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Structural evolution of the Sergipe-Alagoas Basin, Brazil

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STRUCTURAL EVOLUTION OF THE SERGIPE-ALAGOAS BASIN, BRAZIL
Augusto Canellas Monteiro de Castro Junior

ABSTRACT

The evolution of the Sergipe-Alagoas Basin started during the Early Cretaceous, as part of the rift system that initiated the separation between the South American and African plates. The direction of propagation of the rift was controlled by preexisting basement fabric, and the Sergipe-Alagoas Basin developed as a rift bounded by N-S oriented normal faults, formed by crustal extension oriented obliquely to the direction of propagation of the rift. Different rates of crustal attenuation along the basin, due to the heterogeneous nature of the continental crust, were accommodated by transfer faults which divided the basin in three separate Domains. Crustal extension was substantially less in the Northern Domain than in the Central and Southern Domains. The first marine incursions in the basin occurred during the Aptian, after the end of the rifting phase, and the period is marked by the deposition of large amounts of evaporites. From the Albian to the Santonian, the basin was covered by a shallow but permanent sea, and great thickness of carbonates were stacked on high proximal areas, whereas in the distal portions of the basin only a thin, condensed section was deposited. Open oceanic conditions were installed towards the end of the Cretaceous, during the Campanian, and a prograding clastic wedge started to be deposited. The distribution of the post-rift sediments, as evidenced by isopach maps, indicates that the Northern Domain remained essentially stable throughout the post-rift evolution of the basin, and that the post-rift subsidence was mostly concentrated in the Southern and Central Domains. Structures formed after the rifting phase are restricted to those associated with sediment mobilization (especially evaporites), but the distribution of both structures and sediments in the post-rift phase was strongly controlled by the tectonic framework created during the rifting phase.
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TABLE I 23
1. INTRODUCTION

The Sergipe-Alagoas Basin is located on the northeastern Brazilian Atlantic margin (Fig. 1), extends about 330 km along the coast of the states of Sergipe and Alagoas, and has an elongated shape oriented N45E. Its oceanward termination is not precisely known, but the total area of the basin, out to the 1,000 m isobath, is estimated to be 27,000 km², 45% of which are onshore.

The formation of the basin is associated with the extensive rifting process that took place along the future South American and African Atlantic margins during the Late Jurassic and Early Cretaceous. Sedimentary fill of the basin is estimated to reach thickness of up to 10,000 m (including both syn and post-rift deposits).

The onshore area of the basin was a prime target for the early petroleum exploration efforts during the 1940s, and the first commercial accumulations were found in the mid-1960s. Twenty-three oil and gas fields have been discovered (Fig. 2), producing from reservoirs of all ages, from fractured Precambrian basement (Carmópolis field), to Eocene turbidites (Dourado field), and in many different traps. Geochemical analysis in the basin has shown that source rocks are mainly shales deposited during the rifting phase. Oil reserves ("in place") in the basin are 773 x 10⁶ barrels (Bacoccoli, 1988), and the average production during 1987 was 64,389 barrels per day, corresponding to 11% of the total brazilian production (Petrobrás, 1988)
Fig. 1 - Location map of the Sergipe-Alagoas Basin.
The geology of the basin has been discussed by several authors, and several evolutionary models have been proposed. My objective in this work will be to advance the idea that the Sergipe-Alagoas basin evolved from an extensional rift system, and that the complex geometry of the basin is a result of both the fragmentation of the rift into separate compartments, and of the independent behavior of each individual compartment.

2. STRATIGRAPHICAL SUMMARY

The Sergipe-Alagoas basin has one of the most complete stratigraphic records found in Brazilian eastern coast basins. Stratigraphic evidence is found for all the tectonic episodes which affected the basin. Figure 3 shows a schematic representation of the stratigraphy of the basin, and its relationship to the tectonic stages.

The Basement Complex, as defined by Schaller (1969), includes metamorphic and igneous rocks of Precambrian age, as well as the sediments of the Cambrian Estância Formation, which can range in thickness from 100 to 1,000 m. Overlying this complex was deposited a Permo-Carboniferous intracratonic sequence, the Batinga and Aracaré Formations, which, locally, have preserved thickness of up to 100 m.

The absence of marine microfossils in the oldest Mesozoic sediments has traditionally presented a chronostratigraphic problem. The difficulties were partially avoided by the informal definition of local chronostratigraphic units, but the correlation
between these informal units and the international chronostratigraphic scale remained uncertain. Continuation of paleontological studies, supported by an increase in the volume of available data, allowed the establishment of correlations with stratigraphic markers common to sedimentary basins in Brazil, Africa, Europe and North America. Regali and Viana (1986), and Arai et al. (1987), discussed the criteria utilized in the analysis, and established the equivalency between the local stratigraphic units and the international scale. The criteria used to date the Mesozoic sediments will be discussed in section 5.

The Mesozoic record starts with the Candeeiro, Bananeiras and Serraria Formations, which are a sequence of continental clastic deposits, up to 300 m thick, deposited during the Late Jurassic, and resting unconformably on top of the Precambrian basement or above the Paleozoic sediments.

During the Neocomian, with the start of the rifting phase, were deposited the lacustrine deposits of the Barra de Itiuba, Penedo and Rio Pitanga Formations (all clastic), the Morro dos Chaves Formations (carbonatic), and the Coqueiro Seco Formation (clastic). These sequences can reach local thickness of more than 5,000 m. The lower contact, with the pre-rift deposits or the basement, varies from conformable to unconformable.

The Aptian is represented in the basin by the Muribeca Formation, which is characterized by evaporitic deposits, and is locally thicker than 4,000 m. The Muribeca Formation rests unconformably on the Neocomian sediments, and represents the first marine incursions in
the basin.

From the Albian to the Santonian, shallow marine conditions prevailed in the basin, and the corresponding deposits are the essentially carbonatic Riachuelo and Cotinguiba Formations, which can reach thickness of up to 1,800 m, resting unconformably over older strata.

Since the Campanian, the sedimentation in the basin is largely of marine nature, and the deposits are included in the Piaçabuçu Formation, which thickness can reach up to 2,500 m. Also present are the Pliocene continental deposits of the Barreiras Formation, as well as Quaternary eolian, beach and aluvial sediments.

3. PREVIOUS WORKS ABOUT THE BASIN

Geologic investigation in the Sergipe-Alagoas basin began to be reported in 1870, but the beginning of hydrocarbon exploration activities during the early 1940s, and especially the discovery of commercial accumulations in the mid-1960s brought along a substantial increase in the number of studies conducted in the basin. Until the early 1980s, however, the vast majority of the reports concerned stratigraphical and sedimentological issues, assuming a rift origin for the basin, and even recognizing the importance of the structural control on the sedimentation, but without investigating or detailing the structural development of the rift itself (Schaller, 1969; Palagi and Olivatti, 1970; Fugita, 1972; Figueiredo and Beltrami, 1976; Beltrami and Della Favera, 1977; Figueiredo, 1978;
Figueiredo, 1980; Fernandes et al., 1981). Notable exceptions are the works of Perrela (1963), and Ojeda and Fugita (1972), who proposed that the structures in the basin were caused by shear stresses associated with the opening of the South Atlantic.

Structurally oriented studies started to be published in 1983, and since then a series of papers and reports have attempted to explain the structural development of the basin:

- Lana and Milani (1983) contended that the structures in the Sergipe-Alagoas Basin were related to a stress regime more complex than a simple extensional one, and suggested that the basin was created in a left-lateral transtensional system existing between the South American and African plates, which would evolve to a purely extensional system during the Barremian/Aptian.

- Falkenhein et al. (1983) proposed a three-phase development scheme for the basin, which includes: a) E-W oriented extension, creating N-S oriented normal faults; b) NNE-SSW oriented transpression, during which the preexisting N-S normal faults were reactivated as synthetic transcurrent faults, and which created WNW oriented antithetic faults; c) NW-SE oriented extension, creating an Aptian hinge line.

- Szatmari et al. (1984, 1985) discussed the evolution of the rift along the eastern Brazilian coast, and associated the development of the Sergipe-Alagoas Basin with movement along the margins of a crustal block which was referred to as the "Microplaca do Leste Brasileiro" (Eastern Brazilian Microplate) (Fig. 4). Rotation of this crustal block about a fixed pole, located at coordinates 8°19'S,
Fig. 4 - The Eastern Brazilian Microplate. Insert at the bottom shows the present boundaries of the microplate - the Recôncavo and Tucano Basins to the west, the Jatobá Basin and the Pernambuco Lineament to the north, and the coastline and the Sergipe-Alagoas Basin to the east. In the microplate diagram at the top, point P marks the position of the pole of rotation of the microplate. Large arrow indicates sense of rotation about pole. Broken lines show boundaries of the microplate before rotation, and continuous lines show boundaries of the microplate after rotation. Small arrows indicate relative displacement along the microplate boundaries. Shaded areas indicate basins created by extension in localized segments of the microplate boundary during the Neocomian. Note crustal overlap created at the northeastern corner of the microplate as a result of rotation about the specified pole (Modified from Szatmari et al., 1984).
37°2'W, would generate shear stresses along its eastern margin, creating the structures found in the basin.

