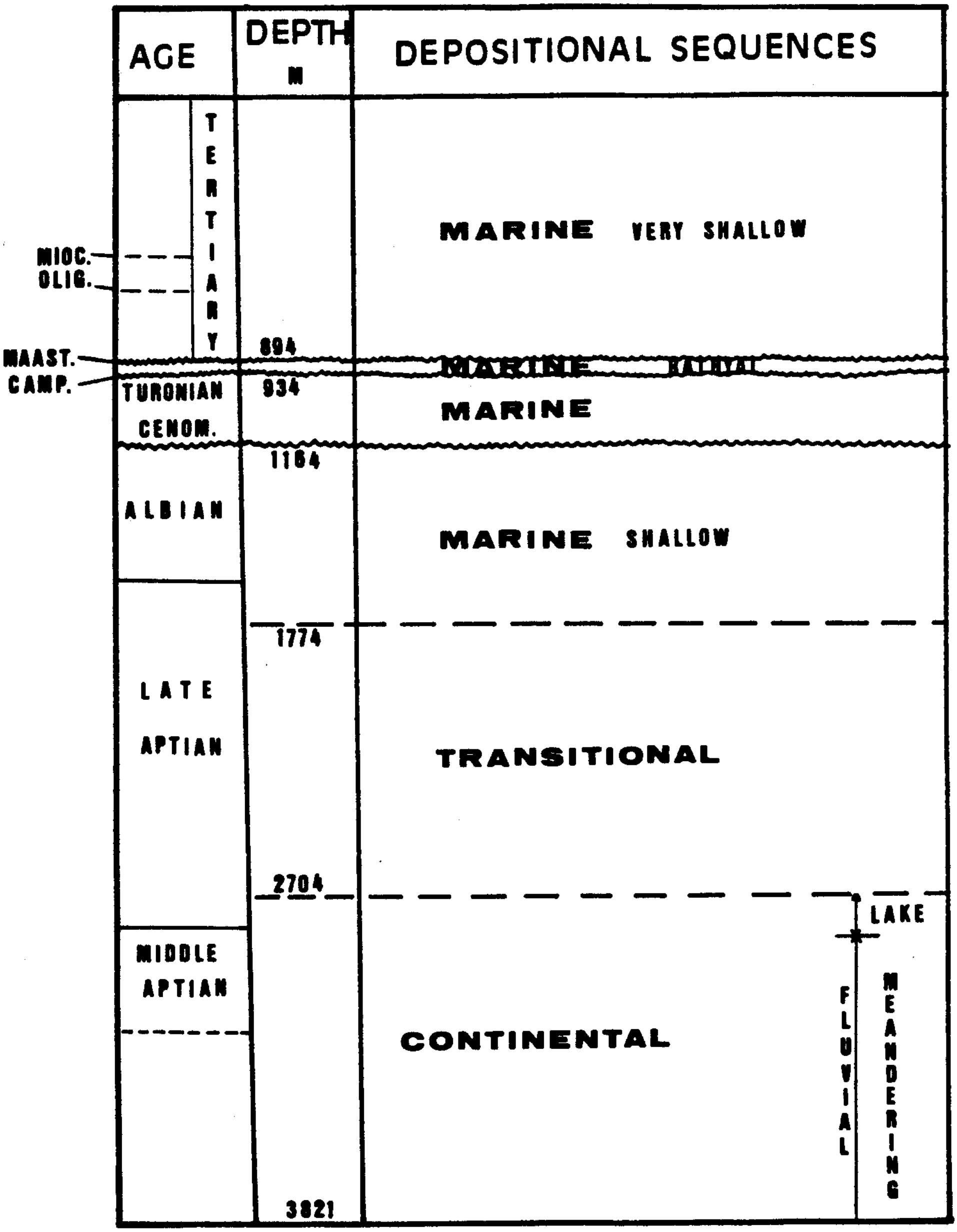


TABLE 9 - Generalized stratigraphic column of the CES-5. Depths are related to sea level.

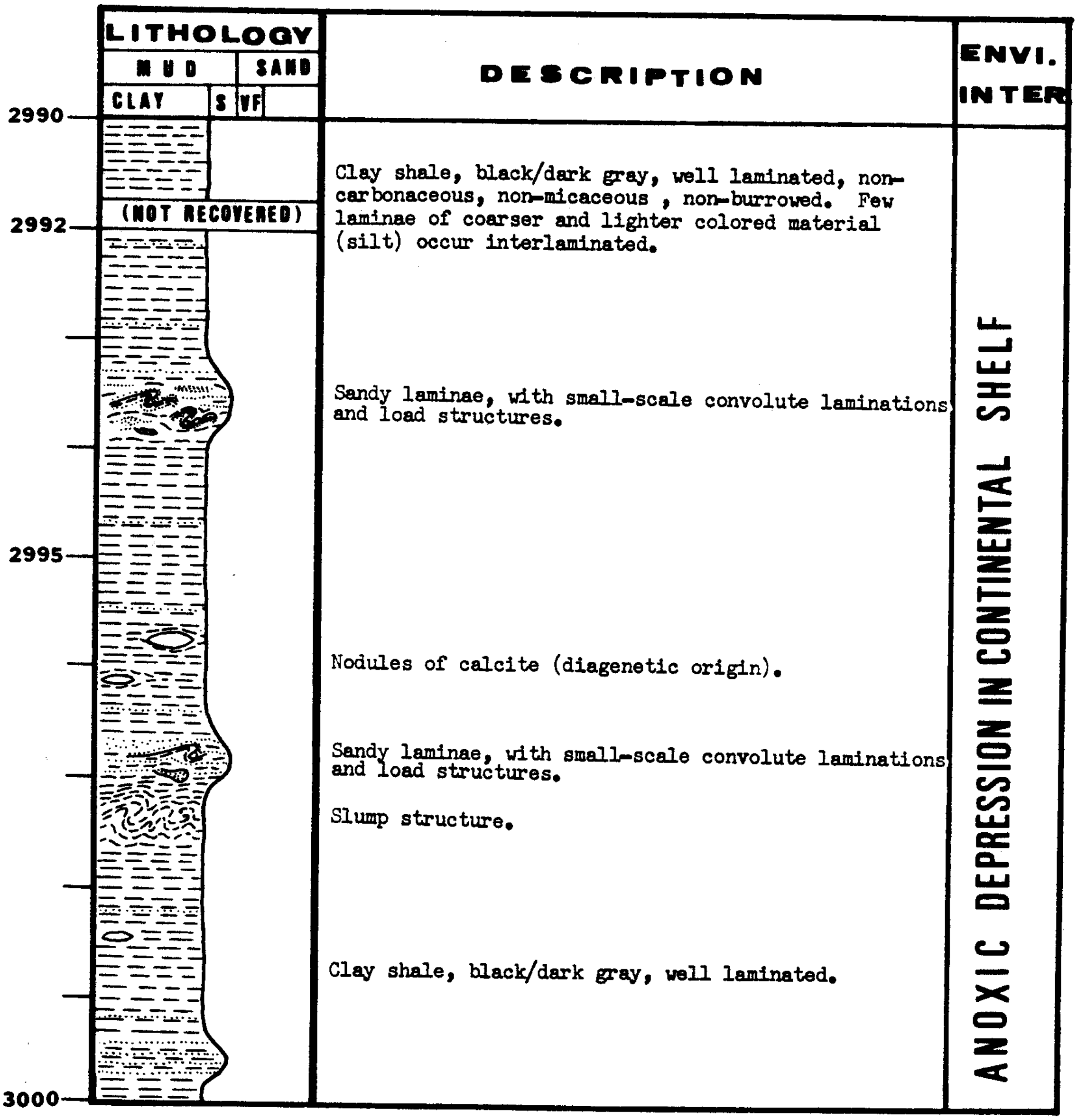


FIGURE 13 - Lithological description and environmental interpretation of cores #4 and #5, well CES-48. Depths in meters.

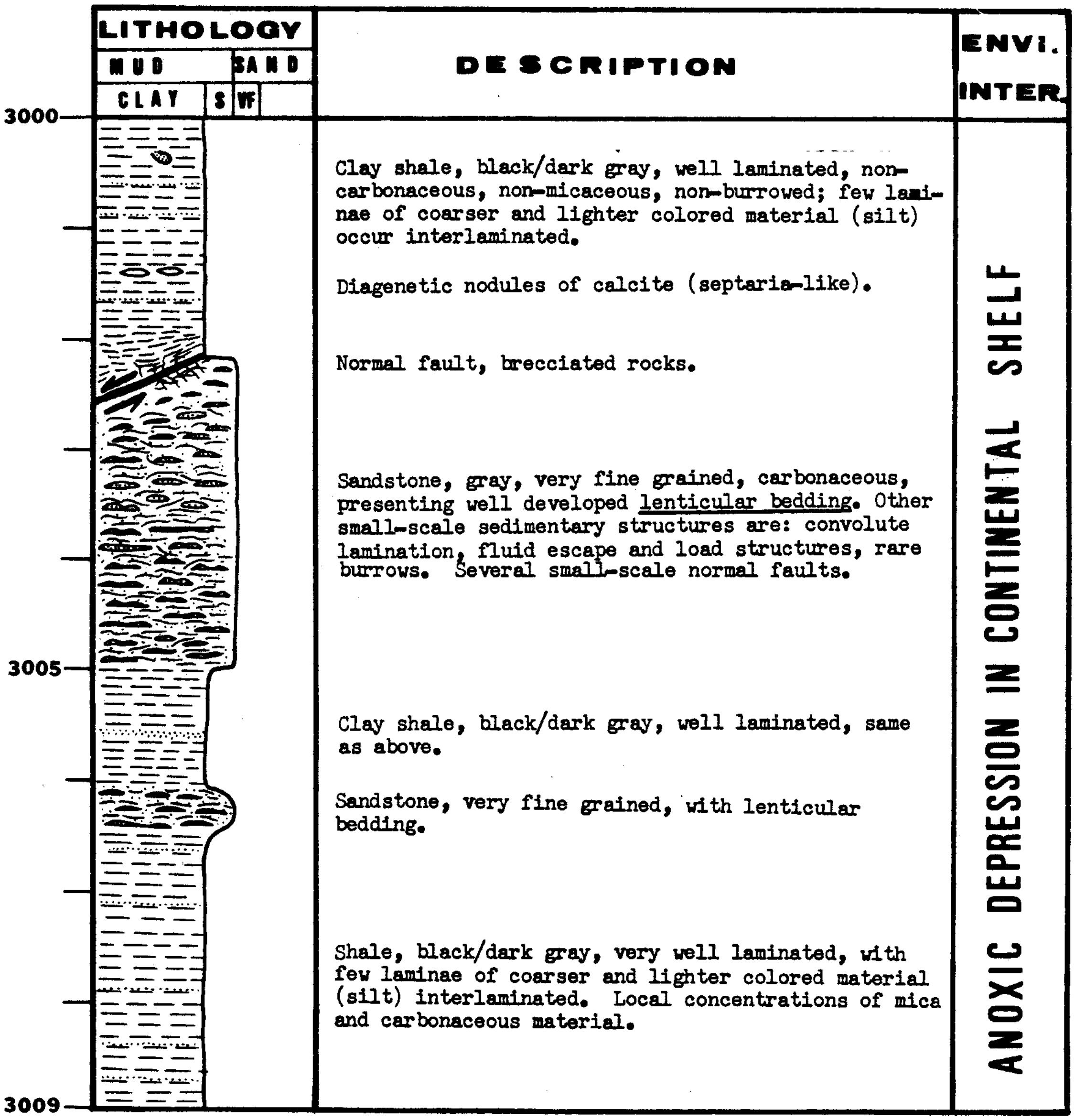


FIGURE 13 (continuation) - Lithological description and environmental interpretation of cores #4 and #5, well CES-48. Depths in meters.

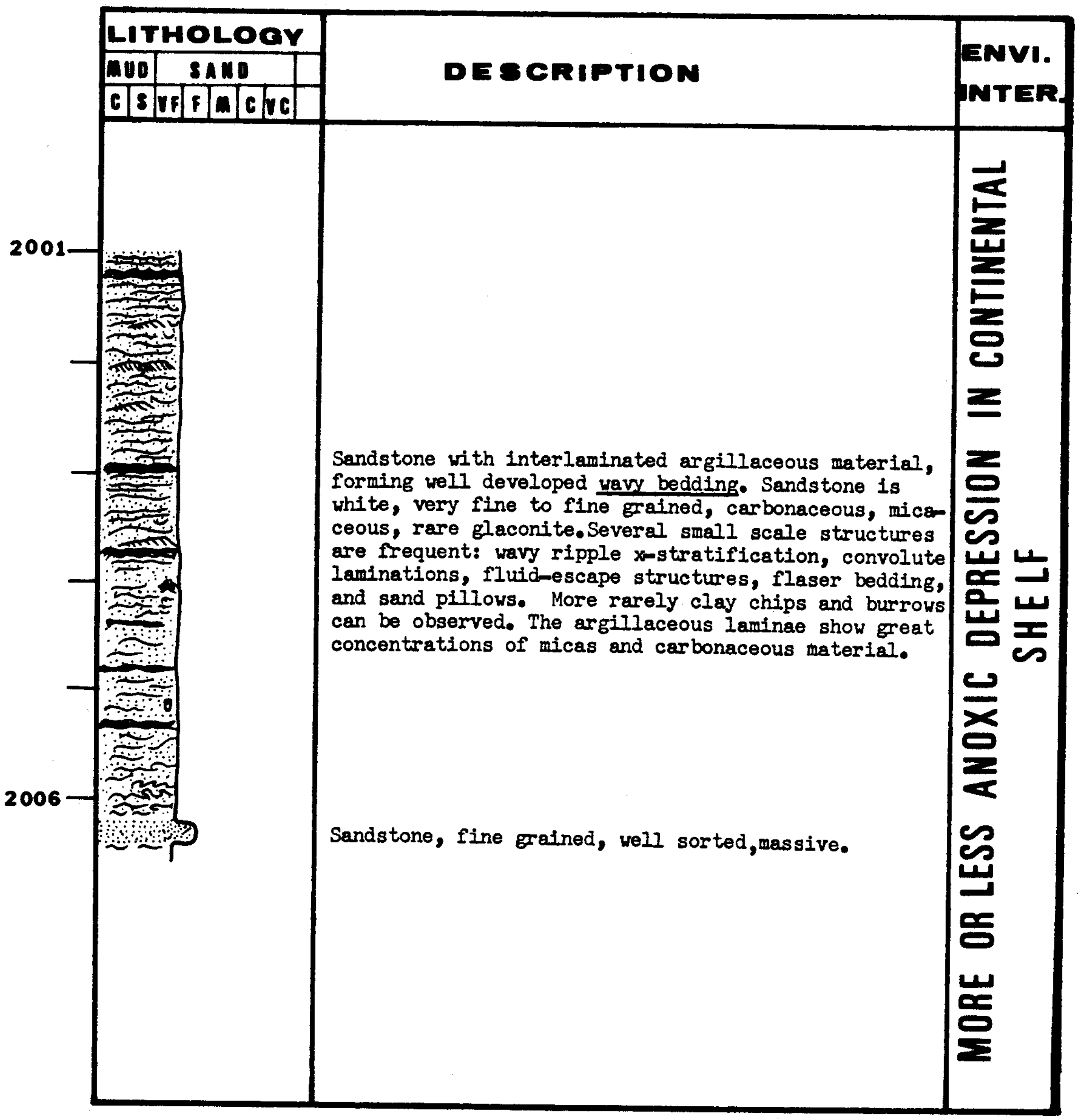


FIGURE 14 - Lithological description and environmental interpretation of core #3, well CES-48. Depths in meters.

could eventually develop (probably due to tectonic movements).

1880-1600 m - thick (10 m) beds of sandstone predominate. Gamma ray log display several blocky and fining-upward patterns. Paleontology indicates shallow marine environments. These sand bodies are interpreted to represent shoreline-related deposits (tidal channels and barrier bars).

1600-1335 m - interval composed predominantly of calcarenites, with mudstones and marls and the lower and upper parts. This interval is interpreted as a carbonate platform, similar to other Albian/Cenomanian carbonate platforms in other Brazilian marginal basins.

1335-870 m - sandstones predominate. Paleontology indicates lower neritic to bathyal environments. Cores #1 and #2 recovered sandstones representing grain flow and turbidite deposits (Figures 15, 16). A large submarine fan complex is suggested as the depositional environment of this interval.

870-630 m - argillaceous rocks predominate. Paleontology indicates bathyal conditions. The interval probably represents continental slope deposits.

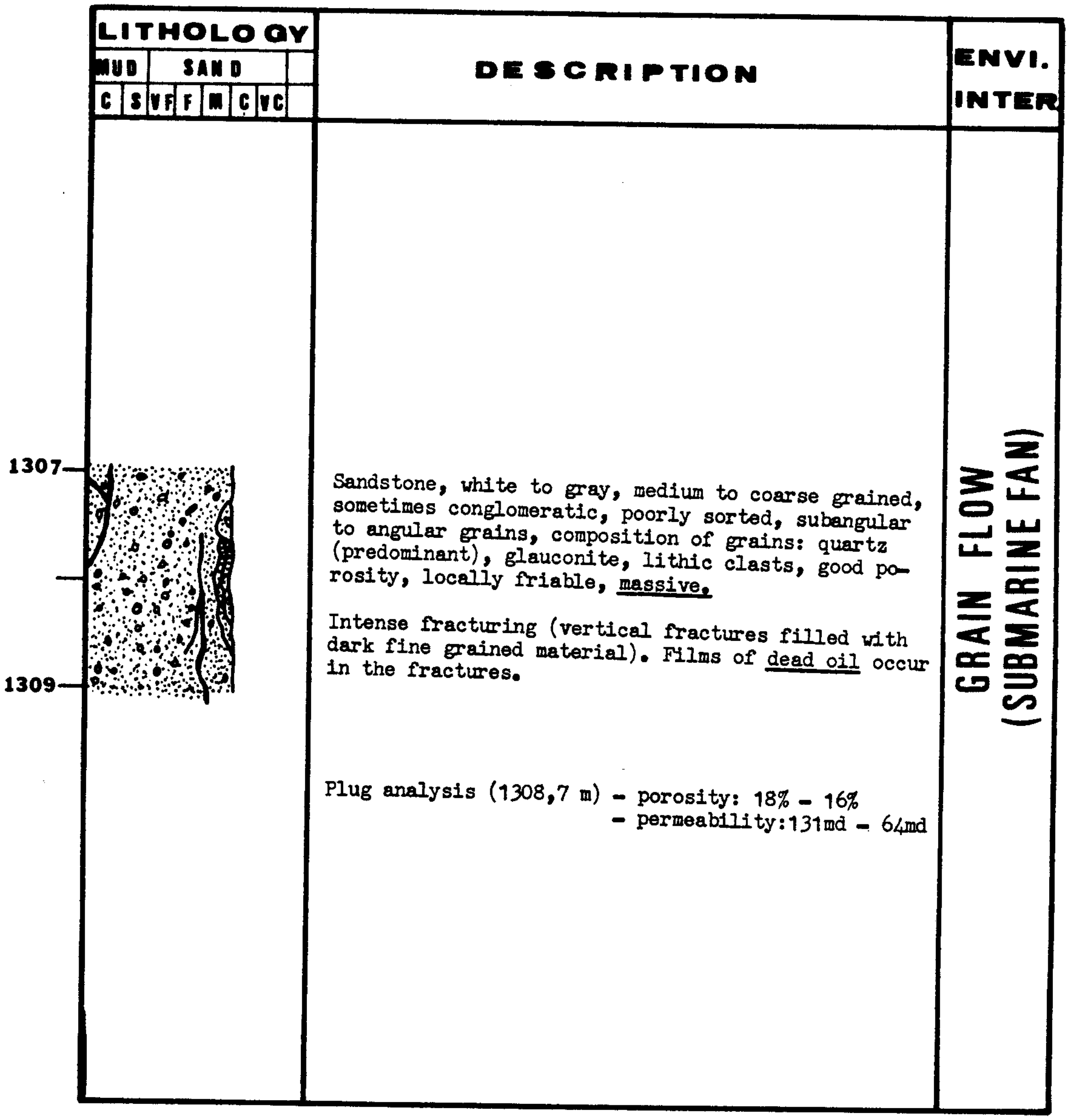


FIGURE 15 - Lithological description and environmental interpretation of core #2, well CES-48. Depths in meters.