- Lana (1985) proposed a dynamic rifting model that evolved from a left-lateral transtensional system to a purely extensional one. This model was based on the concept of the development of the "Eastern Brazilian Microplate" (Szatmari et al., 1984, 1985), and on the interpretation of strike-slip and extensional structures from seismic data.

- Lima (1986) proposed a model for the southern part of the basin in which SE oriented thrust faults in the basement, created during the Brasiliano tectonic event (700-450 Ma), function as detachment surfaces for crustal extension during the Mesozoic.

- Aragão (1987) examined a small area (142 km²) in the southern part of the basin, covered by a 3-D seismic survey, and showed the existence of small transcurrent and thrust faults compatible with left-lateral strike-slip movement along the N100E direction.

- Castro (1987) suggested that the Sergipe-Alagoas, Recôncavo, Tucano and Gabon basins were created in an extensional double rifting system associated with crustal detachment surfaces.

- Guimarães (1988) proposed a system of N-S oriented normal faults associated with crustal detachment surfaces as the expression of an extensional rifting mechanism.

All the models and ideas have varied degrees of support, and they also have their share of problems, which will be discussed in later sections.
4. DATA BASE AND METHODS

This study relied, on its major part, on the analysis and interpretation of seismic and well data, with support from gravimetric and regional geologic information. All seismic, gravimetric and well data were provided by Petróleo Brasileiro S. A. - PETROBRAS. The database in the Sergipe-Alagoas basin includes 40,000 km of digital reflection seismic profiles and over 600 exploratory wells. From these were selected about 5,000 km of seismic profiles (3,300 km offshore and 1,700 km onshore), and 141 exploratory wells (66 offshore and 75 onshore) to be used as data sources (Fig. 5). The seismic data were recorded during the late 1970s and early 1980s, using different seismic sources (dynamite and Vibroseis™ onshore, and airgun offshore). Most of the data were reprocessed from 1982 to 1985, and, in some cases, even as late as 1987. The great majority of the seismic profiles was available for interpretation in both migrated and non-migrated versions, and the velocity functions computed in the stacking process were also used. The well data included composite logs, with lithological and paleontological information, as well as sonic, resistivity, gamma ray and dipmeter logs.

The tie of well to seismic data was done utilizing both synthetic seismograms, constructed from sonic and density logs, and Time x Depth curves computed from sonic logs. Seismic velocity distribution in specific areas was estimated using Time x Velocity and Time x Depth curves computed from the stacking velocities used
Fig. 5 - Location map showing the distribution of seismic profiles and wells used in this study. Seismic profiles shown as individual figures are indicated by heavy broken lines. Crosses indicate wells shown in separate figures. Numbers next to seismic profiles and wells indicate figures in which they appear. A-A' and B-B' are cross sections shown in Figures 52 and 54, respectively.
in the processing of the seismic profiles. The stacking velocity functions, given in time x RMS velocity pairs, were utilized as input for a computer program which calculated interval and average velocities, and depths (Fig. 6). These values were then compared to the well data, which served as control points, for calibration. Figure 7 shows a comparison between seismic and sonic interval velocities. The seismic velocities were computed at a point adjacent to the well location. It can be seen that the seismic velocities are slightly larger than the sonic ones, this being due to the dip of the beds in subsurface, which is not taken into account during the processing of the seismic data. The result is that the converted depth values will be larger than the real ones. This behavior is consistent throughout the basin, as shown in Figure 8, where it can be seen that the depth values computed with seismic velocities are larger than the ones computed with the sonic log data. The comparison of values at the control points is then used to calibrate the distribution of velocities and the depth conversion along the seismic profiles and areas between the wells.

Gravimetric data came into play specially in areas of poor seismic resolution and/or insufficient well and seismic control, and mainly to indicate the position of the basement. The data utilized came from a detailed study by Oliveira et al. (1982), who analysed the density distribution of lithological units from well logs, computed the gravimetric effects for these units, and, in a backstripping process, determined their position in subsurface. Values obtained from the gravimetric data were tied to seismic
Fig. 6 - Print-out of computer program used to compute interval and average velocities and depths, from stacking velocities used in the processing of the seismic data.
Fig. 7 - Comparison between sonic well log and interval velocities obtained from seismic data at a point adjacent to the well. Seismic velocities are larger than sonic ones. See Figure 5 for location of the well.
Fig. 8 - Comparison of Time x Depth curves computed from well logs at two different points in the basin and from seismic data at points adjacent to the same wells. Depth values obtained from seismic velocities are larger than those obtained from well data, as discussed in the text. See figure 5 for location of the wells.
using the calibrated velocities discussed in the previous paragraph. Additionally were used a series of geological maps and reports published by several Brazilian governmental agencies, as well as internal reports prepared by Petrobrás professional staff.

The first step in the work was to define operational stratigraphic packages that could be individually mapped, and would reflect the tectonic phases of basin development. The basic criteria utilized in the definition were general depositional environment (continental, marine, transitional), presence of major unconformities, and age. The stratigraphic record of the basin was thus rearranged in five major units, or sequences, defined as follows (Fig. 3):

- Pre-rift: including Paleozoic and Jurassic strata (Batinga, Aracaré, Estância, Bananeiras, Candeeiro and Serraria Formations);
- Rift: including Neocomian strata (Barra de Itiuba, Penedo, Rio Pitanga, Coqueiro Seco and Morro do Chaves Formations);
- Post-Rift I: including the Aptian strata (Muribeca Formation);
- Post-Rift II (carbonatic): including Albian to Santonian strata (Riachuelo and Cotinguiba Formations);
- Post-rift III (clastic): including Campanian to Quaternary strata (Piaçabuçu and Barreiras Formations, Quaternary sediments).

It was decided that the most efficient form of presenting the relationship between sedimentation and structure, specially for the rift unit, would be in the form of isopach maps superimposed on the structural framework. The operational units were then identified in the well logs, tied to the seismic data, and mapped. Each unit
presented specific mapping problems, which will be discussed in the next section.
TABLE I - Key to stratigraphic references in wells shown in seismic profiles

MIO - Miocene
OLI - Oligocene
EOC - Eocene
PAL - Paleocene
MAS - Maastrichtian
CAMP - Campanian
ALB - Albian
APT - Aptian
NEO - Neocomian
JUR - Jurassic
PRIII - Post-Rift III unit
PRII - Post-Rift II unit
PRI - Post-Rift I unit
RFT - Rift unit
PRT - Pre-Rift unit
BSM - Basement
TD - Terminal Depth of well
5. DATA ANALYSIS

5.1 - THE BASEMENT

- Regional Outlook

The northeastern corner of the South American Platform was defined by Almeida et al. (1977), as the "Província Borborema" (Borborema Province), to describe an area of intense tectonic activity during the Late Proterozoic and the early Phanerozoic (Cambrian-Ordovician). The basement of the Sergipe-Alagoas Basin includes portions of two of the major tectonic elements of the region: the Sergipano Folded Belt, and the Pernambuco-Alagoas Massif (Santos and Neves, 1984) (Fig. 9).

The Sergipano Folded Belt, formed during the Brasiliano tectonic event (700-450 Ma), has a curved axis, which is oriented approximately E-W on its eastern end, and NW-SE on its western end, this trend being followed by the major structures. The folded belt is divided in two distinct zones, or subsystems, separated by an intermediate zone (Santos and Neves, 1984). The southern subsystem is characterized by the presence of alternating clastic and carbonatic sequences affected by low grade metamorphism, insignificant magmatic activity, and structural vergence to the south. The northern subsystem is characterized by low to high grade metamorphism of essentially terrigenous sediments, two phases of magmatic activity (basic-ultrabasic and acidic, respectively), and
Fig. 9 - Integrated map showing major structures in the basement surrounding the Sergipe-Alagoas Basin, and major faults in the basin. Map shows the different basement areas: the São Francisco Craton to the south, the Sergipano Folded Belt (with its three zones), and the Pernambuco-Alagoas Massif. Also shown are the Recôncavo, Tucano and Jatobá Basins. Major rift faults in the Sergipe-Alagoas Basin are indicated. The separation between Central and Northern Domains in the basin is coincident with the separation between different zones in the folded belt. (Sources: Silva Filho et al., 1979, 1981; Cordani et al., 1984; Santos and Neves, 1984; Schobbenhaus et al., 1984).
structural vergence to the northeast (Silva Filho et al., 1979). The intermediate zone, situated between the northern and southern subsystems, confers bilateral symmetry to the folded belt as a whole (Santos and Neves, 1984). It is characterized by frequent occurrences of granitic intrusions and local exposition of Archaean basement. It does not have a defined structural vergence, with strong vertical tectonic movement.