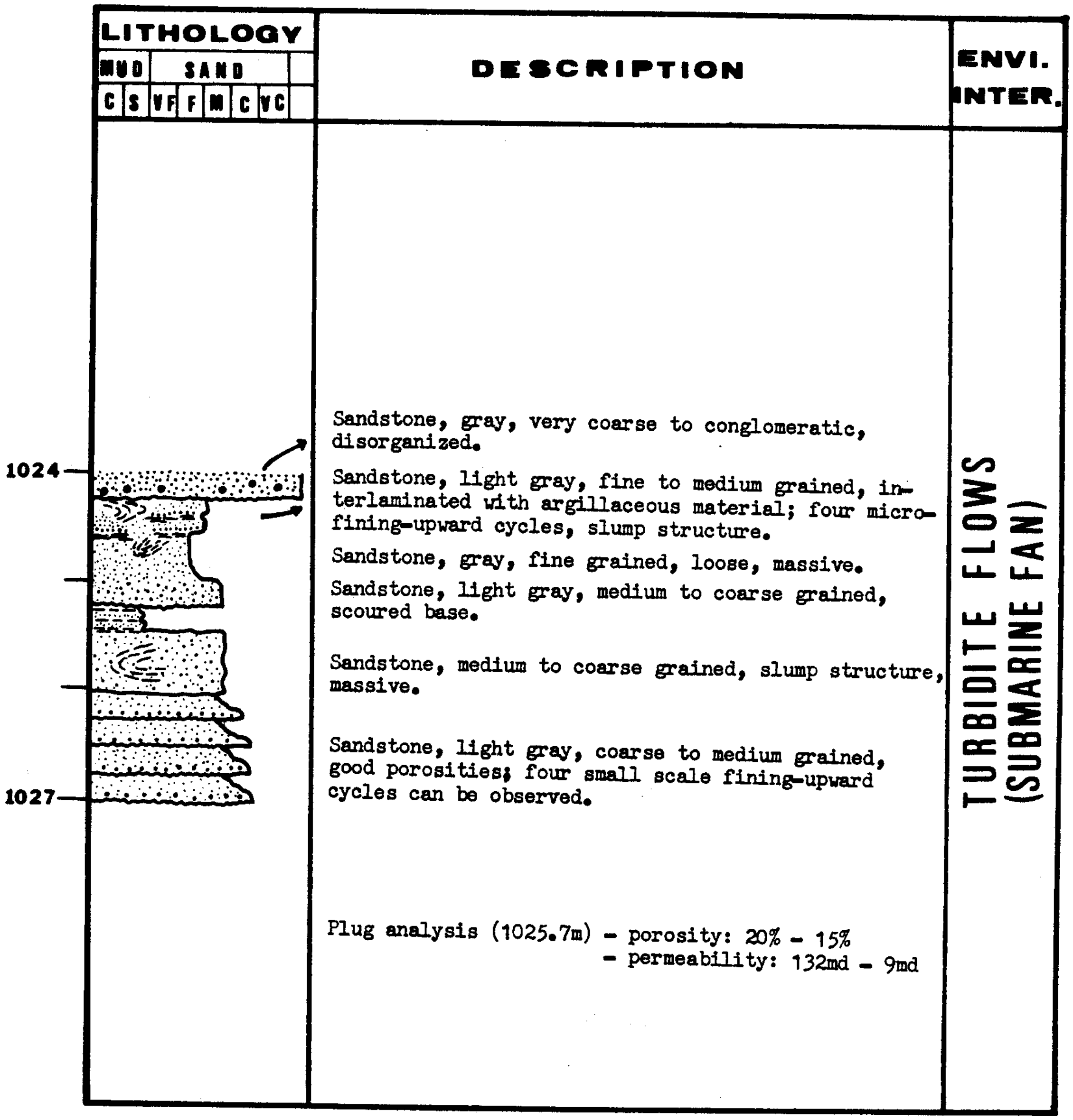


FIGURE 16 - Lithological description and environmental interpretation of core #1, well CES-48. Depths in meters.

The age of these sediments is Albian-Cenomanian and they represent very well a gradual deepening of the sea waters, corresponding to a well documented worldwide sea level rise (Vail et al., 1977; Hancok and Kauffman, 1979).

These intervals comprise an anomalously thick Albian/Cenomanian marine sequence (more than 2570 m). In other wells sedimentary rocks of these ages are never thicker than 850 m. This fact indicates that this area underwent strong subsidence during Albian and Cenomanian while other areas had not. However, during Late Cretaceous this area did not receive sediment accumulation, due probably to structural inversion (positive area instead of subsiding). Other areas (CES-56, CES-55 and CES-52) underwent subsidence and received thick accumulations of Late Cretaceous sediments. The existence of thick, but not laterally extensive, sedimentary piles deposited very rapidly during certain periods of time, together with areas where no or little sedimentation occurred during the same time, is one of the characteristics of basins occurring in oblique-slip mobile zones (Reading, 1980). In such areas certain blocks subside very quickly while others are uplifted and eroded. In subsequent phases reversal of movements is common.

630-sea bottom - interval composed predominantly of calcarenites, with several intervals of loose, coarse-grained sands. They represent the Tertiary shallow marine deposits and their depositional environment was discussed in the previous wells.

Table 10 summarizes the depositional sequences, unconformities and ages occurring in this well.

CES-1 (Plate 11)

2980-2490 m - interval composed of coarse-grained sandstones and conglomerates, of reddish colors. Continental conditions are indicated by paleontology. The lithologies probably represent alluvial fans. The great proximity of this well to the Parnaiba platform (3 km) favors this interpretation.

2490-2150 m - interval composed of sandstones very rich in kaolinite. Red colors are not reported. Paleontology indicates continental conditions. A fluvial braided system is suggested to this interval.

These two intervals represent the continental sequence of this well.

AGE		DEPTH M	DEPOSITIONAL SEQUENCES	
PRESENT TO OLIG.		606	MARINE VERY SHALLOW	
CENOM.		1311	MARINE BATHYAL	CONTINENTAL SLOPE SUBMARINE FAN COMPLEX
ALBIAN	LATE		MARINE SHALLOW	CARBONATE PLATFORM
	MIDDLE	3176		TIDAL FLATS

TABLE 10 - Generalized stratigraphic column of the CES-48. Depths are related to sea level.

2150-590 m - sandstones predominate, but higher amounts of argillaceous rocks occur. Coal beds are also present. The coals were described as being extremely pyritiferous. It is well known that coals accumulated in areas under marine influence such as back-barrier and lower delta-plain environments contain high amounts of pyrite; while coals deposited in areas under freshwater influence such as upper delta plain to fluvial environments have low contents of pyrite (Horne et al., 1978). Paleontology indicates the presence of brackish-water ostracodes, suggesting the influence of marine waters. This inverval is interpreted to represent a transitional sequence (probably a fan delta depositional environment).

590-470 m - black mud-shales predominate. Paleontology indicates marine environments. The depositional environment of this interval is probably a muddy continental shelf.

470-sea bottom - interval composed of calcarenites (upper half) and loose coarse-grained sandstones (lower half). These lithologies represent the Tertiary shallow marine deposits.

Table 11 summarizes the depositional sequences, unconformities and ages occurring in this well.

CES-3 (Plate 12)

3670-2825 m - interval composed of alternations of sandstones and argillaceous rocks. Coals occur near 3400 m. Continental conditions are indicated by paleontology. This interval is interpreted to represent a fluvial meandering depositional sequence.

2825-1150 m - medium-grained sandstones predominate. They are highly arkosic and kaolinitic. Continental conditions are indicated by Paleontology. This interval is interpreted to represent a fluvial braided depositional sequence.

1150-390 m - this interval is lithologically very similar to the lowermost interval of this well. Paleontology indicates continental conditions. It probably represents a fluvial meandering system.

These intervals form the continental sequence of this well. Its age is Middle and Early Aptian. An unconformity occurs at 390 m and represents the greatest hiatus in

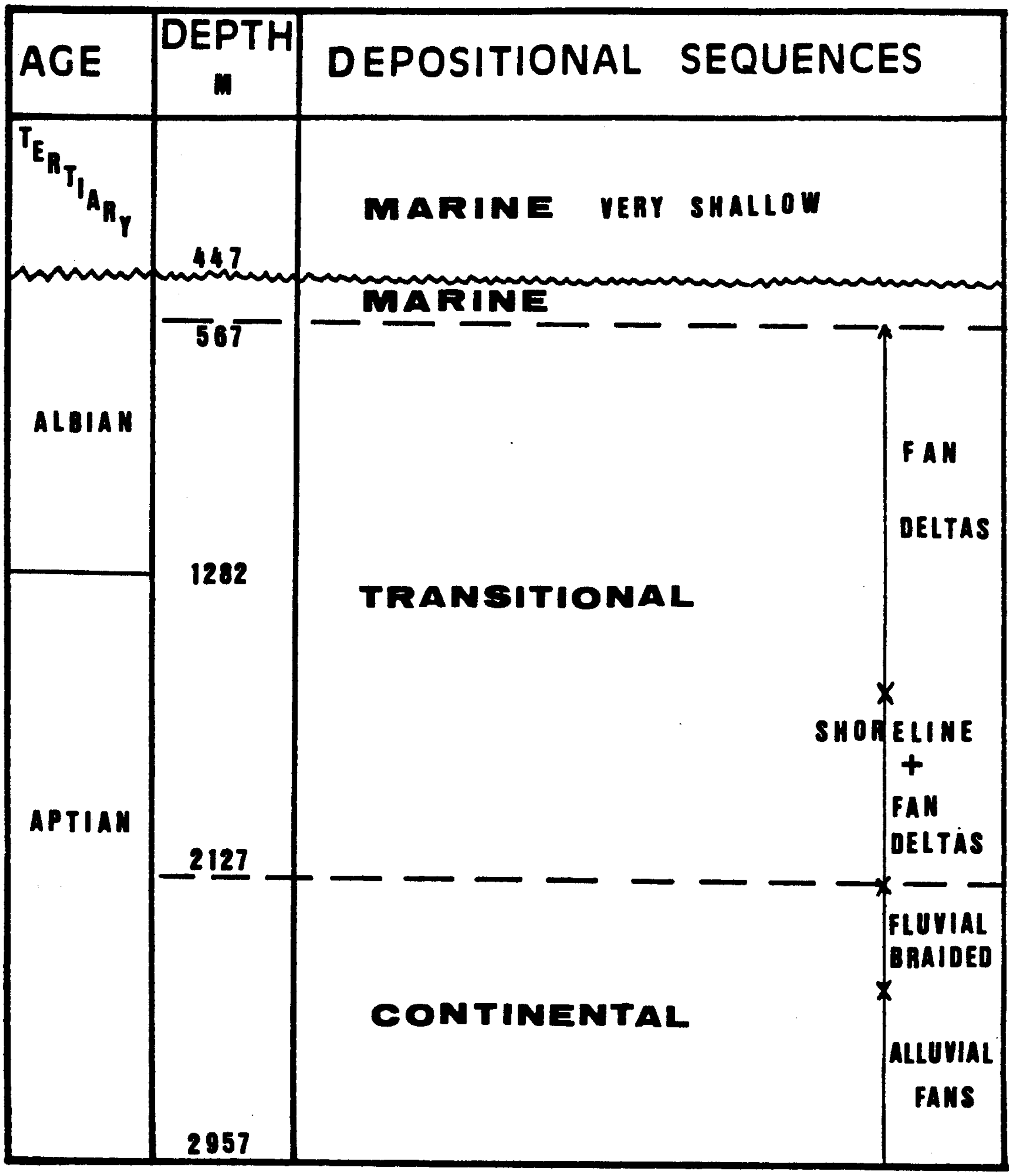


TABLE 11 - Generalized stratigraphic column of the CES-1. Depths are related to sea level.

the studied areas. Tertiary sediments lie over Middle Aptian rocks.

390-sea bottom - interval composed of alternations of sands and calcarenites. Coals occur near 250 m. They represent the Tertiary shallow marine deposits.

Table 12 summarizes the depositional sequences, unconformities and ages occurring in this well.

PIS-1 (Plate 13)

3850-3150 m - interval composed predominantly of argillaceous rocks, with several thin intercalations of sandstones. Continental conditions are indicated by paleontology. This interval is interpreted to represent a fluvial meandering depositional sequence. Basalt flows occur at 3535-3490 m, and possibly at 3690-3620 m.

3150-2835 m - sandstones predominate. Paleontology indicates continental environments. This interval probably represents a fluvial braided system. The interval 3070-3010 m is a thick bed of mud-shales with excellent source rock properties. It is interpreted as a lacustrine deposit.

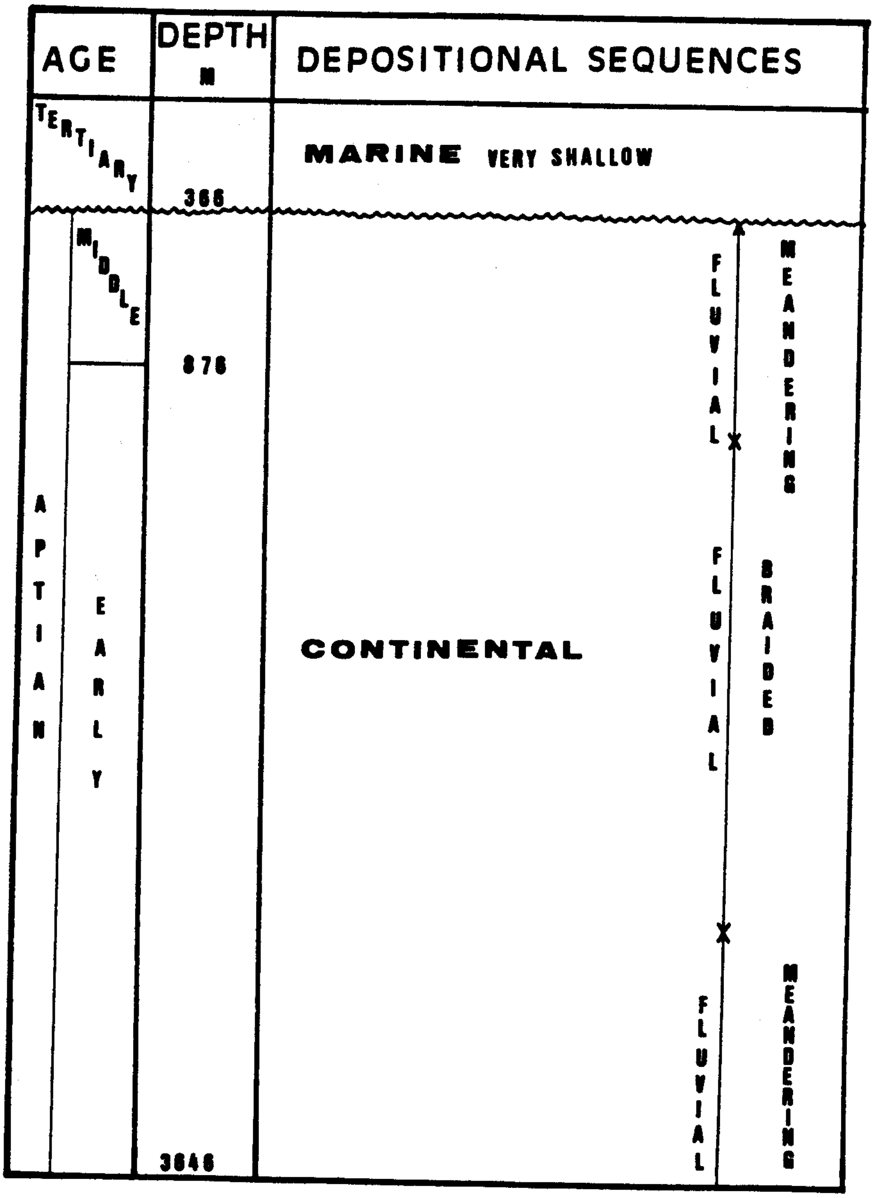


TABLE 12 - Generalized stratigraphic column of the CES-3. Depths are related to sea level.

These intervals form the continental sequence of this well.

2835-675 m - interval composed almost exclusively of argillaceous rocks. Foraminifers and dinoflagelates occur above 2275 m, indicating marine conditions. This interval is the thickest sequence of argillaceous rocks found in the studied areas. These lithologies are interpreted to represent prodelta deposits in front of a delta prograding from the Barreirinhas basin (adjacent to west). The PIS-1 is situated exactly in the depocenter of the Piaui-Camocim basin (Piaui trough) and this probably explains the great thicknesses of sediments.

675-335 m - marls predominate. They are interpreted as distal equivalents of Albian/Cenomanian carbonate platforms, situated in the Barreirinhas basin (Bonfim formation).

335-sea bottom - interval composed of intercalated sands, limestones and dolomites. It represents the Tertiary shallow marine deposits.

Table 13 summarizes the depositional sequences, unconformities and ages occurring in this well.

AGE		DEPTH M	DEPOSITIONAL SEQUENCES	
TERTIARY		312	MARINE VERY SHALLOW	
CENOM.			MARINE DISTAL CARBONATE PLATFORM	
ALBIAN		852		
APTIAN	LATE	2252	MARINE TO TRANSITIONAL (?)	PRODELTA / OFFSHORE
	MIDDLE (?)		CONTINENTAL	FLUVIAL: FLUVIAL BRAIDED; MEANDERING
		3827		

TABLE 13 - Generalized stratigraphic column of the PIS-1. Depths are related to sea level.

IV - STRATIGRAPHY OF THE BASINS

The individual analyses of the wells (Chapter III) are here integrated in order to define the regional interrelationship of the various sequences described. Such a regional view is more easily obtained by means of cross sections and interpretation of seismic sections. Two cross sections were constructed for the Acarau sub-basin (Plates 1, 14 and 15). The first passes through 5 wells in a northeast-southwest direction (dip-stratigraphic cross-section) (Plate 14). The second passes through 4 wells in a southeast-northwest direction (Plate 15). For the Piaui basin one dip-stratigraphic cross-section was prepared, passing through the CES-1 and CES-3 wells (Plate 16). The stratigraphy of the PIS-1 well is projected into this section in order to illustrate the depositional environments present in the Piaui trough. This section was based on the interpretation of the seismic section displayed in Plate 17. The location of the cross-sections and the seismic section is shown in Plate 1. The final product of the integration of Chapter II and the cross-sections here presented is Figure 17, which displays the chronolithostratigraphy of the Acarau sub-basin and the major depositional sequences defined. The chart is also valid for the Piaui-Camocim sub-basin, with the exception that Late Cretaceous sedimentary rocks of Turonian through Maastrichtian age have not been found yet.

The stratigraphic framework of the studied areas is comprised of 5 major depositional sequences, ranging in age from Early Aptian to the present (Figure 17). Their stratigraphic succession represents the gradual infilling of an Atlantic-type marginal basin, highly influenced by tectonics in the earlier stages and by sea level changes in the later phases. The highly irregular thickness distribution of the first two sequences indicates sedimentation in an oblique-slip mobile zone; where the synchronous existence of extensional and transpressional stress regimes causes time-stratigraphic units to be very thick in some areas and very thin or absent in others (according to Reading, 1980) (see Plates 14, 15, 16; and discussion in Chapter III, well CES-48).

Each depositional sequence encompasses sediments deposited in one of these three major realms: continental, transitional and marine. These depositional sequences can be represented by one or several depositional systems (e.g.: fluvial, lacustrine, shoreline, submarine fan, etc.) (as explained in Chapter III). The first sequence was deposited under strictly continental

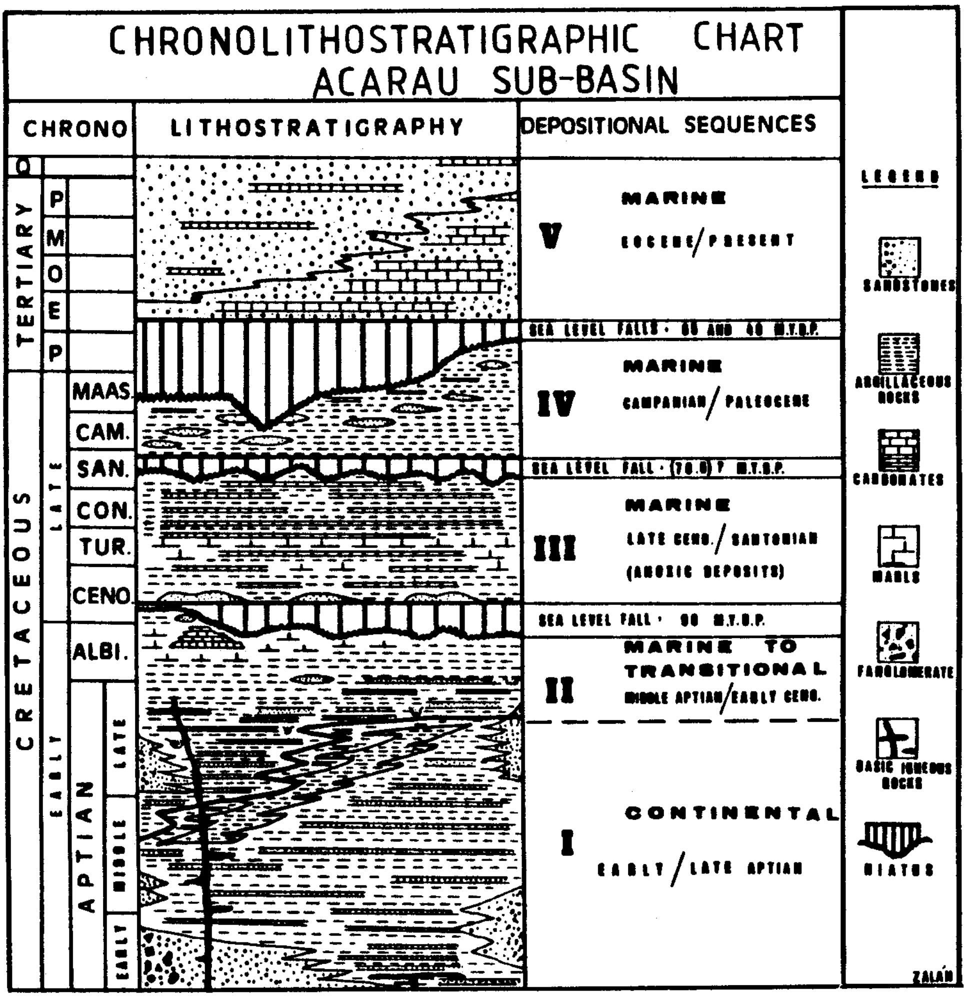


FIGURE 17 - Chronolithostratigraphic chart of the Acarau sub-basin. It is also valid to the Piaui area, however sequences III and IV have not been found yet. Generally sequence V rests directly upon sequences II (CES-1, PIS-1) or I (CES-3).

conditions, representing the initial infilling phases of a rift-valley. The second reflects the arrival of marine waters to the basins, where transitional (deltas, shorelines) and even open marine environments are present. The last three sequences were apparently deposited under strictly marine conditions. The first three sequences have the best reservoirs and source rocks and are the most important for petroleum exploration. The fourth can present some potential in very offshore areas, while the fifth has not shown any potential. Their principal characteristics are now described. Each depositional system cited will have one or more wells assigned as references for detailed descriptions.

SEQUENCE I, CONTINENTAL

Sequence I is the most voluminous depositional sequence of the sub-basins. It ranges in age from Early Aptian to Late Aptian. Older sediments have never been drilled in these areas, but they are likely to exist in the deepest parts since the opening of the North Atlantic occurred during the Triassic-Jurassic, and these basins have their geologic evolution more intimately related to the North Atlantic than to the South Atlantic. Several depositional environments can be recognized, such as: (1) alluvial fans (conglomerates and coarse grained sandstones) (CES-1), (2) fluvial braided (thick intervals of coarse- to fine-grained sandstones) (CES-52, CES-50 and CES-3), (3) fluvial meandering (monotonous intercalations of sandstones and argillaceous rocks) (CES-4, most wells), and (4) lacustrine (predominantly argillaceous rocks) (CES-2, CES-55, CES-52, CES-56). All kinds of transitions between these systems are possible. The first two systems are more restricted to marginal positions in the basins, while the last one tends to be concentrated in the upper ?? parts, preceding the invasion of sea waters.

SEQUENCE II, TRANSITIONAL TO MARINE

The arrival of marine waters is marked by several factors, such as: (1) the appearance of dinoflagelates and foraminifers, (2) occurrence of coquinas of brackish water fauna, (3) occurrence of highly pyritiferous coals, and (4) higher frequency of limestones in relation to underlying continental deposits. It ranges in age from Middle Aptian to Early Cenomanian. The contact between Sequences I and II is transitional and it is generally placed where one of the above cited characteristics is first recognized. Naturally, earlier ingressions of marine waters could have occurred slightly below this contact as well as later recurrences of continental environments farther up within Sequence II; but these minor transgressions and regressions are very difficult to recognize without the help of cores. Several depositional environments can be recognized such as: (1) deltas (intercalations of sandstones and argillaceous rocks, with minor coals and limestones) (CES-4, CES-11, CES-55), (2) shoreline-related (intercalations of sandstones, argillaceous rocks, limestones, coquinas and coals) (CES-4), and (3) fan deltas (thick intervals of coarse- to medium-grained sandstones) (CES-1, CES-50). This last system is restricted to marginal positions in the basins.

By the end of Aptian marine conditions prevailed throughout the area. Albian lithofacies are generally representative of moderate to deep marine environments (middle to outer shelf) (predominance of argillaceous rocks and sometimes marls) (CES-56, CES-1). In some places carbonate platforms can be developed (CES-48, and distal equivalents in PIS-1). In the CES-48 well, where unusual subsiding conditions occurred, deeper water depositional environments can be found in the Cenomanian (continental slope and submarine fans).

SEQUENCE III, MARINE

Five main characteristics are diagnostic of Sequence III: (1) monotonous intercalations of argillaceous rocks and limestones, in places marls, (2) brownish to reddish colors of all lithologies, (3) faunal zone of the foraminifer *Hedbergella delrioensis*, (4) complete absence of benthonic foraminifers, and (5) very good to excellent source-rock characteristics. The age of this sequence is not precisely defined. Although it is generally called "Turonian anoxic deposits" the time span which it most probably represents is Late Cenomanian to Santonian (see discussion in Chapter VI). This sequence is bounded by two unconformities, which generally are well displayed in the dipmeter log (Figure 8). It was deposited under marine transgressive conditions. The transgressive character of this sequence is very well displayed in wells CES-50 and CES-56, where a basal sandstone is followed by a well defined fining-upward pattern in the gamma ray log.

Global sea level charts present several sea level falls within the Late Cenomanian-Santonian time interval (Hancock and Kauffman, 1979); however no evidence were found in this work that would permit their recognition within Sequence III. This is partly because paleontological data obtained from analyses of cuttings have limited resolution. Paleontological samples of Petrobras are composite samples representing 15 m of sedimentary section. Such an interval can easily contain two or three unconformities, which will not be resolved by this type of sampling. It is quite possible that future detailed work, using cores and detailed seismic-stratigraphic analyses, will split Sequence III into several units.

SEQUENCE IV, MARINE

Sequence IV ranges in age from Campanian to Paleocene. It becomes thicker and younger in the ocean direction (see Plate 14). In seismic sections it displays reflectors in an off-lap character, characterizing sedimentation on a prograding continental margin. Two depositional environments can sometimes be recognized: (1) lower continental slope (in the lower parts), composed of argillaceous rocks and turbidite sandstones, and (2) upper continental slope/outer shelf (in the upper parts), composed of argillaceous rocks and calcilutites. The top of this sequence is an unconformity. This unconformity represents the superposition of two erosional events, probably related to two distinct sea level falls. During the sea level fall at the end of the Cretaceous (65 m.y.b.p.), Campanian and Maastrichtian sediments were eroded. However, the deeper parts of the basin remained marine, and sedimentation was continuous between Maastrichtian and Paleocene times. Thus, in the deepest parts of the basin there is no unconformity between Cretaceous and Tertiary (CES-56). When sea level fell again (probably around the Early-Middle Eocene boundary, 49.5 m.y.b.p.), the whole basin was affected and unconformity exists between Middle Paleocene and Middle Eocene rocks (CES-56).

SEQUENCE V, MARINE

Sequence V is represented by very shallow marine sediments deposited on a broad erosional platform created by the sea level falls which occurred at the end of the Cretaceous and the beginning of the Tertiary. It rests unconformably over all the other sequences. (See Plates 14 and 16.) In seismic sections it appears as horizontal flat-lying reflections. It is composed of intercalations of thick beds of coarse- to very coarse-grained loose sands and calcarenites. It is predominantly terrigenous sand near the coast and predominantly calcareous in more offshore areas. It ranges in age from Middle Eocene (CES-56) up to the present.

The chronolithostratigraphic chart displayed on Figure 17 can also be applied to the Piaui sub-basin. However, it seems that this area was structurally high during most of the Late Cretaceous, and sediments of this age have not been found (Sequences III and IV). Generally, Sequence V rests directly upon Sequences II (CES-1, PIS-1) or I (CES-3).

Figures 18, 19 and Plate 17 show seismic sections in which the seismic character of Sequences I, II and V can be observed. The lacustrine and fluvial meandering systems of Sequence I are generally represented by regions very poor in reflections. Intervals displaying strong reflections within the continental deposits are generally related to fluvial braided or alluvial fan systems (see Plate 17). Sequence II differs from Sequence I by being richer in well defined, parallel, alternating reflections. In Plate 17 a very strong reflection can be observed throughout the Piaui trough. It represents the basal part of Sequence II and it can be used as an approximate time surface indicating the first invasions of sea waters. Sequence V is characterized by horizontal weak reflections (Plate 17). The stratigraphic cross-section shown in

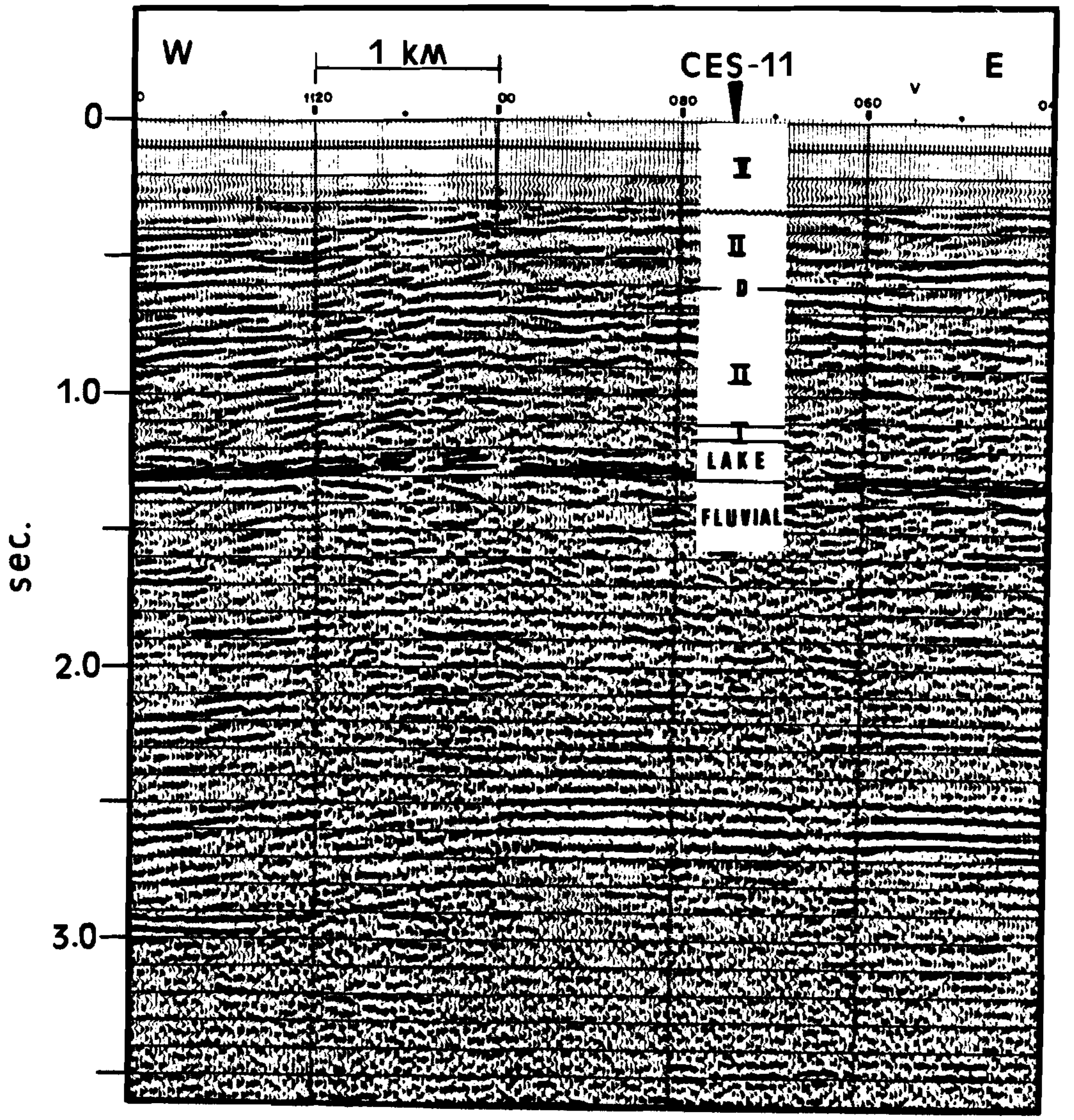


FIGURE 18 - Normal polarity section displaying the typical seismic response of Sequences I and II. The fluvial system corresponds to a zone poor in reflection. Sequence II is richer in reflections. D is a diabase sill. The top of the basement is at approximately 2.7 sec. below the well.

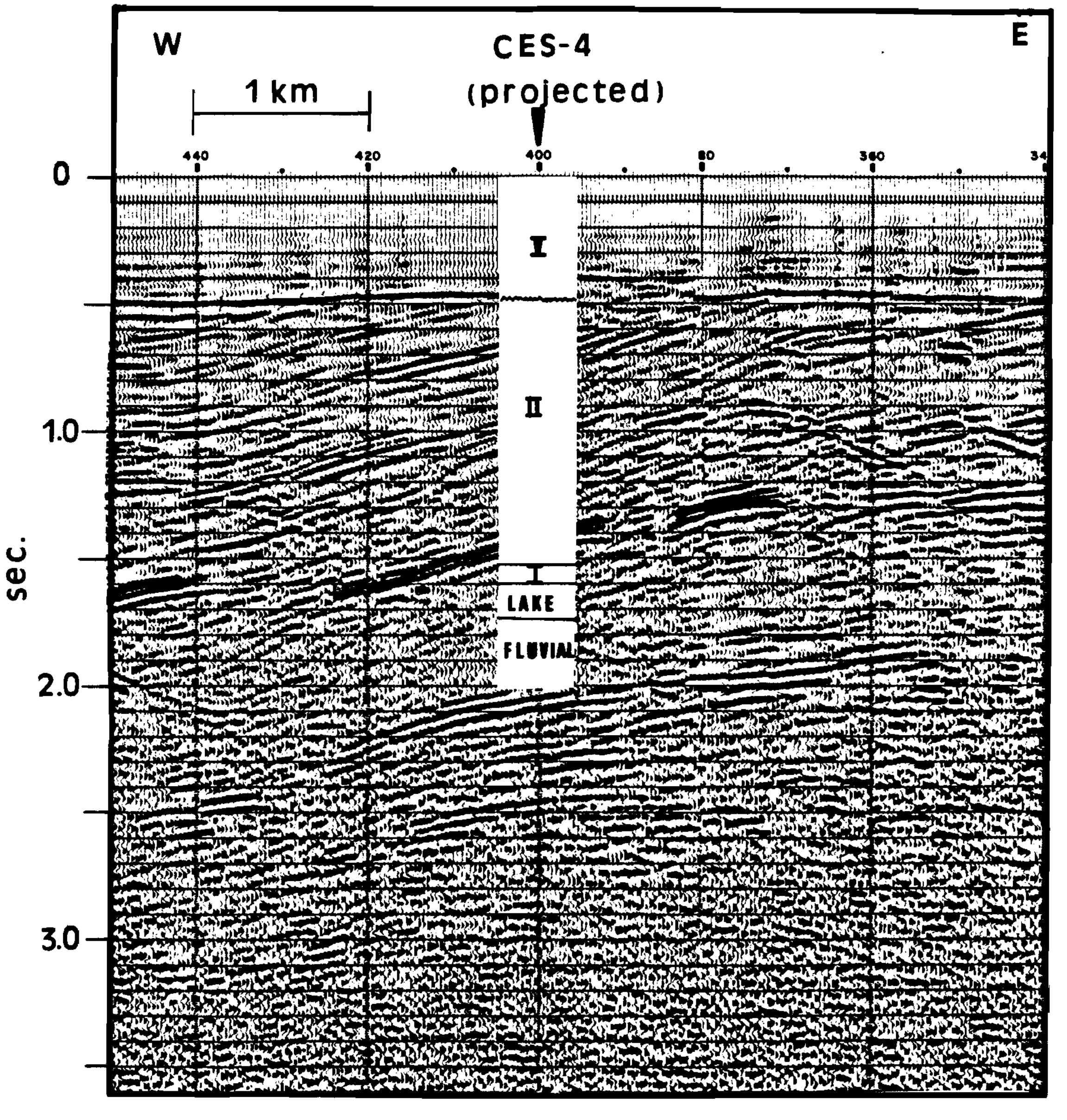


FIGURE 19 - Normal polarity section displaying a highly tectonized area. The occurrence of several difractions at east of the well reveals the presence of faults. The angular unconformity between the Aptian and Tertiary is clearly visible around 0.48 sec.

Plate 16 was constructed based on the seismic interpretation of Plate 17; both display very well the regional structure and the stratigraphy of the Piaui-Camocim sub-basin.

V - GEOLOGICAL EVOLUTION

The beginning of the rifting phase in the equatorial marginal basins of Brazil is not precisely defined. Evidence of very Early Cretaceous tectonic activity can be found in the Cassipore, Amazon Mouth, Sao Luiz and Potiguar basins (Asmus, 1981). Since the opening of this part of the Atlantic is more related to the geological evolution of the North Atlantic rather than the South Atlantic, sediments older than Cretaceous should be expected to be preserved in the deepest parts of these basins. Sediments associated with Triassic basalt flows occur in graben structures in the Amapa basin (Asmus, 1981). The summary of the stratigraphic evolution of the Acarau and Piaui-Camocim sub-basins begins in the Aptian since the oldest sediments available for this study are of Early Aptian age. Several paleogeographic maps and block diagrams are presented in order to illustrate the interpreted distribution of depositional environments and source areas in time and space.