To the south of the folded belt is found a unit composed of a basal sequence of carbonates overlain by a thick clastic section, of Late Proterozoic-Early Phanerozoic age, and interpreted to be the foreland deposits of the folded belt (Silva Filho et al., 1979; Santos and Neves, 1984).

There is a conspicuous absence, in the brazilian geologic literature, of a consistent tectonic model for the development of the Sergipano Folded Belt. Even though it is usually agreed that the folded belt is the result of a plate collision event (Schobbenhaus, 1976; Silva Filho et al., 1979; Santos and Neves, 1984), the type and details of the collision itself are not understood. A major drawback for the study of the tectonic development in the area is the general absence of geophysical, especially seismic, data on the folded terrain, precluding the observation and interpretation of subsurface crustal structures.

The Pernambuco-Alagoas Massif is composed of gneisses and migmatites of Archaean to Middle Proterozoic age, and Late Proterozoic granitic intrusions. Its contact with the northern part of the Sergipano Folded Belt has not been precisely defined, especially
because of the great degree of anatectic regeneration to which the area was subjected during the evolution of the folded belt.

- The Local Framework

Figure 10 is a simplified structural map of the basement of the Sergipe-Alagoas basin, showing the major faults, and how they divide the basin in several compartments. According to their orientation, the faults can be placed in three major groups. The first includes faults striking from N15W to N5E, the second includes faults striking N15E to N30E, and the third includes faults striking N65E to N80E. This latter group is of special interest, because some of these faults correspond to the limits of broad shallow basement areas, which are, from south to north, the Estância, Sergipe and Japoatá Platforms. The relationship between the structural behavior of the basement and the orientation of faults was used to define three principal subdivisions in the basin, which were called the Southern, Central and Northern Domains. These Domains were defined in a general E-W direction, following the limits of the basement platforms bounded by major faults (Fig. 10).

The Southern Domain, bounded on the west by the Estância Platform, is characterized by an abrupt change in basement depth which happens at a NNW trending fault. Basement depth west of the fault is less than 500 m, whereas east of the fault the basement is estimated to be below 10,000 m.

In the Central Domain, the change in depth of the basement (also
Fig. 10 - Simplified structural map of the basement in the Sergipe-Alagoas Basin, and identification of the proposed Southern, Central, and Northern Domains. Also indicated are (A) Estância, (B) Sergipe and (C) Japoatã Platforms, which are the high basement areas in each domain. Depth of basement in most of the offshore area is not known.
from less than 500 m to more than 10,000 m) happens gradually, in a series of steps controlled by NNW to NNE trending faults.

The Northern Domain also presents a step-fashion increase in the depth of basement, but its most striking feature is the presence of extensive N15E to N30E oriented faults, in contrast with the two other domains, where such faults are virtually inexisten.

As one compares the distribution of structures in the basement of the Sergipe-Alagoas Basin with the surrounding Precambrian basement, some points appear to be of interest. First, the Sergipe-Alagoas Basin is on the eastern side of the Sergipano Folded Belt, where its structural axis assumes a general E-W orientation (Fig. 9). Second, the central zone of the folded belt is roughly coincident, in position and orientation, with the Japoatã Platform, the shallow basement area of the Northern Domain. Also, an analysis of surface lineaments in radar images, as presented by Cunha (1987) (Fig. 11), shows that on the basement bordering the Southern and Central Domains, as well as the western portion of the Northern Domain, the majority of lineations are oriented to NW, and a great number of them is concentrated between N10-25W. On the basement bordering the northern end of the Northern Domain, however, there is a substantial increase in the number of lineations oriented to NE, specially between N20-30E. It should be noted, nevertheless, that the presence of lineaments in radar images can be due to effects such as highlights and shadows caused by oblique radar illumination, rather than by actual geologic features (Sabins, 1987).

The lithologic nature of the basement in the basin also seems to
Fig. 11 - Radar-mapped surface lineations in and around the Sergipe-Alagoas Basin. N20-30E lineations in the basement are concentrated predominantly around the northern end of the basin. Heavy line in the map indicates the limit of Cretaceous/Tertiary sediments in the area of the basin. Modified from Cunha (1987).
indicate some correlation between structural characteristics. Samples of basement taken from wells drilled in the Southern and Central domains show it to be composed mainly of schists and phyllites, of low metamorphic grade, whereas samples from wells in the Northern Domain are predominantly gneisses and granites.

5.2 - PRE-RIFT (Paleozoic - Late Jurassic)

The Pre-rift unit, as stated before, includes sediments deposited during the Paleozoic and the Late Jurassic (Fig.3), and has an average thickness of 200 m (Guimarães, 1988). The Estância Formation, interpreted to be of probable Cambrian age (Schaller, 1969), is found in the southern part of the basin, and is considered by Silva Filho et al. (1979), and Santos and Neves (1984) to correspond to the foreland deposits of the later stages of development of the Sergipano Folded Belt. The Batinga and Aracaré Formations, of Permo-Carboniferous age (as determined by sporomorphs of the genera Florinites, Striatites, Lueckisporites, Limitisporites, Vestigisporites, Vitattina, and Striatosacites (Schaller, 1969)), are correlatable with strata found in other Cretaceous basins (Recôncavo, Tucano basins), and in Paleozoic basins (Maranhão, Amazonas, Paraná basins). They are believed to have been deposited during a tectonically stable phase, when the area where the Sergipe-Alagoas Basin sits today corresponded to the eastern reaches of the broad Paleozoic Maranhão basin (Silva Filho et al., 1979; Schobbenhaus et al., 1984).
The Candeeiro, Bananeiras and Serraria Formations, which rest unconformably on top of the Precambrian basement or above the Paleozoic sediments, are considered to be of probable Late Jurassic age, this age being tentatively determined by the presence of the *Darwinula oblonga* ostracoda species (Regali and Viana, 1986; Arai et al., 1987). They are also correlatable with strata found in the Recôncavo and Tucano basins. Estrella (1972), analyzing the distribution of Triassic-Jurassic sediments along the eastern brazilian continental margin, suggested that these formations were deposited in a peripheral basin, formed at the margin of a large domic structure that evolved during the Jurassic, preceding the rifting stage, an idea that will be discussed in greater detail in a later section.

One of the major drawbacks for the identification of this unit was the fact that only 18 of the wells used in this study reached basement (all onshore). Even though the basement could have its onshore position determined by seismic or gravimetry in most of the cases, the Pre-rift sedimentary unit was in many, areas virtually invisible seismically, because of its small thickness.

5.3 - RIFT (Neocomian)

The Rift unit was deposited during the Neocomian (Fig. 3), this age being defined by palynological criteria, specially the association of the *Dicheiropollis etruscus*, *Caytonipollenites pallidus*, *Leptolepidites major*, and *Alisporites ? sp. 1* palynozones (Regali
and Viana, 1986; Arai et al., 1987). The sedimentation reflects the rift activity to which the area was subject. Deposits include the lacustrine basin, slope and turbidite fan systems of the Barra de Itiuba Formation, and the fluvial-deltaic system of the Penedo Formation, which are flanked by the coarse fan-delta deposits of the Rio Pitanga Formation. These sequences can reach thickness of up to 3,000 m. With the continuous infilling of the lakes, these deposits graded into the lacustrine carbonate platforms of the Morro dos Chaves Formation, and the fluvial-deltaic, fan-delta and slope systems of the Coqueiro Seco Formation (Fernandes et al., 1981), which can also, locally, reach thickness of up to 3,000 m.

The Rift unit was mappable on all of the onshore area (and high basement areas offshore), its base defined by a basement (or basement equivalent) reflection, and its top by an unconformity. In most of the offshore area, however, the unit could not be mapped at all. The offshore area is the deepest part of the basin, and the deeper wells do not penetrate below the Post-Rift I unit. Even though the base of this latter unit could be, in most cases, seismically defined (Figs. 12, 13), the base of the Rift unit could not be determined or estimated with any degree of reliability (in a few offshore seismic profiles, sporadic reflections of distinctive high amplitude were tentatively assumed to be the equivalent of acoustic basement; they were not considered to be reliable for consistent interpretation, and were used only as indicators of probable basement attitude).

Figure 14 is an isopach map of the Rift unit, on which were superimposed major faults. In the Southern Domain, as noted before,
Fig. 12 - Location map, interpreted and uninterpreted versions of offshore seismic profile in the Central and Northern Domains, across the main transfer fault system (shown as a subvertical fault, with a possible flower structure, at the left of the profile). Note the abrupt change in thickness of the Post-Rift I unit. Detail on upper left corner shows onlap of the Post-Rift I unit on the unconformity at the top of the Rift unit. The chaotic set of reflectors in the Post-Rift I unit, in the lower right of the profile, is interpreted to represent mobilized evaporites (see Table I for key to stratigraphic symbols in the wells).
Fig. 13 - Location map, interpreted and uninterpreted versions of seismic profile in the Central Domain. The area to the right of the well shows erosional truncation of Rift unit below the Pre-Aptian unconformity (see Table I for key to stratigraphic symbols in the wells).
Fig. 14 - Isopach map of the Rift unit (Neocomian), showing the major faults active during the rifting phase.
the basement deepens abruptly at a major NNW trending fault, and it was not possible to map the Rift unit east of the fault, because the existing wells do not reach the unit, and its base cannot be clearly recognized.

In the Central Domain the Rift unit can be mapped with rather good confidence, specially because several of the wells used have reached beyond the base of the unit. The isopach map shows that the unit thickens next to the NNW to NNE trending faults, and that the average thickness increases in each stepblock to the east. Seismically, the Rift unit is characterized by fairly continuous, medium to high amplitude reflections, which occasionally are seen onlapping the acoustic basement or the Pre-Rift unit (Fig. 15), and, more commonly, tend to parallel the structural attitude of the basement (Fig. 16).

In the Northern Domain the Rift unit has the same seismic character, with rather continuous, medium to high amplitude reflections (Fig. 17). In some areas the unit displays a high level of internal structuring (Fig. 18), but these structures follow the same basic pattern of those mapped in the basement or the Pre-Rift unit (Fig. 19). Also, the same stepblock thickening is observed, and the unit thins to the north, towards the limits of the basin (Fig. 14).

The top of the Rift unit corresponds to an unconformity created by a widespread erosional event. This unconformity (the Pre-Aptian, or Pre-Alagoas unconformity (Fugita, 1971) -- Alagoas being the Brazilian stage equivalent to the Aptian) can be correlated along the entire eastern brazilian margin (Asmus and Ponte, 1973).
Fig. 15 - Location map, interpreted and uninterpreted versions of onshore seismic profile in the Central Domain, in the southern part of the basin. A shallow basement platform (at left and center of the profile) is offset by a normal fault (to the right), with basement on the downthrown block dipping towards the fault, in half-graben pattern. Reflections within the Rift unit onlap the basement in the downthrown fault block. The Post-Rift 1 unit shows structures possibly associated with salt mobilization, and is overlain by the essentially carbonatic Post-Rift 2 unit (see Table I for key to stratigraphic symbols in the wells).
Fig. 16 - Location map, interpreted and uninterpreted versions of onshore seismic profile in the Central Domain. Reflections in the Rift unit are continuous and tend to parallel the basement (see Table 1 for key to stratigraphic symbols in the wells).
Fig. 17 - Location map, interpreted and uninterpreted versions of onshore seismic profile in the Northern Domain. Reflections in the Rift unit are fairly parallel and continuous. The fault in the Post-Rift I unit is possibly associated with salt mobilization (see Table I for key to stratigraphic symbols in the wells).
Fig. 18 - Location map, interpreted and uninterpreted versions of onshore seismic profile in the Northern Domain. Two sets of normal faults are visible, one offsetting the basement, the other within the Rift unit. In spite of the internal faulting, reflections in the Rift unit are fairly continuous and parallel (see Table I for key to stratigraphic symbols in the wells).
Fig. 19 - Structural map at the 9-A sand, in the Barra de Itiuba Formation (Rift unit) (modified from Dauzacker et al., 1984), in the area of the seismic profile shown in Fig. 18. Contour values are in meters. Faults follow a general N-S trend, parallel to the main fault trend in the basin. Black dots are wells drilled in the area. Hachured areas are oil/gas fields. The broken line across the map corresponds to the approximate position of the seismic profile in Fig. 18.
5.4 - POST-RIFT I (Aptian)

The Post-Rift I unit was deposited during the Aptian (Fig. 3), above the unconformity created after the end of the rifting phase in the basin. The determination of the Aptian age of this unit is, once more, based on palynological criteria, the time interval being marked by extinctions of *Dicheiropollis etruscus*, *Inaperturopollenites crisopolensis*, and *Sergipea varierrucata* (Regali and Viana, 1986; Arai et al., 1987). This unit corresponds to the Muribeca Formation, which is locally thicker than 4,000 m. Sediments range from lacustrine, fan-delta and platform to platform carbonate and evaporitic systems, and the Muribeca Formation is highlighted by the presence of thick evaporitic deposits, which mark the first marine incursions in the basin.

The Post-Rift I unit was mapped onshore and offshore, out to the 100 m isobath (Fig. 20). Mapping of the unit beyond this water depth was not considered reliable, due to the seismic effects of the shelf break, sloping ocean floor, slope topography, and the overall loss of seismic quality with increase in depth. The mapped offshore area, however, presented a special problem. Since the wells do not penetrate below the unit, its base and thickness had to be seismically defined. The base, which corresponds to an unconformity, can be determined either by the truncation of underlying reflections (Fig. 13), by an onlap pattern of the overlying reflections against the unconformity (Fig. 12), or by contrast
Fig. 20 - Isopach map of the Post-Rift I unit (Aptian), showing also the major faults active during the rift phase. The Rift II unit is absent in great part of the Northern Domain, and thickens considerably offshore.
SERGIPE-ALAGOAS BASIN

ISOPACK MAP
POST-RIFT I UNIT (APTIAN)
C. I. : 200 m

km
0 10 20
between the characteristic seismic facies. While the Rift I unit is characterized by somewhat continuous, linear reflections, the seismic configuration of the Post-Rift I unit shows signs of internal deformation, with discontinuous, sinuous or curved, variable amplitude reflections (Fig. 21), and internal structures (faults, folds) not connected with basement structures (but apparently controlled by them) (Fig. 22). Such structures often affect younger units. These distinctive features are not always found together, and in a few cases are not seen at all, but the seismic grid utilized and the overall consistency of those patterns ensures a substantial degree of confidence in the result, except in small areas where the seismic quality is extremely poor. The thickness of the Post-Rift I unit in the offshore area was determined in a two-step process: velocity distributions for different areas were computed and calibrated by the methods described in Section 3 (Database and Methods), and the velocity values were then applied to the measured time isopachs to obtain the final thickness. The seismic data show that the pre-Aptian unconformity, at the base of the unit, was only very slightly affected by rift phase faults, if at all.

In the Southern and Central Domains, there is a characteristic increase in thickness in the offshore areas (Fig. 20), even though the unit is present over much of the onshore area. In the Northern Domain the unit is absent in great part of the onshore area, but the maximum mapped thickness in this Domain is located onshore, next to a NE trending fault (Fig. 20). The boundaries between the defined Domains are sharply accented by the changes in thickness along the
Fig. 21 - Location map, interpreted and uninterpreted versions of offshore seismic profile in the Central Domain. Area beneath the well shows pattern of curved reflectors in the Post-Rift I unit (see Table I for key to stratigraphic symbols in the wells).
Fig. 22 - Location map, interpreted and uninterpreted versions of offshore seismic profile in the Central Domain, illustrating the internal structuration of the Post-Rift I unit (outlined), and the control of both the structures and the topography of the base of the unit by rift-phase faults (see Table I for key to stratigraphic symbols in the wells).
ENE trending faults, visible both in the isopach map (Fig. 20), and in the seismic profiles (Figs. 12, 23, 24).

The Post-Rift I unit is marked by the presence of massive evaporites, mainly in the form of anhydrite and halite associated with dark shales and dolomitic limestones. In the onshore portion of the Central Domain, however, the unit is characterized by the occurrence of carnalite, sylvinitite and tachydrite along with the anhydrite and halite (Ojeda, 1982). The presence of evaporites has been ascertained by well data, and the seismic data show evidence of the mobilization of large evaporitic masses, either in the form of piercing diapirs (Fig. 25) or ridges (Figs. 24, 26).

The top of the Post-Rift I unit is marked by an unconformity, seismically correlatable across the basin. This unconformity is eventually affected by faults created by the movement of evaporites within the unit. (Figs. 22, 27, 28).

5.5 - POST-RIFT II (Albian to Santonian)

The next post-rift phase in the Sergipe-Alagoas basin starts in the Albian (Fig. 3), with the establishment of regional shallow marine conditions which prevailed until the Santonian, and is represented by the fan delta, carbonate shelf and calcareous slope systems of the Riachuelo and Cotinguiba Formations, reaching up to 1,800 m thickness. The Albian age is determined by the ammonites Mortoniceras sergipensis and Douvilleiceras sp. sp. (Schaller, 1969).