APTIAN

By the beginning of the Aptian two major rift-valleys had already been defined in this area: The Piaui trough and the Acarau basin. They were asymmetric grabens; the deepest parts are situated in the south and abruptly end against the scarps of the Parnaiba platform. The northern boundaries were the slopes of the Atlantic and Ceara highs. The easternmost region of the Acarau sub-basin (adjacent to the west side of the Sobral lineament) was deeper than the western region, which was bounded by the slopes of the Ceara high.

The presence of fluvial braided systems in the wells CES-50, 52 and 3, and fluvial meandering systems in the wells CES-11, 4, 2, 55 and 5 during the Aptian, indicates the fact that elevated source areas existed to the north and northeast of the studied areas. Besides this, the deepest parts of the rift-valleys were situated to the south (near the Parnaiba Platform) and constituted the pathways for the invading marine waters coming from the west. It can be concluded that sediments were sourced from the north (probably the African plate or the Ceara and Atlantic highs), and were carried to the south until they reached the escarpments of the Parnaiba Platform.

Sediment transportation was then deflected to the west, until reaching the approaching seas (Plates 18, 19, 20). Seismic section in Plate 17 clearly shows the direction of sediment transport from north to south, onlapping against the scarps of the Parnaiba Platform.

During the Early Aptian continental conditions prevailed throughout the area. (See Plate 18.) Alluvial fans with associated braided rivers existed in marginal areas, while meandering rivers and minor lakes predominated in the deepest parts. The main flow directions were to the south (Acarau area) and to the west (Piaui area).

During the Middle Aptian the first sea waters arrived in the area, coming from the west through the Piaui trough (see Plate 19). The pathways of the invading sea waters were the deepest parts of the asymmetric grabens. It is interesting to note that a lacustrine system generally precedes the transitional environments (see Plate 19). Plate 22 shows the isopach map and age distribution of the lacustrine system. It is clearly thicker in the deepest parts and becomes younger from south to north. The best source rocks occur in the deepest parts of the lakes, probably because of anoxic conditions created at their bottoms. Transitional environments appear during the Middle Aptian in the PIS-1, CES-11, CES-4 and CES-2 (see Plate 20). By

Late Aptian most of the studied area is flooded by sea waters and transitional environments prevail throughout the basins (see Plate 21). A very favorable situation occurs during this stage when good reservoir rocks of the transitional sequence cover the source rocks of the lacustrine system. At the end of the Aptian true marine conditions existed in most areas.

ALBIAN-CENOMANIAN

The worldwide transgression of the Albian and Cenomanian is also well documented in these areas. Sediments representing shallow to moderately deep neritic environments represent the Albian in most wells. Carbonate deposits occur in some areas (e.g.: CES-48), probably related to localized shoaling conditions. Where Cenomanian sediments are well preserved (CES-48) bathyal depositional environments can be found. In some areas deep-water conditions were attained also in the Albian (CES-56).

By this time Aptian sediments had probably undergone sufficient burial to attain thermal maturation stages favorable for oil generation (see Chapter VI). The Cenomanian sea-level fall associated with intense tectonic activity which lasted until Late Cenomanian-Early Turonian created the first large hiatus in the basins. The age of this tectonism is determined by the fact that Sequence II is intensively faulted, either by reverse faults (see cores #1 and #2, CES-55) or normal faults (see core #5, CES-48; and Figure 5); or present local unconformities within it (see Chapter III, well CES-56). The overlying sequences do not present evidence of tectonic deformation. It is quite probable that some early hydrocarbon accumulations were profoundly affected, or even destroyed, during this tectonic/erosional event.

TURONIAN-SANTONIAN

Following the erosional period described above a large marine transgression occurred, and sediments displaying characteristics of anoxic environments were deposited unconformably over the eroded top of Sequence II in the Acarau area. Figure 20 displays the interpreted depositional environment of Sequence III. The age of this Transgressive event is not precisely defined (see discussions in Chapters VI and IV). In some wells it is dated as Turonian- Cenomanian (CES-2), in others as Turonian-Santonian (CES-56, CES-50), and in others as Coniacian-

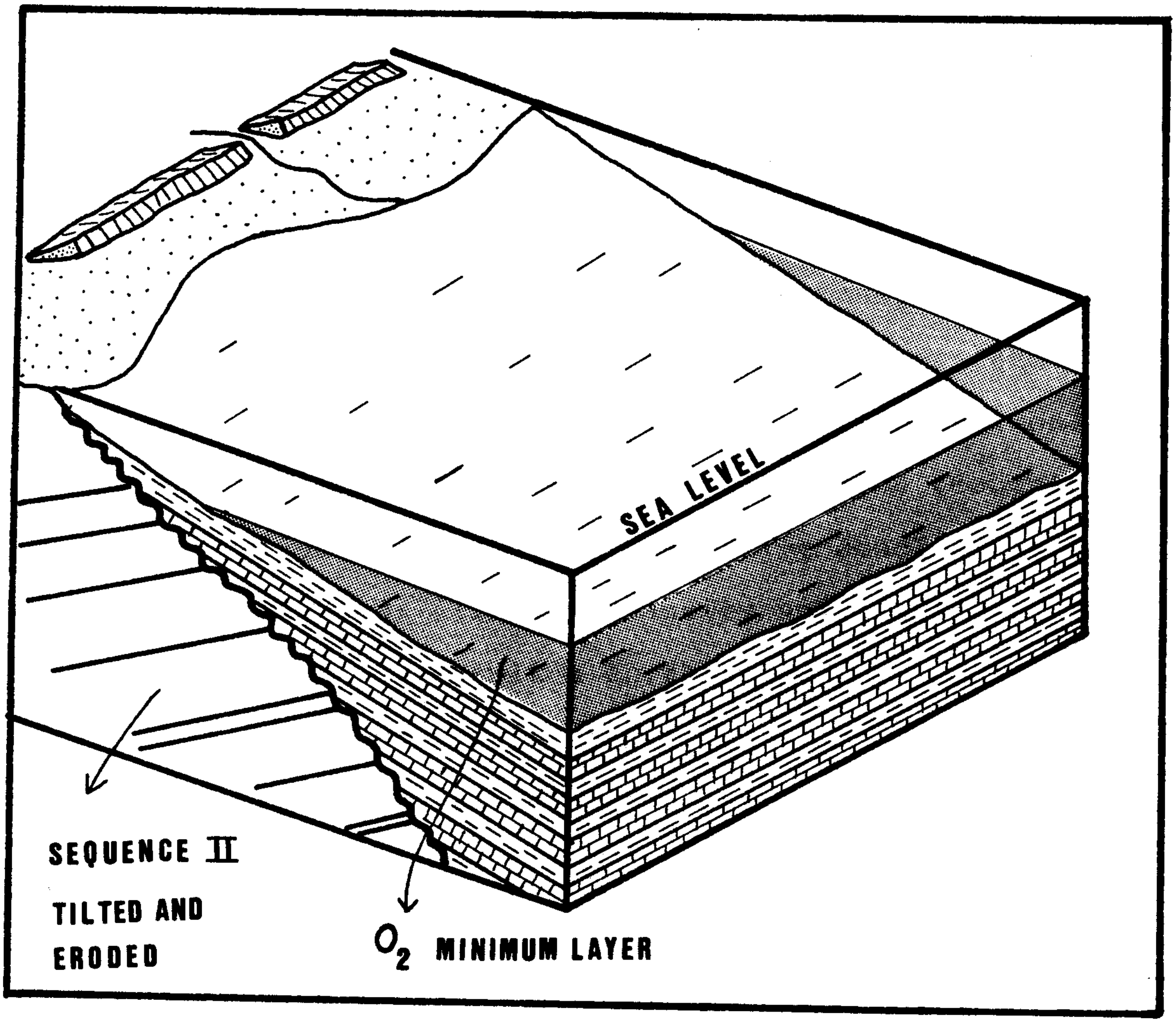


FIGURE 20 - Depositional model of Sequence III. Intercalations of argillaceous rocks and limestones (thicknesses are exaggerated) progressively onlap Sequence II. Oxygen minimum layer is thick and widespread.

Santonian (CES-55, CES-52). Apparently these rocks were deposited under a single transgressive event (see CES-56 and CES-50). Hancock and Kauffman (1979), however, present evidence for three transgressive events during this time span (Earliest Turonian, Coniacian and Middle Santonian) which should be recognized worldwide. Arthur and Schlanger (1979) cite two distinct oceanic anoxic events during this time span (Cenomanian-Turonian and Coniacian-Santonian). In the Acarau sub-basin only one transgression and only one anoxic event can be recognized from the available data. Two alternative conclusions are immediately deduced: (1) the quantity and quality of the analyzed data do not permit a further subdivision of these deposits (see discussion in Chapter IV), or (2) this area experienced only one transgression during the Turonian-Santonian, during which anoxic conditions prevailed at the bottom of the ocean, and thus those transgressive events cited by Hancock and Kauffman (1979) do not have a truly worldwide expression. The only way to clarify this doubt is to cut three cores in this sequence (top, middle and bottom), in the next well; interpret them and carefully tie them to seismic section. Careful paleontologic and seismic-stratigraphic analyses are probably the best ways to solve the problem.

This sequence contains the best source rocks of the Acarau sub-basin, but they are not always thermally mature. Exploratory attention should be shifted to areas where the already formed structures of Sequence II are in contact with thermally mature source rocks of Sequence III (see Plate 25). Fractures in rocks of Sequence II can serve both as pathways for oil migration and as open spaces for oil accumulation.

The Piaui area and the region around the CES-48 constituted a structurally positive platform during most of the Late Cretaceous. This series (with the exception of the Cenomanian stage) is not represented in these areas.

CAMPANIAN/PALEOCENE

Following an erosional event, which could be a sea-level fall at 87.5 or 78.5 m.y.b.p. (depending on the age of Sequence III), another relative sea-level rise took place. The influx of sediments during this time was so large that a prograding continental margin prevailed as the main depositional environment (see Figure 21). Large volumes of argillaceous material with intercalated turbidite sands were deposited at the base of the prograding continental slopes. These were later covered by outer

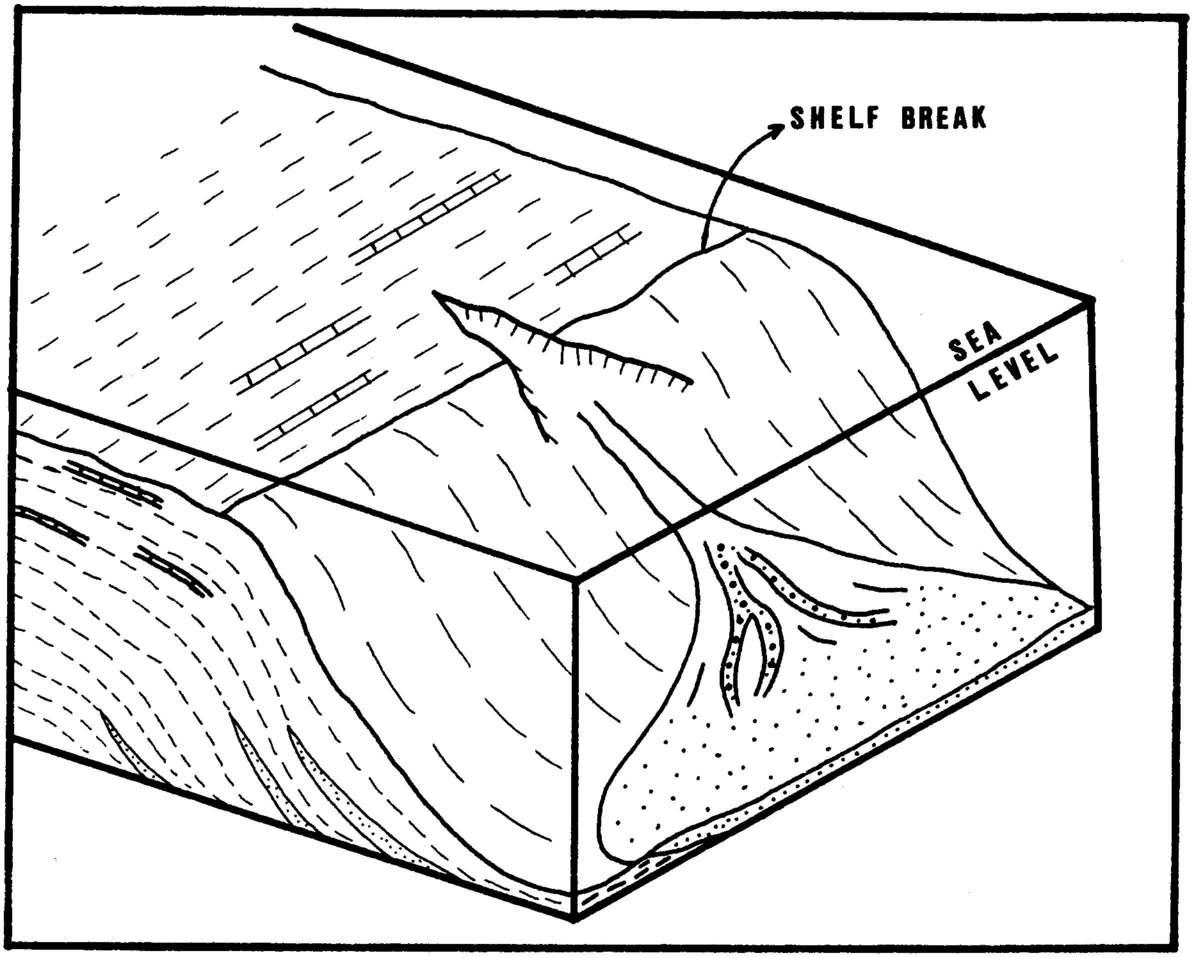


FIGURE 21 - Depositional model of Sequence IV. Turbidite sandstones occur at the base (bathyal environments) and calcilutites at the top (outer neritic environments).

shelf/upper slope intercalations of argillaceous rocks and calcilutites. When the sea level fell again at the end of the Cretaceous (65 m.y.b.p.) large areas of Sequence IV were eroded; however, it seems that the deepest parts of the Acarau sub-basin were not affected and sedimentation was not interrupted during Paleocene. Another sea level fall (probably at 49 m.y.b.p.) exposed again Sequence IV and even Paleocene rocks were then eroded (see discussion in Chapter IV). The Piaui and the CES-48 areas still remained as a structurally positive platform, largely sub-aerially exposed during this time interval.

EOCENE-PRESENT

Marine sedimentation resumed by Eocene and gradually the whole exposed platform was covered by fan deltas, sourced from the continent, intertonguing with carbonate platform deposits. The Piaui and the CES-48 areas were also covered. Sequence V was not studied in detail since it apparently does not present any interest for petroleum exploration, thus no additional comments about its evolution are made.

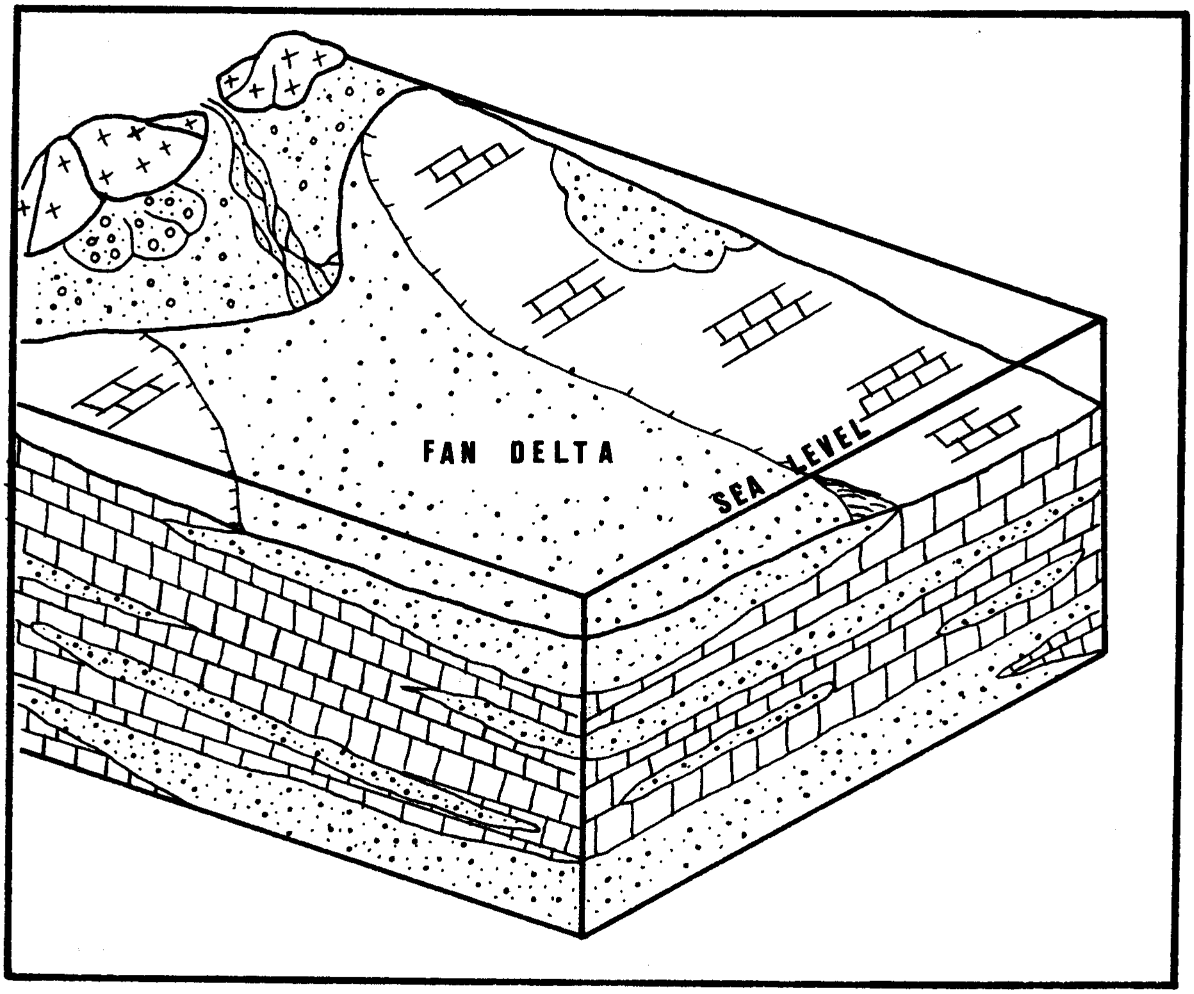


FIGURE 22 - Depositional model of Sequence V. Water depths were probably less than 10 meters.

VI - PETROLEUM POTENTIAL OF THE BASINS

INTRODUCTION

In this chapter the results of the geochemical analyses and their discussion are presented. The main objectives are: (1) to identify good oil-prone source beds, and (2) their maturation stage, (3) to determine their age and depositional environments, (4) to correlate them from well to well, and (5) to determine their areal distribution with respect to the regions where they probably have undergone favorable geologic history (maturation) for oil generation.