The isopach map of the Post-Rift II unit (Fig. 29) was based
Fig. 23 - Location map, interpreted and uninterpreted versions of offshore seismic profile in the Central Domain. There is a drastic change in thickness of the Post-Rift I unit as one crosses the fault on the right side of the profile. Note also the continuous dip towards the south of the Post-Rift I and Post-Rift II units. Upper Cretaceous and Paleocene sediments onlap the Post-Rift II unit, and pinch out before reaching the fault zone (see Table I for key to stratigraphic symbols in the wells).
Fig. 24 - Location map, interpreted and uninterpreted versions of offshore seismic profile in the Central Domain. Discontinuous, curved reflections in the Post-Rift I unit, in the lower right of the profile, are interpreted to be mobilized evaporites (see Table I for key to stratigraphic symbols in the wells).
Fig. 25 - Location map, interpreted and uninterpreted versions of offshore seismic profile in the Central Domain, showing a salt diapir piercing through the post-rift units (see Table I for key to stratigraphic symbols in the wells).
Fig. 26 - Location map, interpreted and uninterpreted versions of offshore seismic profile in the Southern Domain. Basement goes from a shallow platform (on the left) to an undetermined depth (to the right). The Post-Rift I unit is affected by internal structuring, associated with mobilization of evaporites, and the top of the unit is erosional. The large mass intruding the younger post-rift units, on the right, is considered to be formed by evaporites, especially because of growth faults developed at its top (see Table I for key to stratigraphic symbols in the wells).
Fig. 27 - Location map, interpreted and uninterpreted versions of offshore seismic profile in the Central Domain. The unconformity at the top of the Post-Rift I unit is clearly visible, and the topography of the base of the unit is controlled by rift structure (see Table I for key to stratigraphic symbols in the wells).
Fig. 28 - Location map, interpreted and uninterpreted versions of offshore seismic profile in the Central Domain, parallel to that showed in Figure 27. Faulting in the Post-Rift I unit (interpreted to be associated with mobilization of evaporites), offsets the Post-Rift II unit (see Table I for key to stratigraphic symbols in the wells).
Fig. 29 - Isopach map of the Post-Rift II unit (Albian to Santonian). Also shown are major faults developed during the rift phase. The unit was not affected by rift phase faults, but the isopach distribution clearly follows the preexisting structural framework (compare with Figures 14 and 20).
entirely on well data. The reason for not using seismic support is twofold: in most of the onshore areas, where the carbonates reach maximum thickness, seismic quality is so poor that the available profiles are rendered useless (as a matter of fact, the great thickness of carbonates is one of the three major factors deteriorating seismic quality -- the other two are the thick coarse Pliocene sandstone - the Barreiras Formation - overlying the carbonates, and the rugged interface between them). Offshore (with the exception of a small area at the middle of the basin), the carbonates are very thin (usually less than 100 m), and are seldom resolved by the seismic method, top and base usually being within one or two cycles of the seismic trace.

The Post-Rift II unit is absent in the Northern Domain (Fig. 29), and the greater thickness are concentrated in the onshore portion of the Central Domain, whereas in most of the offshore area, where only a condensed section is present, thickness are seldom greater than 100 m. Sediments are predominantly carbonatic, locally associated with sandstones and conglomerates. In the onshore area lithologies include oolitic to pisolithic limestones, algal and reef limestones, coquinas, and dolomites, but offshore lithologies are almost entirely restricted to calcilutites and shales. The unit is not affected by rift phase structures, but rather by those developed by the mobilization of evaporites within the underlying Post-Rift I unit (Fig. 28). Even though the Post-Rift II unit is not found on the Japoatã Platform, which corresponds to the shallowest basement area in the basin, the greater thickness are found in areas of high
basement in the Central and Southern Domains (Figs. 10, 29).

5.6 - POST-RIFT III (Campanian to Holocene)

The Post-Rift III is the uppermost operational unit defined, and corresponds to sediments deposited during the subsidence phase of the basin. From the Campanian to the Miocene, as subsidence progressed, sedimentation turned into the largely prograding clastic slope and associated fan delta and carbonate platform systems of the Piaçabuçu Formation, which can reach thicknesses of up to 2,500 m. The latest sedimentary records in the basin are the Pliocene continental deposits of the Barreiras Formation, and Quaternary eolian, beach and alluvial sediments. The abundant occurrence of fauna (ammonites, foraminifera, nanofossils) in the strata allows a good correlation with the international stratigraphic units (Schaller, 1969).

The overall shape of the basin in which the Post-Rift III unit rests had already been defined in the tectonically active rifting phase. Since the top of this unit corresponds to the present surface, a structural contour map of its base was chosen to show possible differences in subsiding behaviour between different parts of the basin. Figure 30 is the structural map in time contour, and Figure 31 is the depth contour map, controlled by well data and by analysis of seismic velocity distribution in the unit.

The Piaçabuçu Formation corresponds to sediments deposited during the open marine phase of the Sergipe-Alagoas basin, and is
Fig. 30 - Structural contour map (in time) at the base of the marine section of the Post-Rift III unit (corresponding to the base of the Piaçabuçu Formation). Also shown are major faults developed during the rift phase. The unit is almost totally absent in the Northern Domain, and the shape of its base follows the limits of the basin defined during the rift phase (compare with Figures 14, 20 and 31).
SERGIPE-ALAGOAS BASIN
STRUCTURAL TIME CONTOUR MAP
BASE OF PIÇABUÇU FORMATION
(POST-RIFT III UNIT)
(CAMPANIAN TO MIOCENE)

C. I. : 250 ms

km

0 10 20
Fig. 31 - Structural contour map (in depth) at the base of the marine section of the Post-Rift III unit (corresponding to the base of the Piaçabuçu Formation). This map was created by the application of a velocity distribution function, calibrated by well velocity information, to the seismic data. Also shown is the position of major faults created during the rift phase.
composed largely of slope and basinal shales, with intercalated sandstones, and platform carbonates and sands. It is found only on approximately 25-30% of the onshore area, and reaches maximum thickness in the Southern and Central Domains (Figs. 30, 31). The base of the unit has been affected by structures created by salt mobilization within the Post-Rift I unit (Figs. 22, 28), but the structural map clearly reflects the continued influence of the major faults bounding the Domains.

The Barreiras Formation, which is found along the entire Brazilian coast, is composed of poorly consolidated, coarse to conglomeratic sandstones, and occurs as extensive tabular beds. The average thickness is 60 m, but locally it can reach up to 300 m. The tabular nature of the deposits creates a smooth topographic relief, usually known as "flat tops" ("tabuleiros"), which drop sharply at the coastline, forming a series of rather spectacular cliffs which extend for tens, and sometimes, hundreds of kilometers. The Barreiras Formation rests unconformably above all the older strata in the basin, and covers about 95% of its onshore area, therefore severely restricting geologic field work. Figure 32 is a subcrop geologic map below the Barreiras Formation and Quaternary deposits, showing the distribution of older sediments in the basin. The unconformity between the Barreiras Fomartion and older strata is visible only in specific locations in the field, usually in river valleys and gorges, but it is too shallow to appear in conventional seismic data.
Fig. 32 - Subcrop geologic map below the Barreiras Formation (Pliocene) and Quaternary deposits (modified from Asmus and Ponte, 1973). The map clearly shows the separation between the Central and Northern Domains.
5.7 - THE CONTINENTAL CRUST

As a complement to the data base, a crucial thickness map of the Sergipe-Alagoas basin, published by Kiang and Kowsmann (1986), was used to provide general information about the continental crust behavior (Fig. 33). The method utilized by these authors to generate the map included several steps: compute the subsidence curves for 98 wells in the basin using a backstripping technique (Steckler and Watts, 1978); compare these curves with theoretical subsidence curves calculated using the McKenzie (1978) model, for different degrees of crustal stretching; construct cross sections using matching stretching values; calculate the gravimetric anomaly generated by the cross sections and compare it with measured gravity values, and adjust the model by a trial and error procedure, using a computer program.

Kiang and Kowsmann (1986) list several assumptions made during the different phases of construction of the map, including the critical estimates of depth of the basement, which were based partially on gravimetric data (mainly onshore), partially on seismic interpretation. Notwithstanding the merits or precision (or lack thereof) of the seismic interpretation, it is interesting to note that it is possible to identify the three basement Domains defined earlier, the continental crust in the Northern Domain being noticeably thicker than in the other two. Possible implications of this conclusion will be discussed later, along with the interpretation of the data. It should be kept in mind, however, that
Fig. 33 - Crustal thickness map in the Sergipe-Alagoas Basin, as presented by Kiang and Kowsmann (1986). Broken lines indicate position of the boundaries between the Southern, Central and Northern Domains.
the crustal thickness map is the result of an interpretation, not a direct presentation of data.
6. INTERPRETATION

6.1 - RIFT DEVELOPMENT: GEOMETRY AND DYNAMICS

- The South Atlantic

It is widely accepted that the South Atlantic Ocean originated from a wedge-shaped north-south oriented sea that was formed as Africa and South America slowly moved away from each other, the process being completed when South America and Africa separated along the belt of equatorial fractures. This drifting phase was preceded by a rifting episode that began during earliest Jurassic, and lasted for about 80 Ma (Rabinowitz and LaBrecque, 1979; Emery and Uchupi, 1984). The evolution of the South American and African passive margins created a series of coastal basins on both continents (Fig. 34), and the tectonic evolution of the basins is expressed in their stratigraphic record, which can be correlated and reflects their common origin.