The results are presented in a columnar format. Each well has organic matter quantity, quality and thermal maturation indicators. The TOC column represents the percentage of total organic carbon present in the rock. The alginite + liptinite column represents the percentage of oil-prone material in the kerogen, analyzed by visual means. In the older wells (PIS-1, CES-1, 2, 3, 4 and 5) the results of the analyses of the type of kerogen present are expressed in terms of verbal qualifiers. This system was transformed into a numerical one in order to facilitate interpretation. The arbitrary percentage values assigned to the following qualifiers are: rare - 10%, dispersed - 20%, common - 30%, more common - 50%, abundant - 70%. In this way a semiquantitative analysis of the data is possible. Regarding thermal maturation indicators, three types can be displayed on the columnar sections.

(a) Wells drilled more recently present a profile of light gases. Low molecular hydrocarbon gases ranging from methane to pentane are called light gases. By having a continuous profile of the relative amounts of methane in relation to the other gases in a well we can determine the depths of the maturation zone (see Figure 23). The immature zone corresponds to the predominance of biogenic methane. As temperature increases and oil is generated the other gases (ethane to pentane) become predominant over methane (mature zone). In the supramature zone all oil has been transformed into thermogenic methane and this gas is now predominant again. This method is widely used by PETROBRAS. Cuttings from every 30 m drilled are canned at the wellsite and sent to the laboratory. The gases liberated are extracted and analyzed. This technique corresponds to Cl/H.C.G. ratio of Heroux et al. (1979, p. 2137), where H.C.G. represents the light gases from methane to butane.

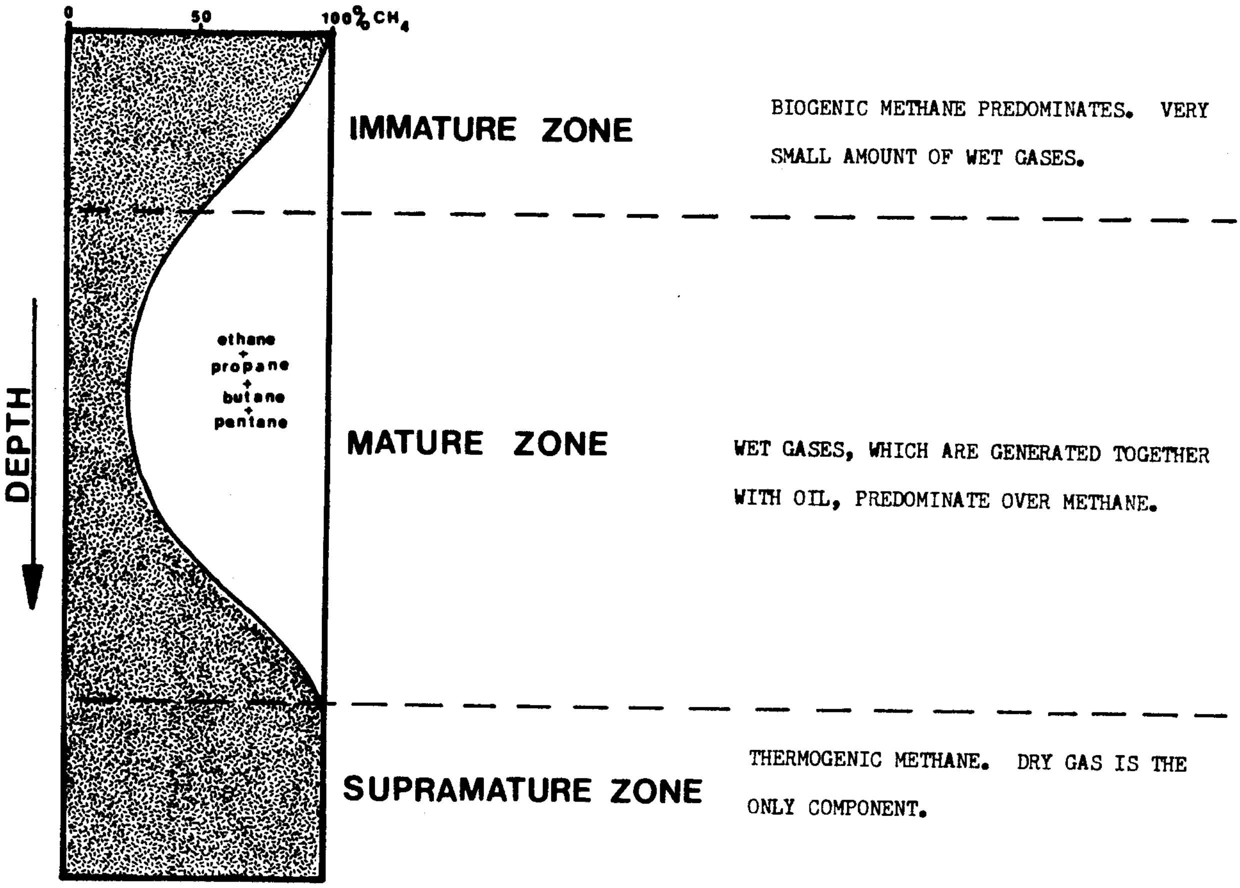


FIGURE 23 - Relative abundance of light gases relative to maturation zones. Stippled area corresponds to methane.

(b) Older wells were analyzed for the thermal alteration index (TAI). With increasing temperatures the color of kerogen changes. The oil-generative zone (the "liquid window," 65° C - 150° C) is thought to correspond approximately to the golden-brown through brown stages. Several schemes have been introduced for rating the color intensities of kerogen. The most widely used system employs a scale from 1 to 5. The figures and the related colors vary for every different laboratory. PETROBRAS utilizes the following values to determine the mature zones: 2.75/3.00 (lower limit) and 3.75 (upper limit).

(c) Very few analyses of vitrinite reflectance are available; where they exist they were indicated. It is the most precise thermal maturation indicator and should be used more frequently.

In each well the top of the mature zone and the top of the supramature zone (if present) were determined. The methodology used in the identification and classification of source beds is described below.

The approach used in this study to evaluate the potentiality of the source rocks present was the one described in Wapples (1979). He defined two parameters (total oil and oil already generated) which permit a semiquantitative prediction of oil source capacity. The total oil value for any sample may be calculated by the product of scaled parameters for quantity (Q1) and quality (Q2) of the organic matter in the sample. The oil-already-generated value for any sample is calculated by multiplying the total oil value by a scaled parameter representing the degree of thermal maturity of the kerogen. In the method described by Wapples vitrinite reflectance is preferred because it is less subjective and more precise than thermal alteration index. Because only some few vitrinite reflectance results were available in the wells studied only the first parameter (total oil) was used to perform a semiquantitative evaluation of the source rocks analyzed.

Total oil reflects the oil generating capacity of the source rock. It permits comparisons between different source beds, and once good or excellent source rocks are identified by this parameter the exploratory attention should be shifted to locate geologic environments where these potential oil sources have been exposed to the proper maturation conditions for oil generation (Wapples, 1979). The quantity factor for the organic matter quantity (Q1) can be found by using Figure 1 of Wapples (1979, p. 240), where the percentage of organic carbon in the rock (TOC) is employed. The quantity factor for the kerogen quality (Q2) can be calculated from Figure 2 of Wapples (1979, p. 240), where the percentage of alginite + liptinite is used. From the definition of total oil and the relationships displayed in those graphs the following equation can be deduced and used to calculate the total oil value of any sample:

$$\text{TOTAL OIL} = (\%\ \text{ORGANIC CARBON}) \times (\%\ \text{ALGINITE} + \text{LIPTINITE}) \times 0.02$$

Once this value is obtained we have to compare it with some scale in order to know the kind of source rocks. Wapples (1979) cites three values with which to begin a comparison: (1) an organic-lean, poor-quality kerogen has a total-oil value around 0.025, (2) an "average" source bed will have a value of 1, and (3) a superb source rock, like the Green River shale, can have total oil values as high as 36. Based on these figures and on some boundary values obtained by using selected values for total organic carbon and percent alginite + liptinite I devised a classification of source-rocks according to total oil values; as displayed in Table 14. Five classes and four boundary values are proposed and will be used.

% $C_{ORGANIC}$	% ALG. + LIPT.	TOTAL OIL	CLASSIFICATION	
		(<0.3)	POOR	BELOW AVERAGE
0.5	30	0.3		
			REGULAR	
1.0	50	1.0		
			GOOD	ABOVE AVERAGE
2.0	70	3.0		
			VERY GOOD	
4.0	90	7.0		
		(>7.0)	EXCELLENT	

TABLE 14 - Classification of source rocks as related to total oil value. Values of total organic carbon and % alginite + liptinite used in the calculations of the boundary limits of total oil are presented. Total oil values were rounded.

In the columnar sections displaying the geochemical results of each well the column termed "total oil" shows all source beds classified as "above average." Their geological environments, their ages, their maturation stages, and later the distribution of the best ones are discussed. Source beds with total oil values less than 1 are neither indicated nor analyzed.

GEOCHEMICAL DATA

CES-4 -

The top of the mature zone coincides with the unconformity at 347 m, which separates Tertiary rocks from Albian ones. TAI values just below the unconformity are situated around 2.75 - 3.00, increasing gradually until 3.50 - 3.75 at the bottom of the well. Values higher than 3.75 were not found, but the top of the supramature zone is not much deeper. It is probably between 3000 and 4000 m (see Figure 24).

No good oil-prone source rocks are present in this well. This is mostly due to the proximal position of this well in relation to the southern margin of the basin. One sample around 640-610 m has a total oil value of 1.0 (average source rock). It is related to the basal part of the

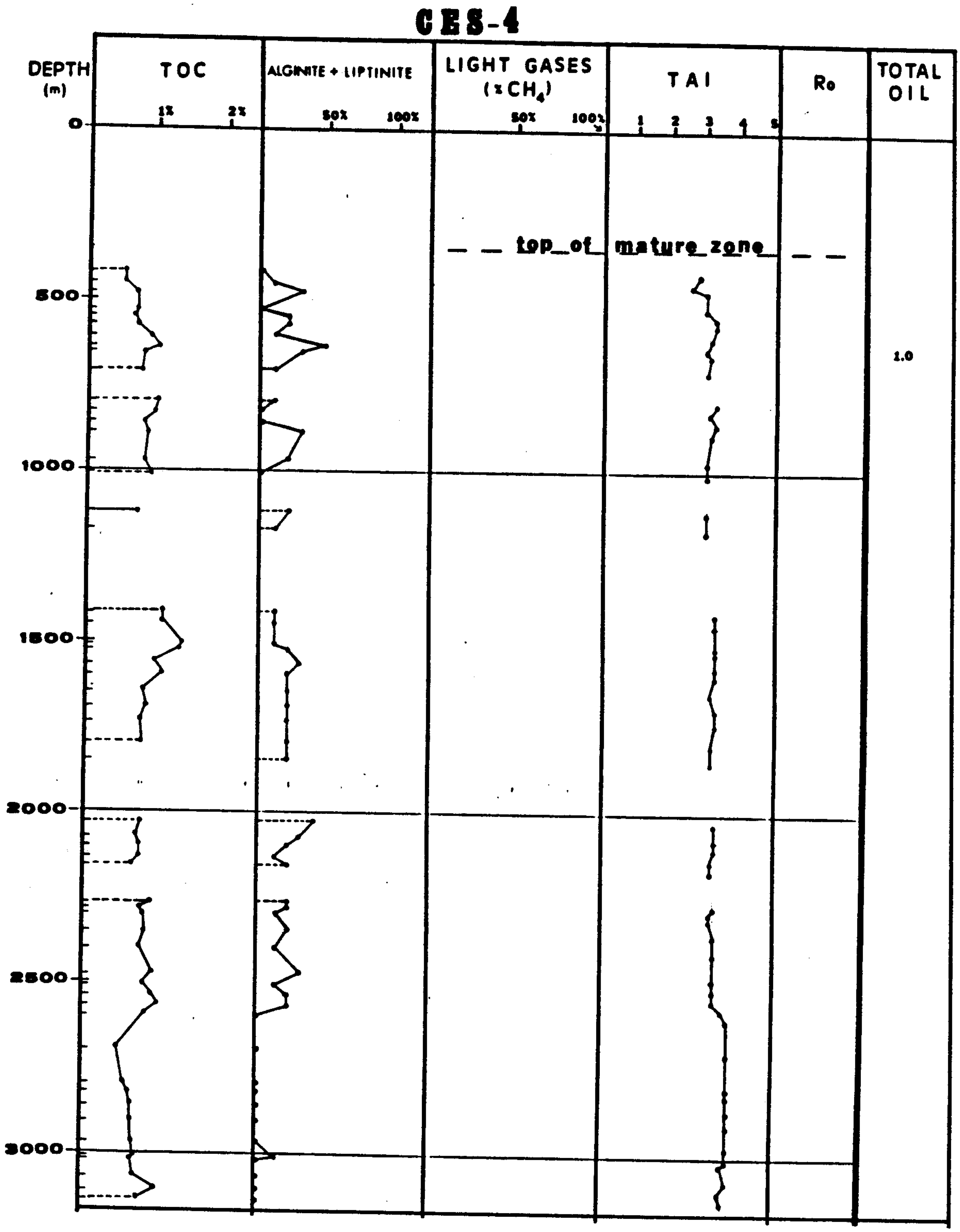


FIGURE 24 - Geochemical data, CES-4.

Albian shallow marine sequence. Average TOC values for the rest of the section are equal to 1.0% or less. The predominant organic matter is by far vitrinite. Practically no algal material is present. Alginite appears in low proportions (less than 50%) in all sedimentary sequences, with the exception of the fluvial section where only vitrinite is present. Although the source rocks are predominantly gas prone, the weak shows of oil indicate that small amounts of oil could have been generated by the argillaceous rocks containing some exinite.

CES-11 -

The top of the mature zone probably coincides with the unconformity at the top of the Aptian. The light-gases profile shows a distinct predominance of C_2 - C_4 gases over methane. The first four samples (600-480 m) are very rich in methane but probably represent local concentrations such as others found at 1260, 1680 and 1800 m. There are no indications of proximity to the supramature zone (see Figure 25).

There are absolutely no good oil-prone source rocks. The argillaceous rocks are very poor in TOC (less than 1%) and very rich in vitrinite (generally more than 80%). An isolated sample at 2340-2310 m presents the higher content

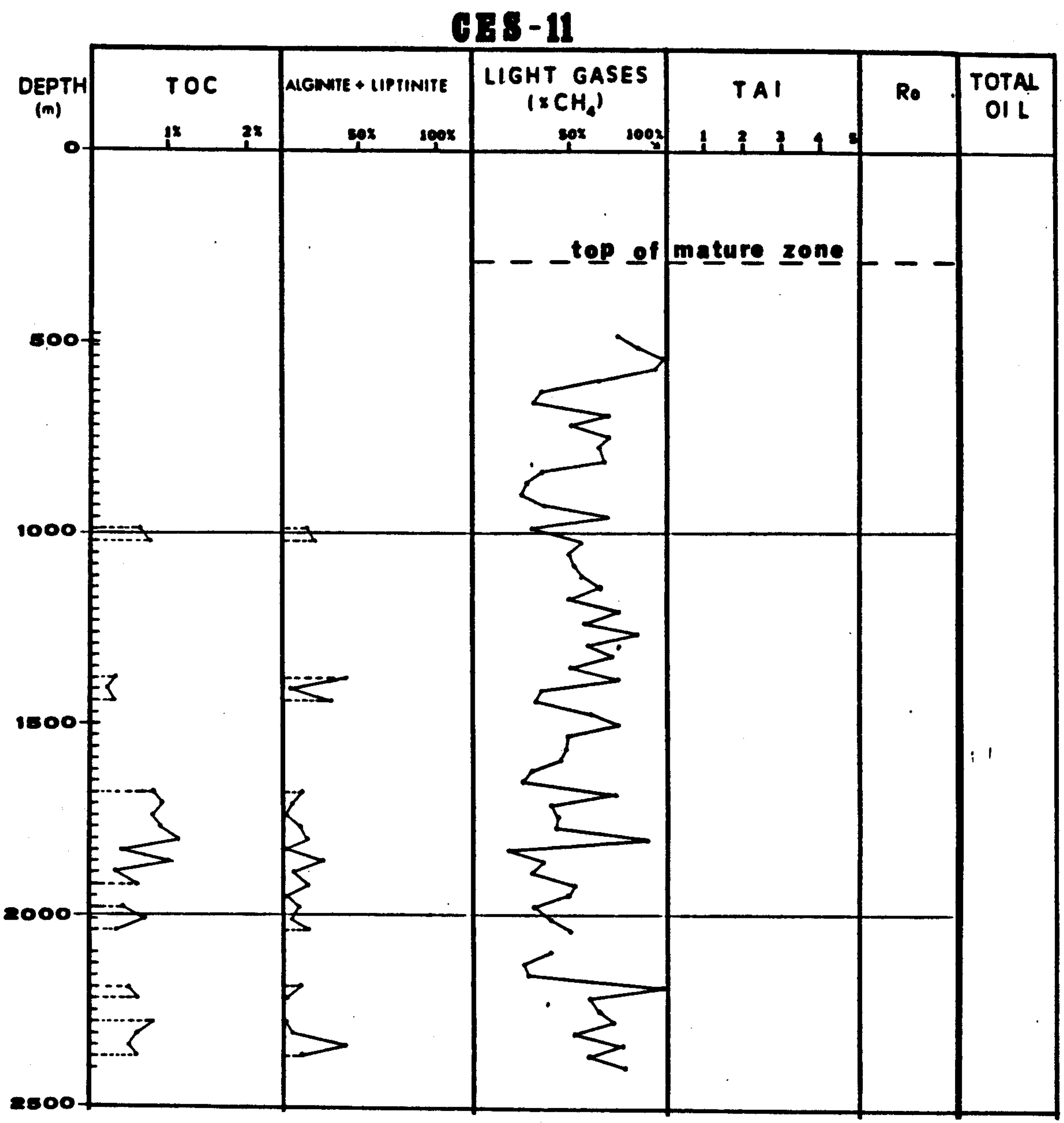


FIGURE 25 - Geochemical data, CES-11.

of oil-prone material (40%), however, the TOC is too low (0.6%). It probably represents a restricted lacustrine deposit within the fluvial meandering system. The sedimentary section is entirely gas prone.

CES-2 -

The top of the mature zone is between 1340 m (TAI = 2.75) and 1675 (TAI = 2.75/3.0, vitrinite reflectance = 0.60). It is arbitrarily chosen as 1500 m, where the first shows of gas appear. The top of the supramature zone was not reached, however a vitrinite reflection value of 1.19 at 2925 m and TAI values of 3.50/3.75 at the bottom of the well indicate its proximity; probably around 4000 m (see Figure 26).

Several good source rocks appear between 2640-2700 m and are associated with highly radioactive shales of lacustrine origin (TOTAL OIL = 1.1 - 1.3). The intercalated sandstones have shows of oil. Another good source rock occurs at 1675 m (total oil - 1.2) and it is associated with a deltaic complex. Turonian anoxic deposits occur between 910-745 m, but their samples were not analyzed due to intense contamination of collapsed Tertiary sands. However they do not constitute source rocks in this area because they are situated far above the mature zone. With

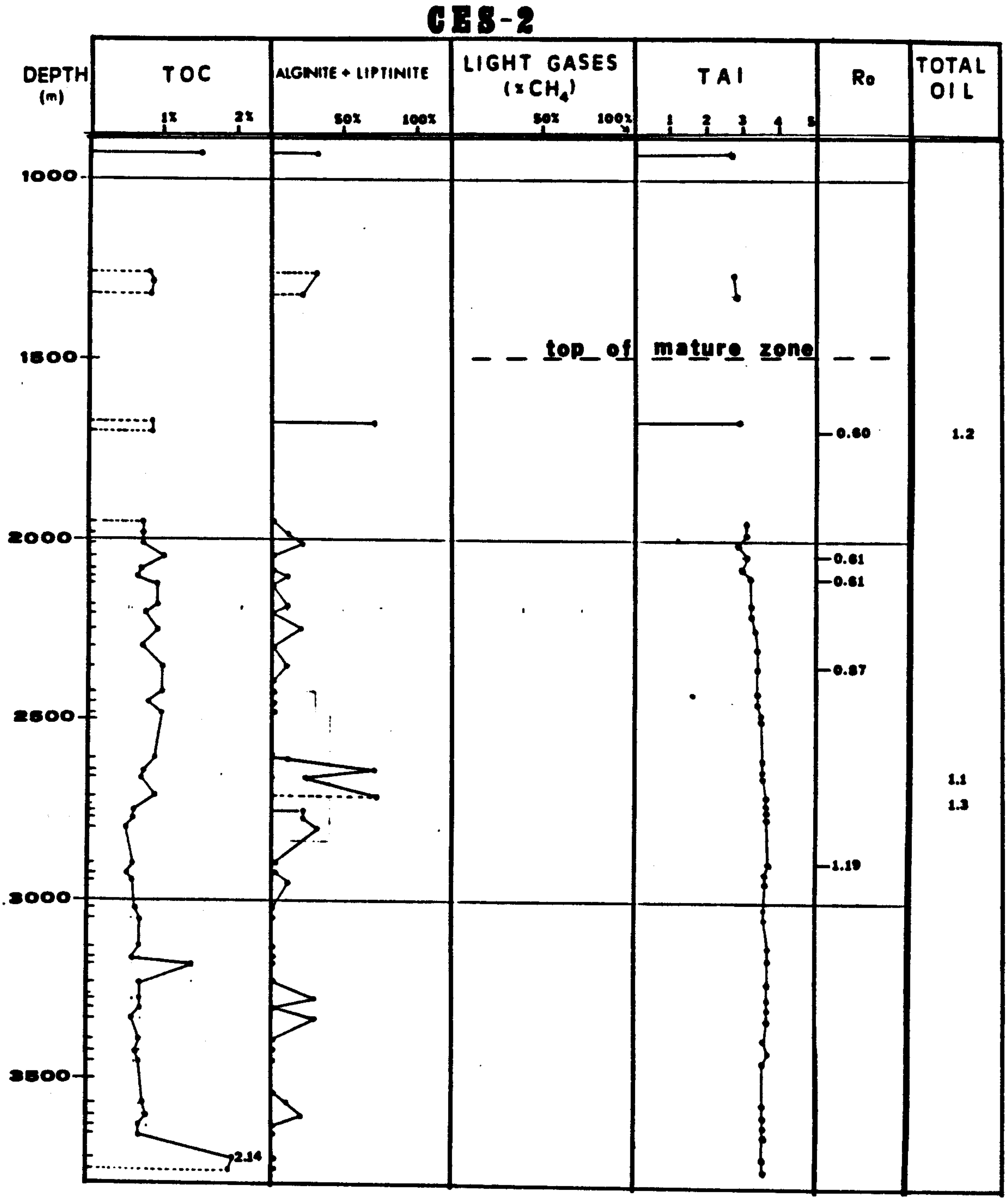


FIGURE 26 - Geochemical data, CES-2.

the exception of these intervals the rest of the sedimentary section is essentially gas-prone. This fact is confirmed by the abundant gas shows and the gas-bearing reservoirs tested between 3500 and 3100 m. Sources for this gas could be intervals such as 3690-3750 m which have TOC values as high as 2.14%, but are completely devoid of oil-prone material.

CES-55 -

The passage from the immature to the mature zone is clearly transitional. Percentages of C_2 - C_4 gases increase gradually between 900 - 1500 m. The top of the mature zone is placed at 1500 m, below which these gases attain values near 100%. There are no indications of the proximity of the supramature zone (see Figure 27).

This well contains good examples of the two best source rock systems of the Acarau sub-basin. The first one, between 2370-2490 m, represents lacustrine deposits of Late Aptian age. Shows of oil occur above and below this interval. Total oil values can reach 2.6 (good source rocks). The other interval, between 1230-1410 m, has total oil values between 2.2 and 3.4 (good to very good source rocks). These samples represent the Turonian anoxic deposits, however, they are once again above the

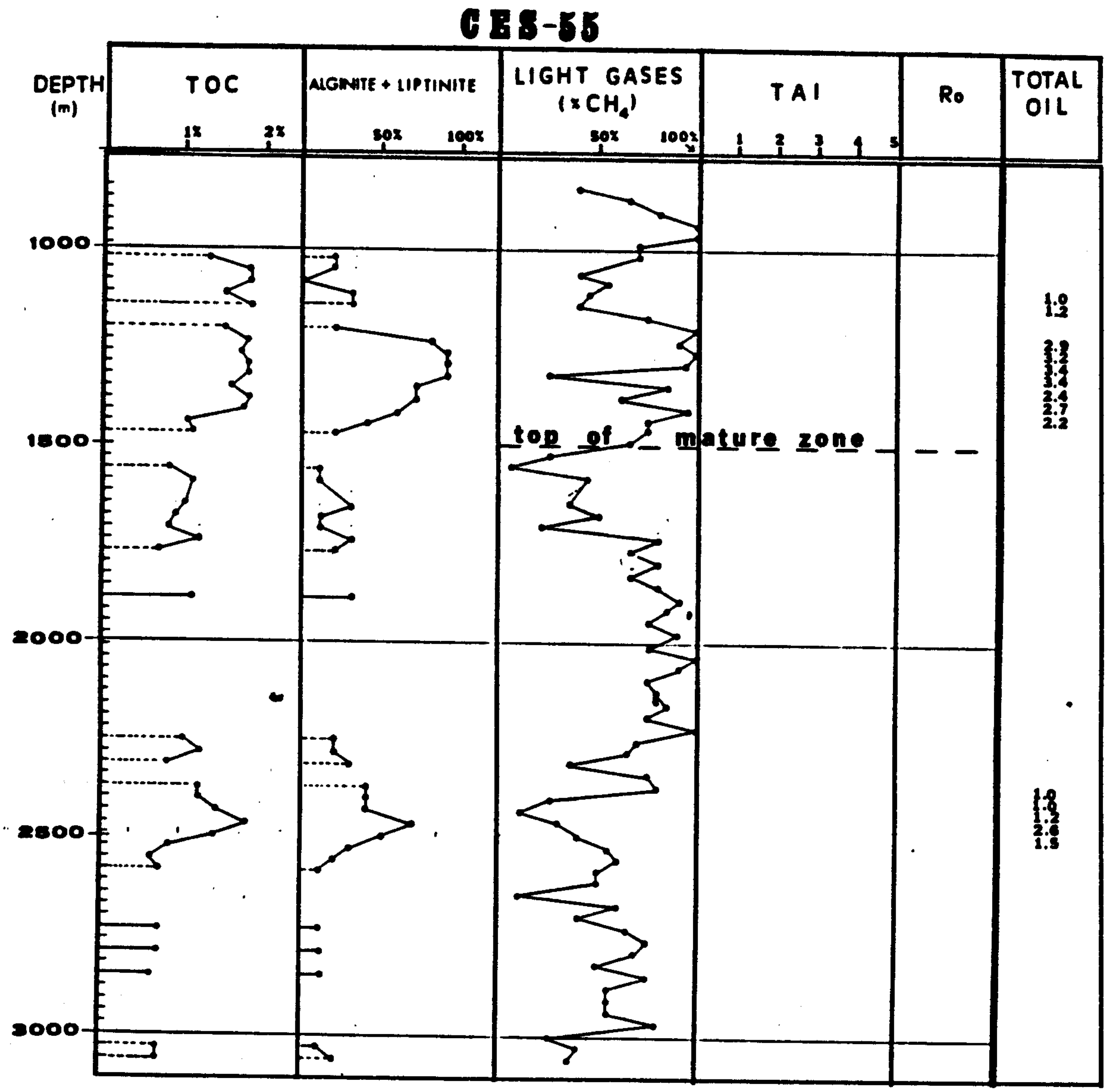


FIGURE 27 - Geochemical data, CES-55.

mature zone. Shows of oil associated with them are due to the fact that these deposits are situated within the transition zone. The interval 1110-1140 has total oil values between 1.0 and 1.2. It represents organic-rich slope deposits of Late Cretaceous age. These beds when located in very offshore positions (within the mature zone) can be the source for oil in intercalated beds of turbiditic sandstones (as in the Espada field, Mundau sub-basin). The origin of the oil found around 1620-1630 m is still doubtful. No chromatograms have been made. It could have been migrated from the lacustrine deposits or from Turonian mature beds situated farther offshore.

CES-52 -

Once again the passage from immature to mature conditions is transitional. The top of the mature zone is placed at 1950 m. From this depth down C_2 - C_4 gases are much more abundant than in the overlying deposits. At the bottom of the well there is a clear transition from the mature to the supramature zone. The top of the supramature zone is tentatively placed at 3900 m (see Figure 28).

The Turonian deposits (1290-1350 m) contain very good source rock characteristics, but they are completely

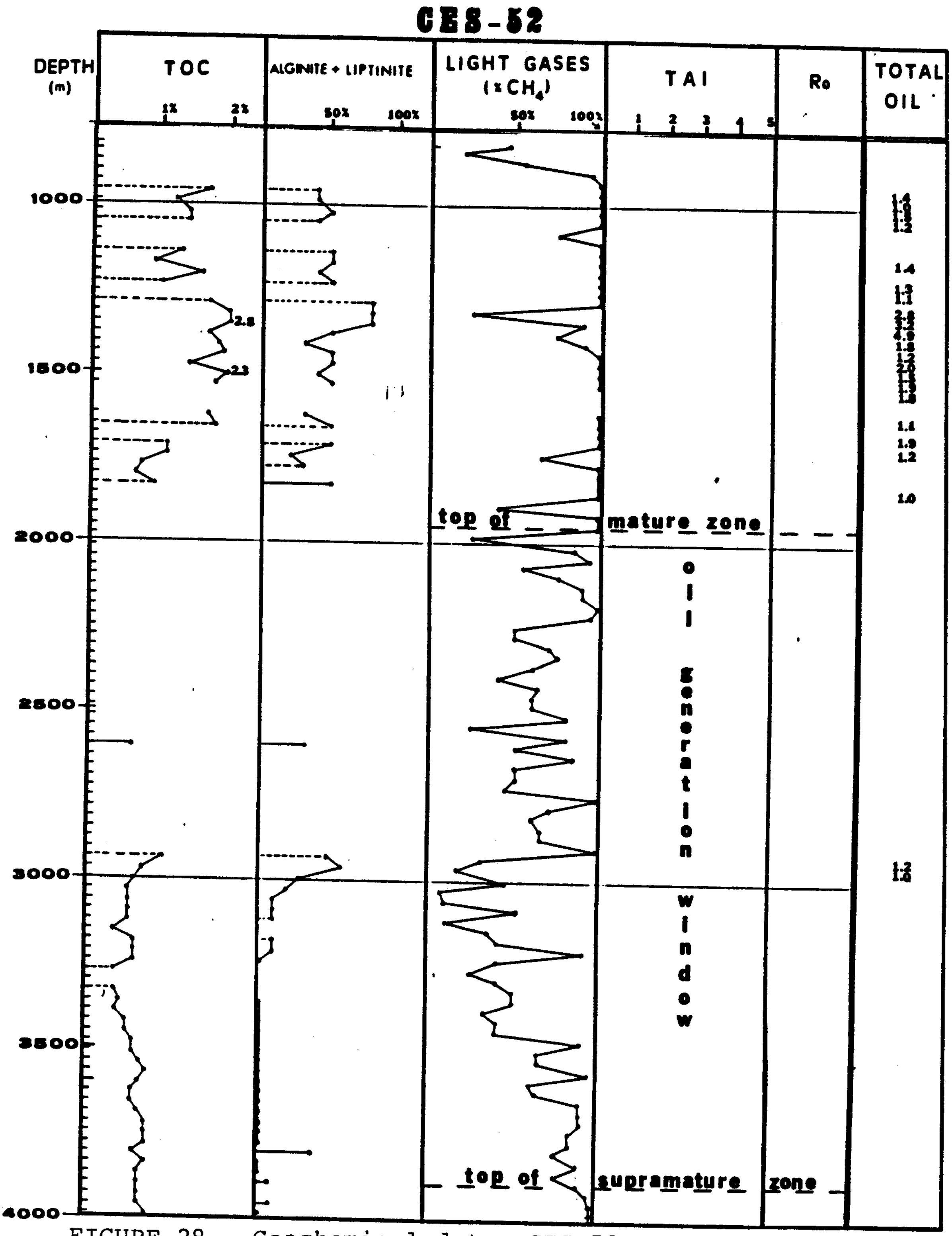


FIGURE 28 - Geochemical data, CES-52.

immature. Late Cretaceous slope deposits (960-1050 m, 1140-1200 m) and Late Aptian marine and deltaic shales (1380-1700 m) all have total oil values between 1.0 and 2.0; however, they are all above the top of the mature zone. The frequent occurrence of oil shows in these intervals are related to these potentially good source rocks being subjected to temperatures very near the maturation stage (transitional zone). At 2940-2970 m mature, good source rocks occur and are related to restricted lakes within a fluvio-lacustrine sequence of Late Aptian age.

CES-50 -

The top of the mature zone is placed at 1500 m, despite the fact that there is a great quantity of C_2 - C_4 gases in the overlying section. This is due to the fact the upper 1000 m is rich in very porous, loose sandstones intercalated with limestones of Tertiary age which can accumulate large amounts of upward-diffusing gases. They also collapse very much and can contaminate the samples of the underlying sections. From 1500 m down the predominance of C_2 - C_4 is clear enough to indicate the presence of the maturation zone. There are no indicators of the presence of the supramature zone (see Figure 29).

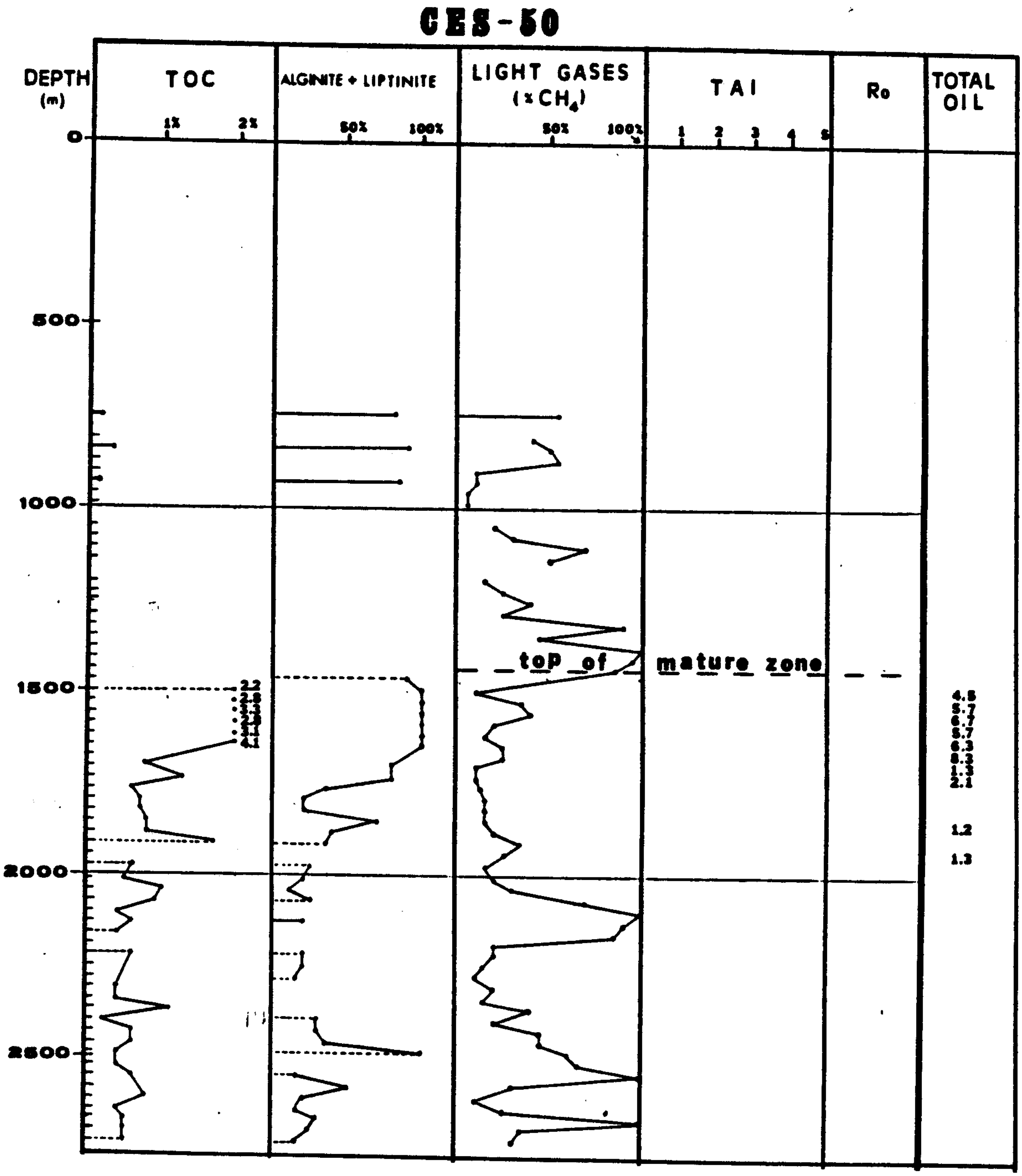


FIGURE 29 - Geochemical data, CES-50.

Samples from the Turonian anoxic beds contain good to excellent properties of source rocks (total oil values between 1.3 and 8.3). TOC values can be as high as 4.1%, and the organic matter present is frequently 100% oil-prone. A very interesting feature associated with the anoxic beds in this well was the occurrence of abundant sour gas shows. Based on the following facts: (1) these source beds are within the mature zone, and (2) absolutely no shows of oil were found in this well, it is concluded that the oil generated has migrated away from this region. Long distance migration of hydrocarbons seems to be a plausible mechanism in the Acarau sub-basin (based on the results of this well and the CES-55). However, the presence of sour gas is frequently associated with thermally degraded oils, so this constitutes an alternative hypothesis for the absence of oil shows. Two samples from the Late Aptian marine sequence also presented good source rock characteristics.

CES-5 -

The passage from the immature zone to the mature zone is transitional. The light-gases profile is affected by upward diffusion of gases and does not present a typical immature zone. TAI range from 2.50/2.75 at 1100 m to 3.00

around 1800 m. Vitrinite reflectance around 2000 m is 0.60. The top of the mature zone must be situated slightly above 1800 m and it is placed at 1750 m above the first sample which indicated 0% methane. The top of the supramature zone is probably between 4000 and 4500 m. Vitrinite reflectance values below 3500 m are 1.18, TAI values are 3.75, and the light-gases profile begins to show a gradual increase in the methane content (see Figure 30).

Source rocks in this well are related to two depositional environments: (1) Turonian anoxic beds, 1170-1200 m, total oil values between 1.5 and 1.8 (in the immature zone), and (2) marsh deposits in the Transitional sequence with very high contents of organic matter (up to 3.1%), 1980 m, 2280 m, and 2370-2430 m. These last deposits have low contents of oil-prone material but their high TOC values make them good source rocks. They are associated with coal occurrences. The lacustrine rocks between 2880-2730 m do not present TOC values high enough to make them good source rocks, despite the regular values of alginite + liptinite (30% to 50%).