Asmus (1984), supporting an idea introduced by Estrella (1972), proposes that, during the Triassic-Jurassic, the area which today includes the Santos basin in South America, and the Mossamedes basin in Africa was the site of intense regional uplift, which was suggested to be related to a thermal anomaly in the mantle. The uplift reached its peak during the Late Jurassic, and the area was a source of sediments for intracratonic basins adjacent to the elevated area: the Paraná basin, in Brazil, the Congo basin, in Africa,
and the Afro-Brazilian depression (Ponte, 1971; Estrella, 1972) (Fig. 35a). These sediments correspond to the pre-rift sequences found in the Camamú-Almada, Recôncavo and Sergipe-Alagoas basins, in Brazil, and the Congo-Cabinda and Gabon basins, in Africa, and they are characteristically absent in the Espírito Santo, Campos, Santos, and Pelotas basins, in Brazil, and in the Cuanza and Mossamedes basins in Africa. Also, during the Late Jurassic-Earliest Cretaceous, the uplifted area was the site of intense volcanic activity, and it is interesting to note that the distribution of the volcanic rocks follows an exact inverse pattern as that of the sediments of the same age. Thus, there is no record of volcanic activity in the pre-rift stage in the Camamú-Almada, Recôncavo, Sergipe-Alagoas, Congo-Cabinda and Gabon basins, while in the Espírito Santo, Campos, Santos, Pelotas and Cuanza basins the rift-phase sediments are found overlying basalts -- the complete stratigraphic record of the Mossamedes basin is not known (Emery and Uchupi, 1984), and the presence of volcanics has not been verified.

The rift phase, which took place during the Neocomian, is represented in all the basins, and is characterized by intense tectonic activity, and typically lacustrine sedimentation, defining an elongated, north-south oriented rift system (Fig. 35b), similar to the one found presently in East Africa.

-The Sergipe-Alagoas Basin

The interpretation of the data indicates that the Sergipe-Alagoas
Fig. 35 - Schematic evolution of the South Atlantic rift, as proposed by Asmus (1984); (A) during Late Jurassic, crustal uplift to the south created a source area for sediments that were deposited in periferic intracratonic basins; (B) during the Neocomian, the uplifted area was initially the site of intense volcanic activity, while the rift propagated to the north; (C) during the Aptian, the extensive evaporitic basin was bounded, to the north, by the crustal limits of Africa and South America, and to the south, by the Walvis-São Paulo/Torres ridge. South of this ridge, oceanic crust was already being formed.
basin evolved as a series of half-graben following a general N-S orientation. This geometry is indicated both by the basement configuration, where visible, and the distribution of depocenters, which are concentrated next to the faults.

The traditional model adopted for the evolution of the eastern Brazilian margin basins assumes the existence of an initial symmetrical rift valley (Asmus and Porto, 1980; Ojeda, 1982; Asmus, 1984). However, Bally (1981, 1982) pointed out the worldwide near-absence of symmetrical rifts in seismic data, and suggested that rift valleys are mainly half-graben systems, a suggestion that has gained support since then, especially with the work done by Rosendahl (1987) in the East African rift basins. As a result, structurally asymmetric models for continental extension, such as those proposed for the Basin and Range province in the United States (Wernicke, 1981, 1985; Wernicke and Burchfiel, 1982; Davis, 1983) have been favored over symmetrical, pure-shear extensional models (McKenzie, 1978; Le Pichon and Sibuet, 1981), as the accepted mechanism for the formation of rift valley systems and, eventually, passive margins. The asymmetric, simple-shear models are based on the idea of detachment surfaces, or shallow-dipping crustal shear zones, along which extension would be accommodated. In a further development of the concept, Lister et al. (1986) presented a model for the architecture of passive margins resulting from asymmetric continental extension along detachment surfaces. The major predicted consequence of this model is that opposing continental margins should exhibit complementary
asymmetry (Fig. 36). Emery and Uchupi (1984) presented geophysical data off the northern coast of Gabon, the area on the west African coast opposed to the Sergipe-Alagoas Basin, which indicate that the transition from continental to oceanic crust is abrupt and relatively close to the coast line (Fig. 37), features that correspond to an upper-plate margin in the Lister et al. (1986) model (Fig. 36). The complementary structural characteristics along parts of the Brazilian and the African margins were integrated by Castro (1987), who suggested that the Sergipe-Alagoas Basin was formed as part of a complex rift system that extended along multiple detachment surfaces (Fig. 38). This kind of adjustment between the Brazilian and African margins was also suggested, in a somewhat different perspective, by Ussami et al. (1986), who analyzed the relationship between the Reconcavo and the Gabon basins.

In spite of the nice correlation between the structural features of the opposing continental margins, which fit very well in the geometry predicted in the detachment model, good evidence for the existence of the necessary detachment surfaces in the present study area, as well as in the African side, is still lacking. Deep crustal seismic data either do not exist, or are not available. As mentioned before, the existing seismic profiles from the Sergipe-Alagoas Basin were acquired and processed according to petroleum industry standards (in the majority of the cases, the available records are only six seconds long), and do not image deep crustal structures. Guimarães (1988) interpreted intra-basement reflections as shallow detachment levels (Fig. 39), and, in the present work, it was
Fig. 36 - Detachment-surface model of passive continental margin geometry showing the characteristics of complementary margins. Arrows indicate position of detachment surfaces. (A) Lower-plate margin, highly structured; tilted fault blocks are remnants from the upper-plate above the detachment surfaces. (B) Upper-plate margin, with very low degree of structuring. Rather than being symmetrical, the opposing margins exhibit a complementary geometry (Modified from Lister et al., 1986).
Fig. 37 - Line drawing of a seismic profile in the Niger delta region. The southern end of the profile, at the northern coast of Gabon (B), shows an abrupt transition from continental to oceanic crust, close to the coast line, features expected to be found in an upper-plate margin in the detachment-surface model (compare with (B) in Fig. 36). (Modified from Emery and Uchupi, 1984).
Fig. 38 - Schematic cross sections showing the development of the Gabon and northeastern Brazil basins (Sergipe-Alagoas, Recôncavo and Tucano Basins) associated with crustal detachment surfaces, as proposed by Castro (1987). The arrows indicate the points of minimum effective crustal thickness, which defines the crustal rupture point and creates the complementary margin asymmetry. The Sergipe-Alagoas Basin corresponds to the lower-plate margin, strongly structured, facing the relatively unstructured northern Gabon margin.
JAPÓATÃ-PALMEIRA ALTA PLATFORM
Fig. 39 - Seismic profile in the Sergipe-Alagoas Basin, as presented by Guimarães (1988). The interpretation shows westward tilt of basement, and the progradation of synrift sediments over the pre-rift strata. Basement is at about 0.7 seconds at the well shown on the right (~1150 m). The low angle normal faults sole out along a group of reflections with high amplitude and low continuity that dip eastward, which was considered to be a shallow detachment surface.
possible to verify that, in some seismic profiles, there are some deep, high amplitude, linear reflections, below the Rift unit (Fig. 40), which could not be consistently followed, specially into greater depths. These indications do not constitute solid evidence of detachment surfaces (they could be, for example, lateral reflections of fault planes), but they also cannot be summarily dismissed, since they could eventually represent the seismic expression of detachment surfaces.

The rift structures in the Sergipe-Alagoas Basin are oriented obliquely to the coast line, a situation which contrasts with what has been described in other eastern Brazilian and western African marginal basins, where major faults and principal structures are parallel to the coast line (Asmus and Porto, 1980; Ojeda, 1982; Brice et al., 1984; Emery and Uchupi, 1984; Schobbenhaus, 1984). The Sergipe-Alagoas Basin itself was previously assumed to follow this general arrangement, even though most of the structures oblique to the coast line have been known since the beginning of exploration in the basin. In order to understand the peculiar orientation of structures in the Sergipe-Alagoas basin, it is necessary to examine the geology of the surrounding area.