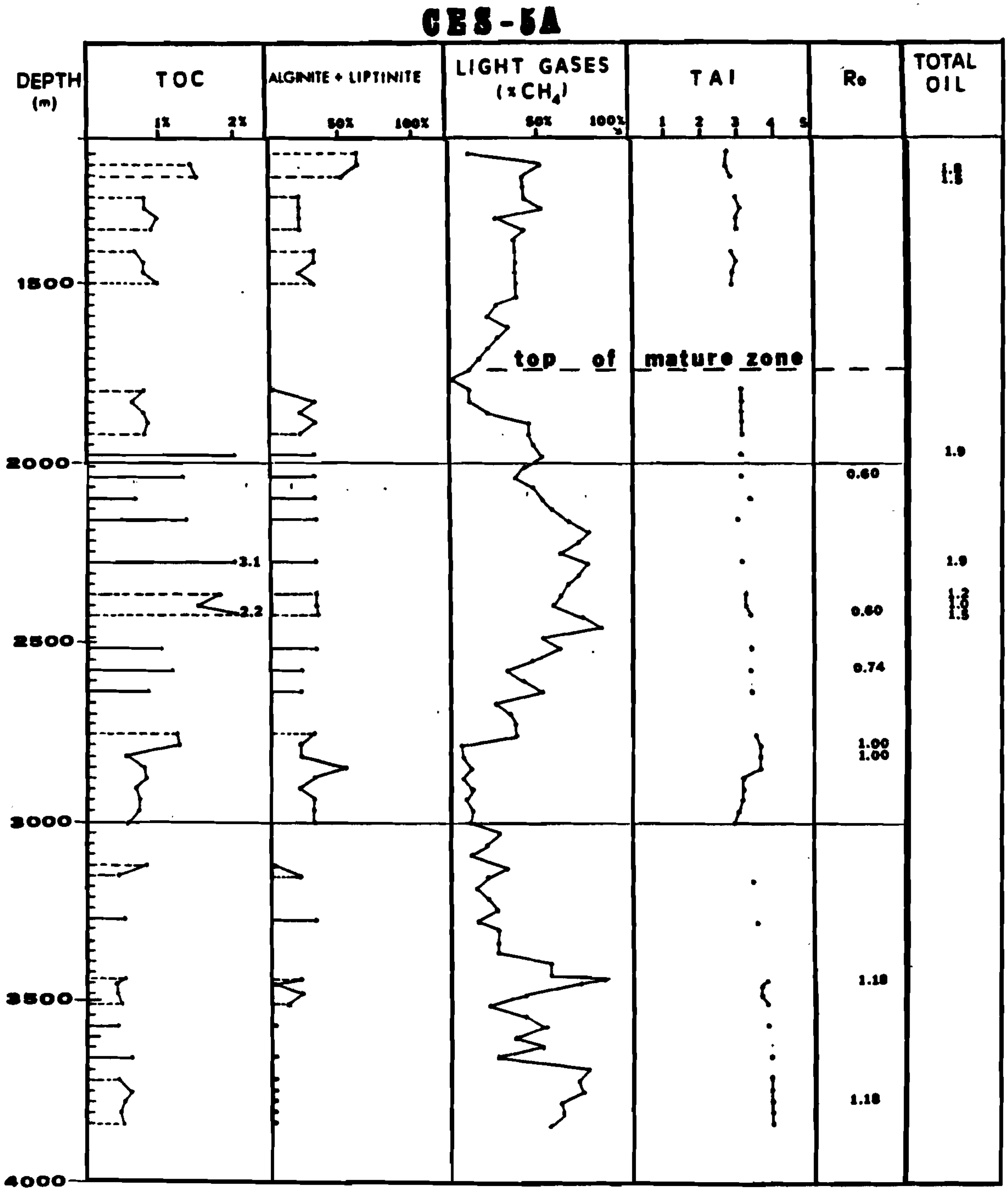


FIGURE 30 - Geochemical data, CES-5.

first sample which indicated 0% methane. The top of the supramature zone is probably between 4000 and 4500 m. Vitrinite reflectance values below 3500 m are 1.18, TAI values are 3.75, and the light-gases profile begins to show a gradual increase in the methane content (see Figure 30).

Source rocks in this well are related to two depositional environments: (1) Turonian anoxic beds, 1170-1200 m, total oil values between 1.5 and 1.8 (in the immature zone), and (2) marsh deposits in the Transitional sequence with very high contents of organic matter (up to 3.1%), 1980 m, 2280 m, and 2370-2430 m. These last deposits have low contents of oil-prone material but their high TOC values make them good source rocks. They are associated with coal occurrences. The lacustrine rocks between 2880-2730 m do not present TOC values high enough to make them good source rocks, despite the regular values of alginite + liptinite (30% to 50%).

CES-48 -

This well contains the deepest mature zone of the basin. The passage from immature to mature conditions is clearly gradual, and the top of the mature zone is placed at 2840 m (see Figure 31). All source rocks present in

CES-48 -

This well contains the deepest mature zone of the basin. The passage from immature to mature conditions is clearly gradual, and the top of the mature zone is placed at 2840 m (see Figure 31). All source rocks present in this well are within the immature zone. The following source rocks were identified: (1) Cenomanian slope shales, 810-870 m, total oil values between 1.0 and 1.4, (2) Late Albian marls, 1410-1440 m, total oil values between 1.0 and 1.4, and (3) Late Albian offshore mudstones, 1710 m, total oil value of 1.0.

PIS-1 -

The top of the mature zone is placed at 1700 m where a sharp change in the TAI values occur, from 2.50/2.75 to 3.50/3.75. No evidence for an unconformity are present, thus a fault is supposed to be responsible for the change. The supramature zone appears at 3050 m where the first TAI values greater than 3.75 begin to occur. The anomalously small thickness of the oil generation window (1370 m) is probably due to thinning caused by a normal fault around 1700 m (see Figure 32).

The best source rocks are located exactly at the top of the supramature zone, associated with lacustrine

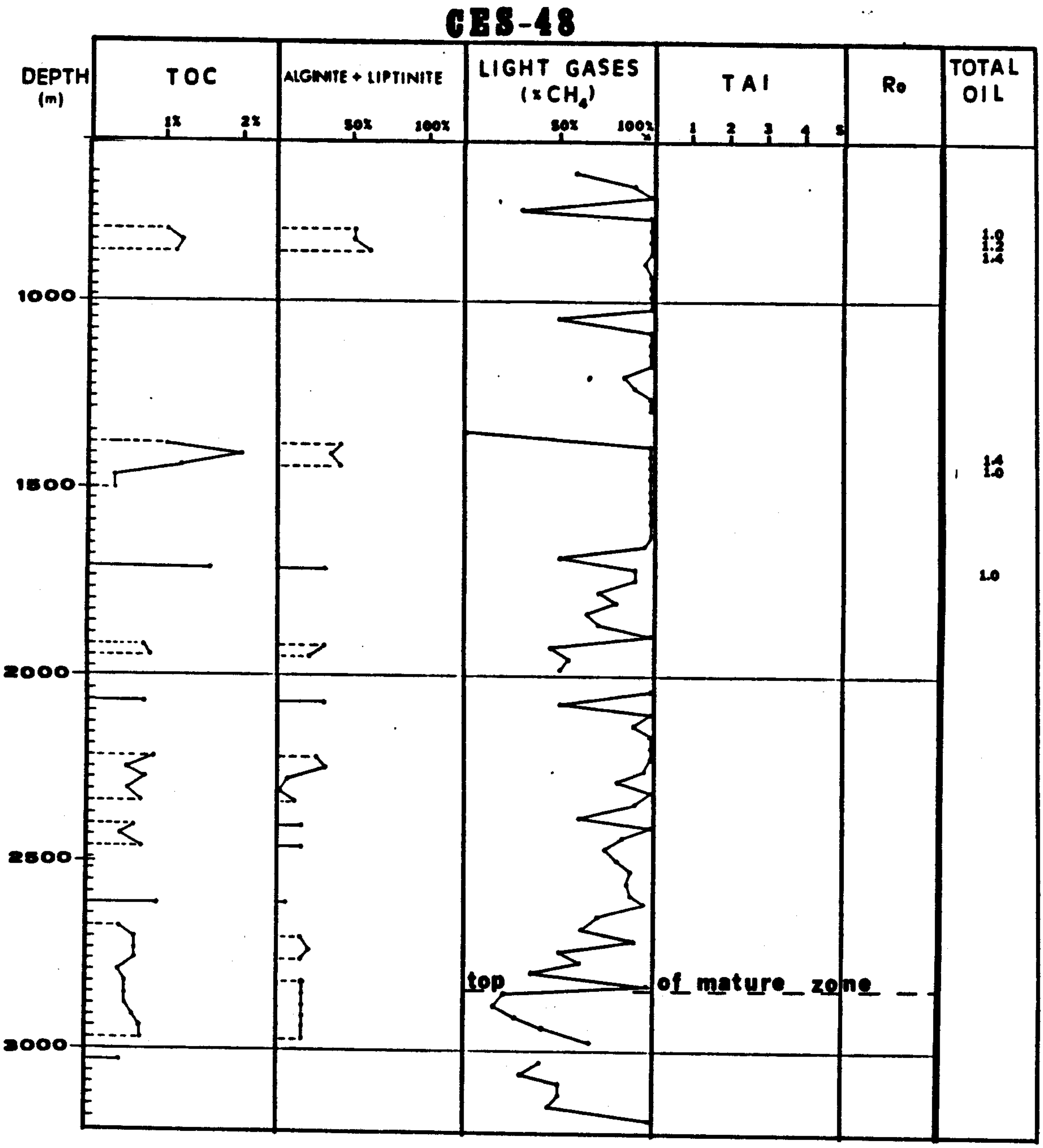


FIGURE 31 - Geochemical data, CES-48.

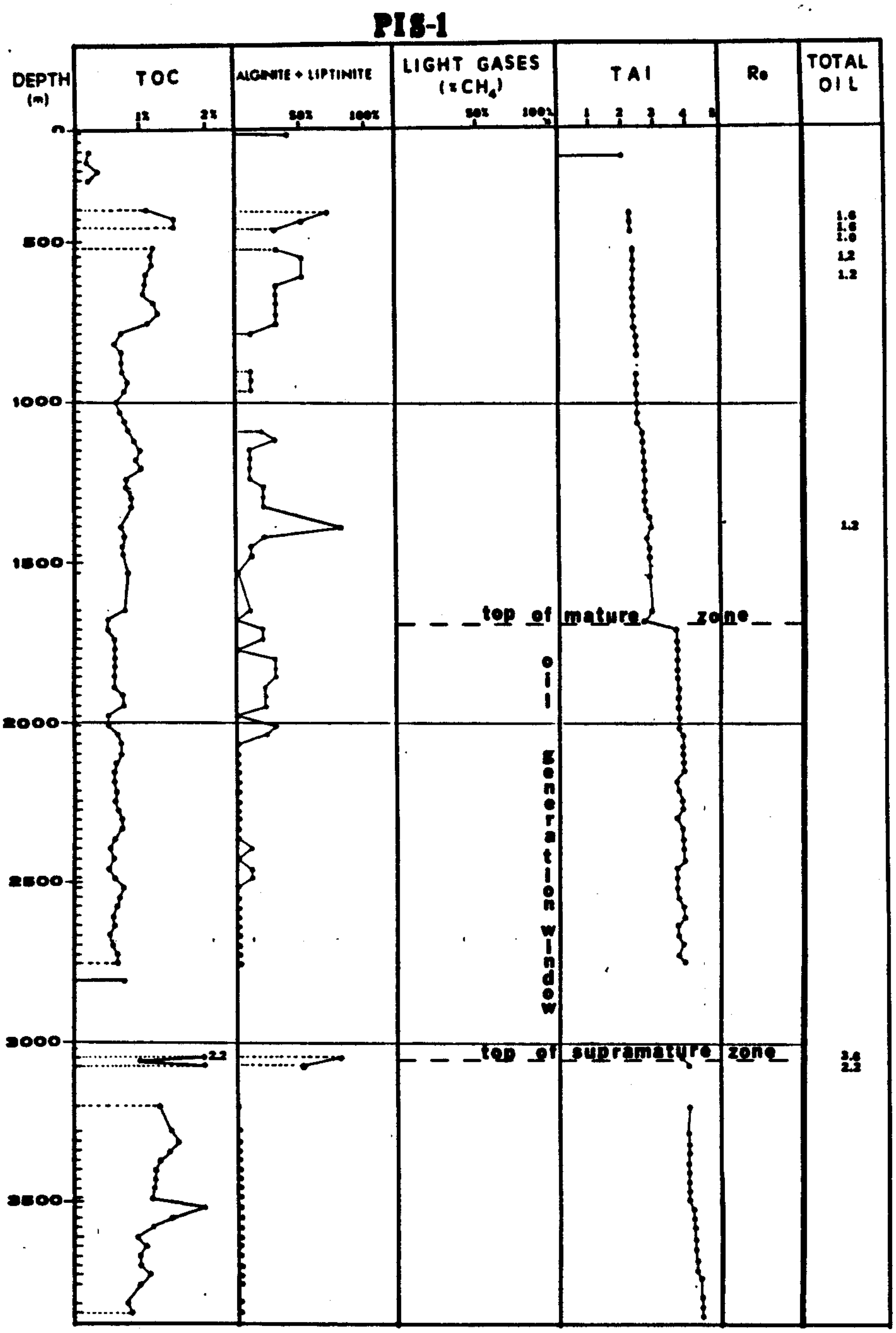


FIGURE 32 - Geochemical data, PIS-1.

deposits. The interval 3107-3080 m was tested and produced gas, which is correlative with the position of both source rocks and associated reservoirs within the supramature zone. The relatively high amounts of oil-prone material (50% - 80%) indicate that a good oil field would be present here, if these rocks were located some hundred meters above the present depth. Other source rocks are located within the immature zone and include: (1) 1415 m, shales associated with turbidites within a thick prodelta sequence. This sample is extremely anomalous due to its high content of oil-prone material (80%, within an average of 10 - 30%) and probably represents organic rich deposits from turbidity currents; (2) Cenomanian marls, 600-400 m, with total oil values between 1.0 and 1.6. Similar organic-rich marls of Late Albian age were also found in the previous wells.

CES-3 -

The top of the maturation zone probably coincides with the unconformity between the Middle Aptian and Tertiary at 390 m. TAI values of 3.0 at 1020 m indicate mature samples. The high content of sandstone in this well is the reason for the low number of samples analyzed

(7). No oil source rocks are present. Only gas can be expected in such an environment (see Figure 33).

CES-1 -

Because of the extremely high content of sand in this well only three samples of the Albian marine sequence were analyzed. They provided vitrinite reflectance values around 0.59. The top of the mature zone must be situated not far below these sampled intervals. The depth of 800 m was chosen arbitrarily, due to absolute lack of additional control. The section is entirely gas prone, due to extremely proximal position relative to the basin margin. Albian marine shales have high TOC (up to 2.1%) and very low alginite + liptinite (10 - 20%) values. The section is entirely gas-prone, but shows of oil were present. These oils are interpreted as having originated in lacustrine environments in the deeper parts of the basin (like the lacustrine interval in the PIS-1) that have migrated updip into this coarse-grained lithofacies (see Figure 34).

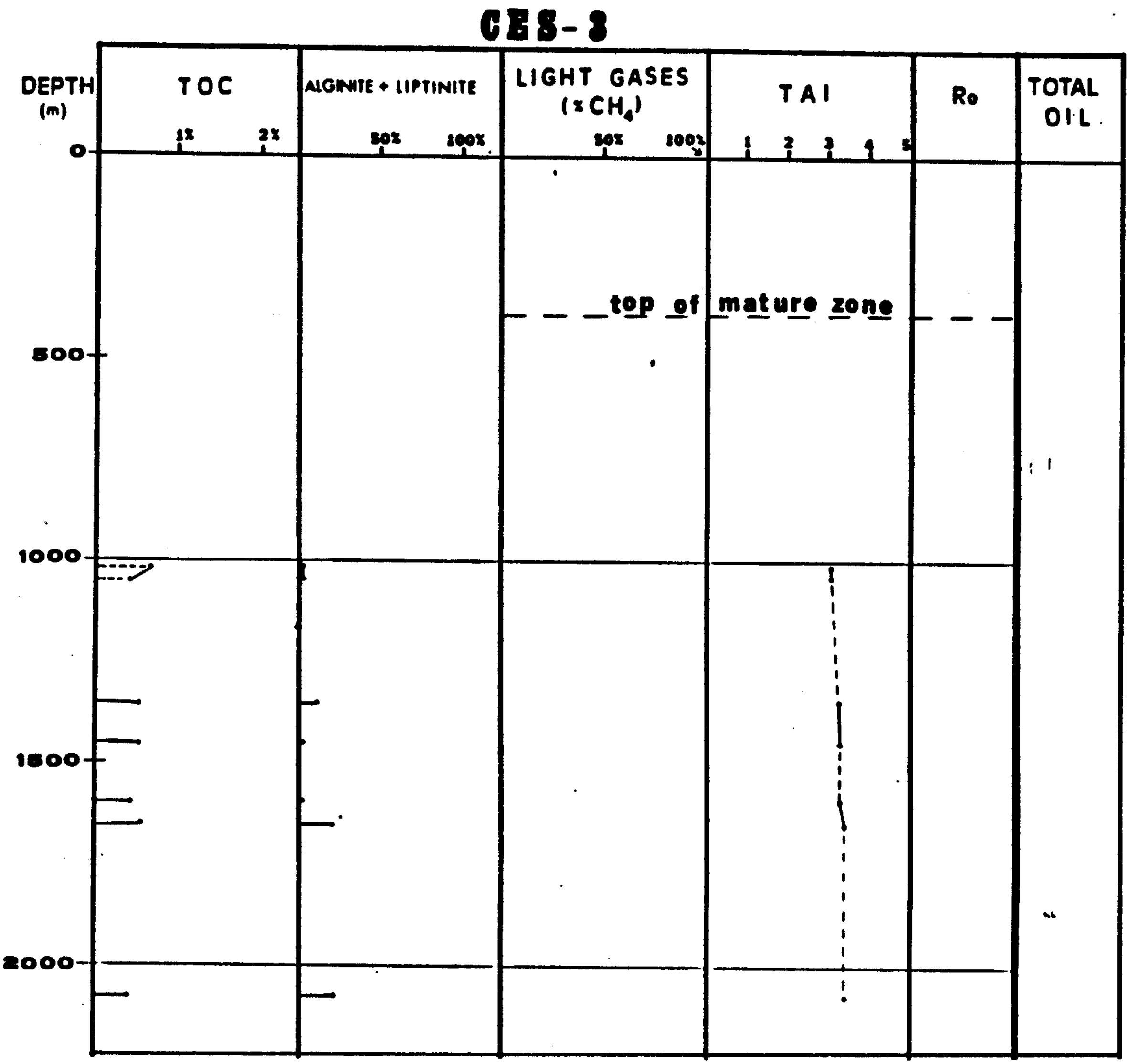


FIGURE 33 - Geochemical data, CES-3.