Almeida (1973) points out that the Atlantic margin of South America is oriented along the same general direction as the structures in the Precambrian basement, with the exception of northeastern Brazil, where ancient structures exhibit a fan-shaped pattern, oblique to the coast line (Fig. 41). Taking a closer look at the regional distribution of Precambrian structures (Fig. 42), we see
Fig. 40 - Location map, interpreted and uninterpreted versions of offshore seismic profile in the Central Domain. The strong dipping reflection at the lower left could be the seismic expression of a detachment surface (see Table I for key to stratigraphic symbols in the wells).
Fig. 41 - Distribution of cratonic areas and Proterozoic folded belts in eastern South America and southwestern Africa. From south to north, rifting followed the structural directions of the folded belts. Square indicates location of map shown in Fig. 42 (Modified from Hasui and Oliveira, 1984).
that these structures, as well as the coast line, change from a N-S to a NE-SW orientation, following the western border of the Congo craton. The superposition of present coast line geometry (and limits of present oceanic basins), and structural orientation in the basement is suggestive (though not necessarily assertive) of some form of causal relationship. The basement upon which the continental margins were installed was formed during a Late Proterozoic-Early Phanerozoic tectonic cycle, known as the Brasiliano (in South America) and the Pan-African (in Africa) tectonic event, which lasted from 700 to 450 Ma (Almeida et al., 1973). Wright et al. (1985) suggested that basins would tend to appear along relatively "young" tectonic areas, since they would be slightly warmer than the adjacent cratons, thus being more easily stretched and rifted.

As we have seen from the data, what we have in the Sergipe-Alagoas basin is a system of half-graben, bounded by N-S oriented normal faults, with the half-graben themselves oriented obliquely to the direction of propagation of the rift (NE-SW), as illustrated schematically in Figure 43. The presence of these "an echelon" basement blocks in the basin, defining the three basement Domains (Fig. 10), can be interpreted as a result of a change in direction of propagation of the rift from a N-S to a NE-SW trend.

The discussion above indicates the existence of an oblique rift, in which the direction of extension is at an angle of approximately 45° to the rift direction. The development of oblique rifts (defined as those rifts in which the relative displacement direction between the
Fig. 43 - Schematic representation of N-S trending half-graben system, connected by transfer faults, oriented obliquely to the direction of propagation of the rift. The creation of such a configuration is discussed in the text (see also Figure 44).
divergent segments is oblique to the direction of propagation of the rift -- this latter direction being designated as the rift trend) was studied by Withjack and Jamison (1986), using both analytical and experimental models, to verify the type, distribution and orientation of faults that are formed when the direction of extension is at several different angles to the rift trend. The results, in both the analytical and experimental models, indicate that when the angle between the rift trend and the relative displacement direction of opposing sides of the rift is 45°, normal faults are formed, and they strike 35°-55° counterclockwise from the rift trend (Fig. 44). In the case of the Sergipe-Alagoas Basin, this would correspond to normal faults oriented to N5W-N5E, which is in excellent agreement with the verified orientation of the majority of the rift normal faults.

The half-graben in the Sergipe-Alagoas Basin are interrupted along a second set of faults, striking N65E to N80E, which separate areas of different basement depth, and were considered to be the limits of individual segments of the basin, the Southern, Central, and Northern Domains (Fig. 10). Due to their orientation, and their relationship with the half-graben systems, these faults were interpreted to be transfer faults, defined by Gibbs (1984) as faults at high angles to the margins of rift systems that accommodate different rates of crustal attenuation, being integral parts of the extension system. As pointed out by Lister et al. (1986), transfer faults are a general feature of extended terranes, should be expected to occur frequently in passive margins, and play an important role in accommodating oblique extension. Gibbs (1984) suggested that the
Fig. 44 - Relationship between direction of extension, rift trend, and direction of normal faults, as determined by Withjack and Jamison (1986). In a system with E-W oriented extension, and the rift propagating to N45E, normal faults will form oriented between the directions N10W and N10E (shaded area).
geometry of transfer faults may be controlled by discontinuities in
the basement. In the Sergipe-Alagoas Basin there is a coincidence of
orientation between the largest transfer fault system, which
separates the Central from the Northern Domain, and the contact
between the southern and central zones of the Sergipano Folded Belt
(Fig. 9). Also, the central zone of the folded belt corresponds to what
is described as the axis of symmetry of the folded belt, where there
is a change in the vergence, and an increase in vertical displacement
of structures (Silva Filho et al., 1979; Santos and Neves, 1984),
suggesting a high degree of verticalization of faults. The fact that
the basin is almost entirely covered by Pliocene and younger
sediments precludes direct field verification of structural
continuity, and at this point, with the scarce data available, any
structural correlation is only speculative. The change in basement
nature along the basin is also evidenced by the lithology of basement
samples taken from wells. Samples from the Southern and Central
Domains show basement to be composed of schists and phyllites, of
low metamorphic grade, which are characteristic of the southern
zone of the folded belt. Samples from the Northern Domain show that
basement is composed of gneisses and granites, which characterize
the central and northern zones of the folded belt, as well as the
Pernambuco-Alagoas Massif.

The transfer faults are seismically identified (Figs. 12, 23, 24)
as high-angle to sub-vertical faults, which separate shallow from
deep basement areas. Even in areas where the basement itself is not
visible (or identified), there is a distinct and abrupt change in
thickness of correlatable stratigraphic units from one block to the other. Gibbs (1984) stated that the displacement along a transfer fault will generally be of an oblique nature, with predominant strike-slip or dip-slip components depending on the orientation of the transfer relative to the extension direction. The apparent displacement of strata cut by the transfer faults in the Sergipe-Alagoas Basin indicates the presence of a normal dip-slip component (and different parts of the faults have been previously interpreted as normal faults), but in some seismic profiles it was possible to identify the presence of flower structures (Figs. 12, 24), suggesting the existence of significant strike-slip displacement (Harding, 1985). It was not possible, however, to quantify the magnitude or sense of this displacement in the seismic data, specially because of the decrease in seismic quality as one approaches the fault zone.

- The Regional Integration Problem

The Sergipe-Alagoas basin is one of a set of basins in northeastern Brazil that present a record of contemporaneous structural and sedimentary activity, the other basins being the Recôncavo, Tucano and Jatobá basins. Since we are dealing with the configuration during the rifting period, before the opening of the South Atlantic Ocean, the Gabon basin, in West Africa, must be considered as well (Fig. 45). Several attempts have been made to propose a consistent model for the simultaneous development of
Fig. 45 - Location map of basins in and around the Eastern Brazilian Microplate in a pre-drift configuration (see also Fig. 4).
some or all the basins, either in the South American side alone (Lana and Milani, 1983; Falkenheim et al., 1983; Szatmari et al., 1984, 1985; Lana, 1985; Milani, 1987), or integrating Africa and South America (Ussami et al., 1986; Castro, 1987).

The models that deal with the South American basins are based on the Rabinowitz and LaBrecque (1979) reconstruction of the opening of the South Atlantic (Fig. 46), and on the concept of the Eastern Brazilian Microplate (Fig. 4). In all of them it was concluded that whereas the Recôncavo, Tucano, and Jatobá basins were the result of extensional processes, the Sergipe-Alagoas basin was initially created by shear stresses acting between the South American and African plates.

Analysing some of the kinematic constraints of the Rabinowitz and LaBrecque (1979) reconstruction, Castro (1987) demonstrated that data from the Equatorial Atlantic did not show evidence of the crustal compression required by that reconstruction (Fig. 46), and concluded that the initial opening of the South and Equatorial Atlantic Oceans was not directly related, but rather that internal deformation in the African Plate controlled two initially independent events (Fig. 47). As a consequence, Castro (1987) proposed that rifting in the Sergipe-Alagoas area was induced by extension, rather than shear.

On a regional scale, the rotation proposed for the Eastern Brazilian Microplate has three problems. First, the Microplate model deals only with the South American basins. The Gabon basin, however, is located at the southern end of the Microplate, where
Fig. 46 - Paleoreconstruction of the South Atlantic Ocean at 107 Ma. (after Rabinowitz and LaBrecque, 1979), obtained by rotating continents 11.1° about a pole (P) located at 2.5° S, 45.0° W from predrift configuration. Arrows indicate vectors of motion of the African plate with respect to the South American plate from 130 Ma. to 107 Ma. Note the development of shear stresses along the northeastern Brazilian margin (the position of the Sergipe-Alagoas Basin is indicated), and of compressional stresses on the northern South American margin.
Fig. 47 - Early Cretaceous opening of the South Atlantic, as presented by Castro (1987). (A) Positions of southwestern Africa between 130 Ma (solid line), and 110 Ma (dashed line). Arrows indicate direction of movement relative to South America. B. F. is Benue transcurrent fault. Heavy lines in southern ocean are fracture zones. Eastward movement of southwestern Africa relative to South America is accommodated by the Benue left-lateral transcurrent fault, and northwestern Africa remains fixed with relation to South America. (B) Configuration of Africa and South America at 110 Ma. Progressive eastward rifting between northwestern Africa and South America propagates into the Benue region. Arrows indicate direction of movement of African plates relative to South America. B. R. is newly created Benue rift. This opening model eliminates shear stresses in the area of the Sergipe-Alagoas Basin (compare with Figure 46).
crustal displacement to the east would be maximum (Figs. 4 and 45), and it is not clear how this displacement affected the basin. Second, the Sergipe-Alagoas basin is presented as being initially developed as a pull-apart basin created by left lateral strike slip deformation (Fig. 4). It should be noted, however, that if one considers the proposed counterclockwise rotation of the Microplate (Fig. 4), the sense of movement in relation to a fixed African Plate should be right lateral, rather than left lateral. Third, rotation of the Microplate about the pole defined creates a compression in the northeastern boundary of the Microplate, which would possibly require some amount of crustal shortening to be accommodated (Fig. 4), but field evidence from the area (Neves, 1983; Santos and Neves, 1984; Schobbenhaus et al., 1984) do not support such an interpretation. Furthermore, on a local scale, Lana (1985) presented a series of seismic profiles in which vertical to high-angle faults, with characteristic flower structures, were interpreted to be evidence of strike slip deformation. However, Guimarães (1988), using reprocessed versions of the same seismic profiles, showed that the structures could also be interpreted as normal faults, created in an extensional regime rather than in a shearing one.