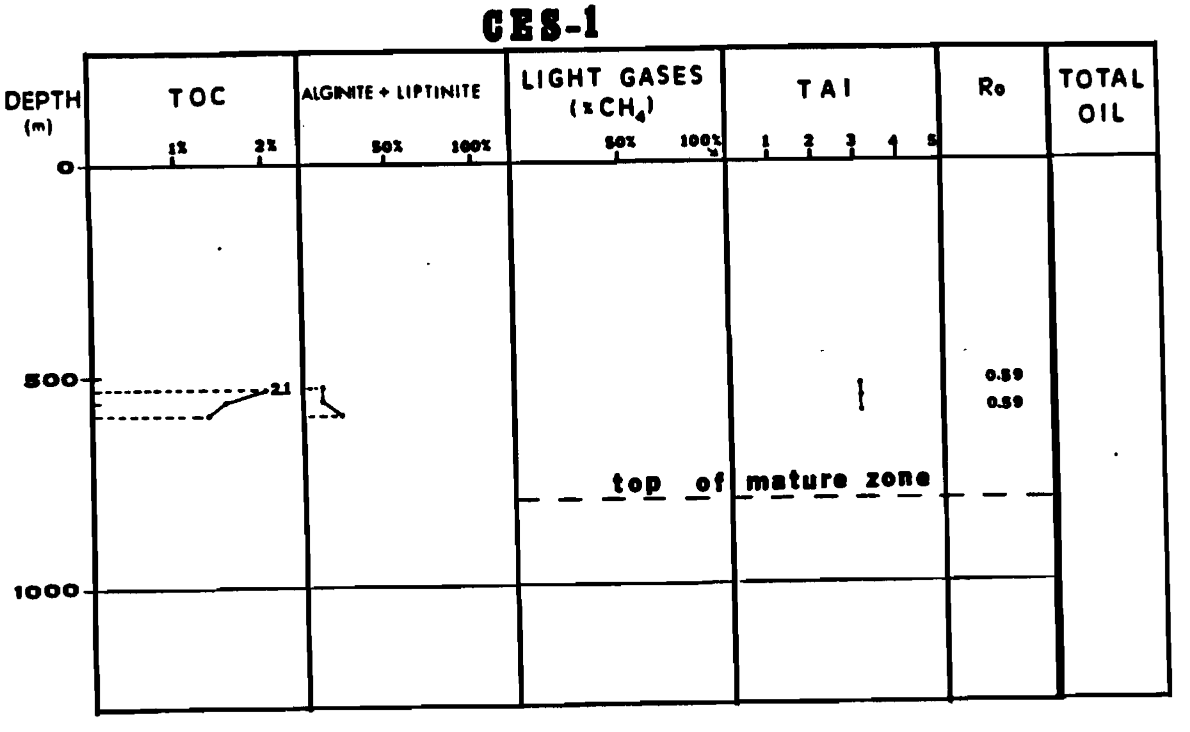


FIGURE 34 - Geochemical data, CES-1.

MAJOR SOURCE ROCK SYSTEMS

Source rocks are not randomly distributed throughout the stratigraphic column. Certain depositional environments as well as certain stages of the Cretaceous tend to be richer in source rocks than others. The combination of specific depositional environments rich in source rocks and their respective age is here called "source rock systems." The areal distribution of the source rock systems contained within the oil-generation window superimposed on the areal distribution of the best reservoir systems determine the areas in which exploratory activities should be concentrated (not considering long distance migration). Five source rock systems contain most of the oil-prone source rocks in the Acarau and Piaui sub-basins. The first two are the most important ones and could be responsible for larger accumulations. The three others are much less important in volume and quality, but could give rise to small oil deposits.

(1) TURONIAN (?) ANOXIC SYSTEM - this is by far the most important source rock system, but it is thermally mature only in very offshore positions. They represent marine transgressive sediments, deposited during the

Mid-Cretaceous oceanic anoxic events. They are discussed in detail in a separate sub-chapter.

(2) APTIAN LACUSTRINE SYSTEM - lacustrine deposits occur in most wells, with the exception of the CES-50, CES-48, CES-1 and CES-3. Plate 22 shows the distribution of this system in both basins and within it the areas which contain good source-rock characteristics. It is interesting to note that such areas are concentrated in the eastern margin of the Acarau sub-basin and in the central part of the Piaui area. These areas correspond to the deepest parts of the basins. Source rocks are shales and total oil values range from 1.0 to 3.6. They are always within the mature zone with the exception of the PIS-1 (supra-mature zone). It is a system of very good quality and constitutes a primary play which should be explored.

(3) LATE APTIAN-ALBIAN-CENOMANIAN MARINE TRANSGRESSIVE SYSTEM - these deposits commonly contain source rock intervals, but they always have low total oil values (1.0 - 1.9). The source rocks are shallow marine shales or outer shelf/upper slope marls and shales, all related to this great transgressive period. Their irregular distribution within the mature and immature zones and their average

quality do not make of them primary exploratory targets. Because source rocks in this system are very common and have an average quality, they eventually lead to the generation of modest amounts of oil, and they necessarily constitute secondary targets in any other major play.

(4) LATE CRETACEOUS SLOPE SYSTEM - the source rocks are generally shales associated with turbidite deposits. Their intimate interfingering with good turbidite reservoirs make them secondary targets in very offshore areas, where these prograding slopes are much thicker and deeper. These distal offshore areas are probably the only places where they can be found within the mature zone.

(5) LATE TO MIDDLE APTIAN TRANSITIONAL SYSTEM - the source rocks are generally shales associated with coals in a deltaic complex. They are more gas-prone than oil-prone, but in places the TOC reaches high values (more than 2%) and then small quantities of oil could be generated. It is a very poor quality system, and exploratory efforts should not focus on it.

Gas-prone source rocks were not studied in detail. However, it is important to note that probably gas is the hydrocarbon most likely to be found in both sub-basins.

Some wells, such as the CES-4 and CES-11, contain only gas-prone source rocks. In all other wells gas-prone source rocks were predominant over oil-prone source beds, although their quality is rarely high. Their organic matter is predominantly composed of vitrinite and inertinite and they have very low TOC values (generally less than 1%).

THE TURONIAN ANOXIC SYSTEM

Undoubtedly the best source rocks of the Acarau subbasin are the anoxic deposits which are here termed "Turonian anoxic beds." Their organic carbon content averages 1.9% and can reach values as high as 4.1%. Regarding organic matter types they are generally rich in oil-prone material, and the sum alginite + liptinite commonly reaches 100%. There is a subtle tendency for the upper part to be more rich in oil-prone material than the lower part. This is due to the fact that these rocks were deposited during a transgressive event. Total oil values average 3.3 and can be as high as 8.3, which classify these source rocks as very good to excellent (according to Table 14). Maturation stages required for significant oil generation were reached only in the two most offshore wells. This fact together with the localization of these source beds in the wells CES-52 and CES-55 (within the transitional zone) indicate that the exploratory activity in the Acarau area should be concentrated in the area situated between the 200 m isobath and a parallel line situated approximately 20 km farther onshore. Plate 24 shows the distribution of this system and within it the areas in which it is probably mature.

The main problem related to these beds is the precise determination of their ages. Indications of ages given by foraminifers and palynomorphs range from Cenomanian to Santonian. The Turonian age is considered the most probable because: (1) localization of beds above the Cenomanian unconformity (98 m.y.b.p.) which is generally well defined in most wells, and (2) correlation with one of the two most widespread oceanic anoxic events (Turonian-Cenomanian, according to Arthur and Schlanger, 1979). However, it must be emphasized that the anoxic deposits of the Acarau basin probably represent a larger span of time. The age of the unconformity at the top of the sequence is not very well defined owing to these uncertainties in age determination. It is most probable that these anoxic deposits also include Coniacian and Santonian rocks. Two facts support this idea: (1) a third oceanic anoxic event is mentioned, but not discussed, by Arthur and Schlanger (1979), and its age is exactly Coniacian-Santonian. Its geographical distribution (Caribbean sea, southern North Atlantic) is not far from the Acarau area, and (2) very good source rocks of Late Turonian to Early Santonian age are described in the Benue trough (Petters and Ekweozor, 1982); and are also related to Mid-Cretaceous oceanic anoxic events. During these times the two basins were not far apart and similar conditions may have affected both. The most important key to solve this problem is to precisely define the distribution in time of the foraminifer Hedbergella delrioensis, which invariably is associated with these deposits. Commonly an upper part of Middle Cenomanian-Santonian age is assigned to it (Noguti and Santos, 1972), and several facts point to the conclusion that this is the most probable time span represented by these anoxic events which affected the equatorial Atlantic ocean. The resolution of paleontologic data obtained from cuttings is not good enough neither to better resolve this time interval nor to define more unconformities within it, as they are expected to occur with basis on global sea level charts (Hancock and Kauffman, 1979).

One interesting feature of these anoxic deposits is the characteristic brown color. Brown marls, brown shales, brown limestones, and even brown sandstones were described in all anoxic sequences studied in this work. In the PIS-1 Cenomanian/Albian brown marls are reasonably good oil-prone source rocks (see Figure 29). These are also probably related to anoxic events which occurred during the Albian. There seems to be an intimate relationship between good source rock characteristics and lithologies with brown colors, in the anoxic deposits. Apparently such an association is contradictory. Good source rock properties are classically associated with black or dark gray rocks, not brownish ones. Red and brown colors are normally associated to oxidizing conditions, where chances for preservation of organic matter are minimal. A hypothesis to explain this paradox is here suggested.

One of the most abundant deep sea sediments is "red clay," but it has been noted that these sediments are not red or brown at their depositional sites (around 5000 m deep) because no oxygen is available for oxidation processes. They become red as the samples reach the surface, when the atmospheric oxygen immediately oxidizes sub-microscopic iron oxide particles (H.C. Kent, 1982, oral communication). The same phenomena is here suggested to occur with the anoxic deposits. The highly anoxic conditions prevalent during their deposition permits the preservations of good quantities of organic matter and also a great amount of sub-microscopic particles of iron oxides and hydroxides (either as gels or crystalline material), which otherwise would be readily oxidized and diluted in oxic conditions. They are probably not brown or red in the subsurface. They turn into this color while they are transported by the drilling muds and reach the surface.

OIL-PRONE AREAS

During the evaluation of the petroleum potential of an area, one has to take into account the spatial and temporal relationship between source rocks and reservoirs, the relationship between the time of migration of hydrocarbons and the formation of structures, the presence of stratigraphic traps, diagenetic history of the reservoirs, and so on. The main emphasis of this work was to define which environments have the best reservoirs and best source rocks and to study their spatial and temporal relationships, which is, in summary, the stratigraphic evolution of the basins.

The evaluation of the hydrocarbon potential of the studied areas presented in this work is heavily based upon the distribution of sandstones with high reservoir potentials, and of good source rocks. Other important aspects such as the structural geology and the diagenetic evolution are not treated in detail in this work. Despite this fact some important generalized statements regarding structural and diagenetic aspects can be made.

(1) The studied sub-basins were developed within an oblique-slip mobile zone, where transpressional and transtensional regimes coexisted simultaneously in different parts of the basins. The separation of South America and Africa in the Equatorial Atlantic ocean was not simply perpendicular pull-apart, but involved a great amount of lateral displacements of the lithospheric plates relative to each other; along major transform faults (such as the Romanche fracture zone). As a result of coexisting compressional and extensional tectonic regimes some regions experienced subsiding phases followed by large-scale uplifts and long-lived subaerial exposures, such as the CES-4, CES-11, and the Piaui sub-basin. In these areas Tertiary sediments overlie Cenomanian, Albian or Aptian sediments. The area around the CES-48 was a continuous

subsiding region, and received thick accumulation of Albian and Cenomanian sediments. However, it did not experience uplifts of the scale of the previous wells, and most of these sediments were preserved. The basin was tectonically active until Mid-Cretaceous, from Aptian to Turonian.

(2) Continuous tectonic activity probably destroyed some hydrocarbon traps formed during this interval. Aptian sediments, and in places Albian sediments, reached thermal maturation stages very early. This hypothesis is demonstrated by wells CES-4, CES-11, CES-1, CES-3, and PIS-1 where the top of the maturation zone is very shallow, coinciding with or being situated slightly below the unconformities at the top of the Aptian, and sometimes within the Albian. This indicates that already mature zones have been uplifted and eroded. In conclusion, major tectonic activities took place after generation of hydrocarbons, and probably destroyed early accumulations.

(3) Average geothermal gradient for both basins is $1.54^{o}F/100$ ft, varying from $1.14^{o}F/100$ ft (CES-50) to $2.01^{o}F/100$ ft (PIS-1). Piaui-Camocim sub-basin ($1.74^{o}F/100$ ft) is hotter than Acarau ($1.47^{o}F/100$ ft).

Two hottest areas are situated in the Piaui-Camocim sub-basin and in the region encompassed by the wells CES-4, 2, 55 and 52. It is interesting to notice that these areas presented the best shows of hydrocarbons (PIS-1, CES-1, 2, 55).

(4) Present geothermal gradients are obviously lower than the prevailing ones during the Aptian and Albian, when this region was situated near the proto-Atlantic mid-oceanic ridge. The geothermal gradients which prevailed from Late Cretaceous until the present have not been high enough to result in maturity of even the Turonian beds, in some areas. The top of the mature zones are generally within the Albian or Late Aptian rocks and probably reflect much more the past gradients than the present ones. Only in very offshore areas, such as in the CES-50 and CES-56 wells, where great subsidences occurred after Mid-Cretaceous, are the Turonian source rocks mature.

(5) Although no detailed petrographic studies were performed on the sandstones it was evident that most of them are plugged by extensive cementation, especially calcite, but also with silica and clay minerals. Porosity values can

be reasonably high, and some deposits of gas can be formed. However, permeabilities are generally extremely low and preclude commercial production (CES-1, CES-2 and PIS-1). The only place where a deposit of oil was found was in highly fractured sandstones of the Transitional sequence in the CES-55. Other sandstones which have reasonable permeability-porosity conditions are tidal channels of the Transitional sequence in the CES-5 and Cenomanian turbidites at CES-48.

(6) Major reservoir systems, all of average to slightly better qualities, can be defined (in decreasing order of potential):

(6a) Sandstones of the transitional sequence, Late Aptian to Albian. They are generally deltaic, barrier bar and tidal channel sandstones. It is a general rule in hydrocarbon exploration that sandstones with the best initial reservoir characteristics also have the best reservoir characteristics after several diagenetic events. It is well known that such sandstones have very good initial porosities and permeabilities. Due to their thick and widespread distribution they are the main targets in the area.

(6b) Lacustrine sandstones of the continental sequence. Lacustrine deltas and turbidites intermixed with good lacustrine source rocks can eventually have development of secondary porosity. It should be considered a secondary play, due to erratic distribution and no known control on the development of secondary porosity.

(6c) Turbidite sandstones of marine bathyal sequences (Cenomanian or Maastrichtian/Campanian). Their reservoir characteristics are generally good but the intermixed source rocks are generally immature. They are secondary targets in very offshore areas.

(6d) Other reservoir systems can be cited, but their potential is so low that any finding of hydrocarbons related to them would be surely due to serendipity. They are:
(1) fluvial sandstones of the continental sequence (with fanglomerates at very marginal positions), and (2) relicts of Cenomanian-Albian carbonate platforms (such as the one in the CES-48), in very offshore positions.

Plate 25 shows the oil-prone areas in the Acarau and Piaui sub-basins. The prospective areas were outlined by taking into account the following considerations: (1) the ideal situation where reservoirs are situated near the source rocks (horizontally and vertically), (2) the major reservoir system is the transitional sequence, which has a very widespread distribution and can be expected almost anywhere in the basins, and (3) the distribution of the Turonian anoxic and the Aptian lacustrine source rock systems is the primary control of the prospective areas (since reservoirs of the transitional sequence are expected almost anywhere). Plate 25 is basically the superposition of Plates 22 and 24. The deepest parts of the Piaui trough, and the eastern and northern part of the Acarau sub-basin are the areas with the highest potential for oil accumulations. Structural and stratigraphic traps should be looked for within these limits. Marginal areas to these can have some potential if long-distance migration is expected to occur.

Once again, the main constraints of this model are emphasized: (1) the main problem is the quality of the reservoirs. No trends for good secondary porosity have been yet established. Fracture-related porosities will probably play a major role in hydrocarbon accumulations. Areas with signs of intense faulting in the seismic sections should be explored within the outlined prospective

areas and (2) continued tectonic activity until the Mid-Cretaceous could have destroyed early oil accumulations related to the Aptian lacustrine, source rocks. (3) The most favorable areas for the occurrence of oil related to the anoxic beds is farther offshore. Some deep-water wells will probably have to be drilled in order to achieve a more complete evaluation of the Acarau sub-basin.
(4) Large areas have not been drilled (they are marked with interrogation tags in Plate 25); thus their potential is completely unknown.

CONCLUSIONS

The Acarau and the Piaui-Camocim sub-basins cannot be considered as typical representatives of Brazilian marginal basins, which are classical examples of Atlantic-type sedimentary basins. Their stratigraphic and tectonic evolutions differ in several aspects from the ones which are normally described in the other basins.

The initial filling phase of both basins (Early to Middle Aptian) (although older sediments can occur) is very similar to the rest of the other basins. Very thick deposits (4000 - 6000 m) representative of fluvial, alluvial fan and lacustrine depositional environments, developed under strictly continental conditions, constitute the oldest studied sedimentary rocks of these basins. The differences in the stratigraphic evolution began with the first invasions of marine waters during the Middle Aptian, through the Late Aptian (transitional environments). No restricted conditions affected this tongue of sea, and thus no evaporites were formed. An important conclusion of this work is that sediments were predominantly sourced from north instead of south, as commonly expected. There are differences also in the open marine sediments of Albian-Cenomanian age. No extensive carbonate platforms can be found, only some scattered evidence of the localized existence of carbonate-rich sediments. However, the most important difference occurring during these times was the existence of a transpressional tectonic regime associated with the normal extensional regime. This fact was responsible for the creation of enormous structural relief which, in turn, was responsible for the development of extreme thicks and thins in the same chronostratigraphic unit. The climax of this tectonic activity took place sometime between the Late Cenomanian and Early Turonian. During this time large areas of the sub-basins were structurally elevated (Piaui sub-basin and the northwestern part of the Acarau sub-basin) and had their stratigraphic evolution interrupted throughout the rest of the Cretaceous.

Only the central and northern parts of the Acarau sub-basin underwent a stratigraphic evolution during the Late Cretaceous which can partly be compared with the other basins. Gradual subsidence oceanward, high influx of terrigenous sediments, and deposition under alternating marine transgressive and regressive conditions characterize the Late Cretaceous in most Brazilian marginal basins.

Regarding their petroleum potential, several factors can be pointed out as favorable and unfavorable. In the first class the following can be cited: (1) common occurrence of oil and gas shows, (2) existence of good source rocks, and (3) the existence of abundant structures. The unfavorable factors are: (1) most reservoir rocks are plugged by extensive cementation, (2) the intensive tectonic activity after the first phase of oil generation in the lacustrine shales probably destroyed and profoundly altered some earlier formed hydrocarbon deposits, and (3) the Turonian-Santonian source rocks are only mature in the most offshore areas. Exploratory activities should be heavily concentrated in the areas depicted in Plate 25. Obviously, poorly explored regions should never be forgotten (such as the western part of the Acarau sub-basin). The final conclusion is that discoveries of hydrocarbons are likely to occur in future exploratory activities in these basins if the basic guidelines outlined in this work are followed.

The stratigraphic descriptions presented in this work have the natural limitations imposed by the small number of wells and the extremely low percentage of cored intervals in relation to the total meterage drilled (approximately 0.2%). However, the consistency obtained in the correlations among the wells and in the geological history deduced probably indicate the usefulness of this sequence model as a predictive exploratory tool in the Acarau and Piaui-Camocim sub-basins.

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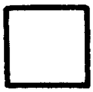
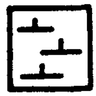
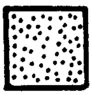
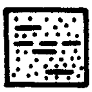
APPENDIX A - LEGEND FOR PLATES 2 - 13

 - ARGILLACEOUS ROCKS

 - MARLS

 - SANDSTONES

 - CONGLOMERATES

 - ARGILLACEOUS LIMESTONES

 - IGNEOUS ROCKS

 - LIMESTONES

 - UNCONFORMITY

 - SHOW OF GAS

 - SHOW OF OIL

Depths are in meters and are related to the kelly bushing of the rotary table.