The models that integrate African and South American basins (Ussami et al., 1986; Castro, 1987) utilized the concept of detachment surfaces. Ussami et al. (1986), however, did not address the change in polarity between the Gabon, Recôncavo and South Tucano basins, where the major normal faults dip to the west, and the North Tucano and Sergipe-Alagoas basins, where the major
normal faults dip to the east, a fact that was considered in the Castro (1987) model (Fig. 38). In both cases, the models were based on the interpretation of gravimetric data and the distribution of structural features, and, as mentioned before, direct evidence for the existence of major crustal detachment levels is still not available.

The analysis of transfer fault orientations can eventually provide useful insight for the examination of possible relationships between the basins and common poles of rotation. The major known transfer faults in the Recôncavo, Tucano and Sergipe-Alagoas basins are shown in Figure 48, as well as small circles about the pole of rotation defined by Szatmari et al. (1984) for the Eastern Brazilian Microplate. The small circles were constructed to intercept the transfer faults, and it is clear that although there is a limited amount of coincidence between some small circles and portions of some of the transfer faults (in the Sergipe-Alagoas and central Tucano basins), the degree of coincidence decreases to the south. In spite of the facts that the known segments of transfer faults are relatively short, and that the faults have not been precisely synchronized (especially due to the scarce paleontological data available), it is reasonable to assume that the transfer faults were not caused by the rotation of a single rigid crustal block about a fixed pole, as proposed in the models that utilize the Eastern Brazilian Microplate, but rather that the transfer faults were created and controlled by a different mechanism. As to the nature of this mechanism, however, the question remains open. Further
Fig. 48 - Schematic representation of the distribution of normal and transfer faults in the Recôncavo, Tucano and Sergipe-Alagoas basins, and small circles traced about the pole of rotation of the Eastern Brazilian Microplate (see also Fig. 4).
attempts to solve the problem will depend on the existence of additional data, to clarify the relationship between the basins and the surrounding basement.

6.2 - POST-RIFT EVOLUTION

The final stage of the transformation of a rift system into a passive margin is reached when the continental crust is ruptured, and the opposing continental blocks are increasingly separated as new ocean floor is created along the rupture. This process, which continues until the present, started in the South Atlantic during the Aptian (Fig. 49), and the African and South American continents were fully separated during the Turonian, when generalized sea floor spreading became dominant in the equatorial region (Emery and Uchupi, 1984). The post-rift phase of development of a passive margin basin is characterized by tectonic activity mainly in the form of regional subsidence, triggered and maintained by a combination of cooling and sedimentary loading of the lithosphere.

THE APTIAN

The transition of the Sergipe-Alagoas Basin from a rift system to a passive margin started during the Aptian, when the basin was initially invaded by sea water, forming shallow inland seas. This stage is characterized by the widespread deposition of evaporites, associated with carbonates, shales, sandstones and conglomerates.
Fig. 49 - Age of ocean floor (basaltic Layer 2) in millions of years. Insert shows rates of opening for whole Atlantic Ocean and its two major parts (from Emery and Uchupi, 1984).
Sediments of this phase are found in all the South Atlantic basins (with the exception of the Recôncavo basin, which did not evolve past the initial rift phase), on both the Brazilian and the African side, and are consistently reported to be separated from those of the earlier rifting phase by an unconformity (Brink, 1974; Asmus, 1984; Brice et al., 1984; Emery and Uchupi, 1984; Reyre, 1984). Another feature common to all the basins is the intense mobilization of the evaporites, forming structures that range from large diapirs and ridges, to small pillows and faults affecting the overlying sediments. The distribution of the South Atlantic evaporitic basin (Fig. 35c) shows the coincidence of its limits with the Walvis-São Paulo/Torres ridge, to the south, and the juxtaposition of northeastern Brazil and Africa, in the Gulf of Guinea region, to the north. This transitional phase is considered to have lasted until the Albian, when sea-floor spreading breached the southern barrier, and sea water was allowed to invade and circulate freely along the area, thus marking the beginning of the drift phase in the coastal basins.

During the Aptian, when the clastic-evaporitic-carbonatic sediments of the Post-Rift I unit were deposited, the rifting period had already ceased, as evidenced by the fact that the rift phase faults do not offset the pre-Aptian unconformity. A look at the the Post-Rift I unit map (Fig. 20), however, shows that there are marked differences between the Southern and Central Domains, and the Northern Domain, and they will be examined separately.

In the Southern and Central Domains, it is possible to distinguish two separate areas, especially as a function of thickness of the
Post-Rift I unit, which is consistently thicker in the offshore area. The increase in thickness of the unit has led previous workers to define an "Aptian Hinge Line" (Fig. 50), which was associated with NW-SE oriented extension, and regional subsidence to the southeast (Falkenhein et al., 1983; Dauzacker et al., 1985; Lana, 1985; Guimarães, 1988). While it is clear that there is indeed an increase in the thickness of the Post-Rift I unit, the concept of an "Aptian Hinge Line" related to such extension cannot be upheld, especially because no evidence could be found to support the existence of a phase of NW-SE oriented extension. Rather, it was possible to verify that the faults formerly interpreted as the hinge line are a set of individual faults following the general direction of the normal and transfer faults in the rift.

The increase in thickness of the Post-Rift I unit in the present offshore area suggests that crustal extension and subsidence was prevalent in this area, an idea that is in good agreement with the results of a study of the subsidence in the Sergipe-Alagoas Basin presented by Kiang and Kowsmann (1986). Figure 51 shows the subsidence curves computed in that study with data from four wells in the basin, two onshore, and two offshore, as well as the crustal stretching factor $\beta$ obtained for each point. The $\beta$ values indicate that the offshore areas were subject to a higher degree of extension than the onshore areas. The subsidence after 115 Ma was interpreted by Kiang and Kowsmann (1986) as being post-rift, and the increase in the slope of the subsidence curves for the offshore wells, between 115 and 110 Ma, indicates a high rate of subsidence during
Fig. 50 - Position of the "Aptian Hinge Line" in the Sergipe-Alagoas Basin. In the northern part of the basin, the precise position of the hinge line has not been determined, and two alternative positions are indicated by the solid and broken fault lines (Modified from Lana, 1985; Guimarães, 1988).
Fig. 51 - Comparison between theoretical and backstripped subsidence curves computed by Kiang and Kowsmann (1986) for four wells in the Sergipe-Alagoas Basin. Wells (A) and (B) are onshore, wells (C) and (D) are offshore (see Fig. 5 for location). $b$ values were obtained by best fit, and indicate greater crustal attenuation in the offshore area. The portion of the curves to the left of the vertical lines is interpreted to be rift phase subsidence, and the portion to the right is the post-rift subsidence. Note high subsidence rate for the offshore area during the Aptian.
this period, which accounts for the increased thickness of the Aptian deposits. It is also interesting to note that the increase in slope is conspicuously absent in the curves for the onshore wells, reinforcing the idea that crustal extension and subsidence were highly emphasized in the present offshore area. In the same study, Kiang and Kowsmann (1986) presented a crustal thickness map (see section 5.7 - The Continental Crust), and the map, along with seismic, well and gravimetric data, was used to construct a schematic cross section along the Central Domain (Fig. 52), to verify the vertical correlation between the structures and sediment distribution interpreted in the present study, and the crustal behavior as presented by Kiang and Kowsmann (1986). It can be seen that there is a very good match between the points of crustal thinning and the structures in the basin -- the basin border itself, a major fault onshore, and the fault bounding the area of increased thickness of the Post-Rift I unit offshore, the latter coinciding with the point where the crust is dramatically thinned.

The Northern Domain presents a rather different scenario. The Post-Rift I unit is entirely absent from almost its entire onshore area, indicating the activity of the transfer faults separating high from low areas. The structural picture is characterized by the presence of a system of large faults striking N15E to N30E, which are virtually inexistent in the two other Domains. Although they are bounded, to the south, by the transfer faults, it was not possible to determine their relationship with the N-S trending faults, or in which way they affect the distribution of sediments of the rift
Fig. 52 - Schematic cross section in the Central Domain. Crustal thickness values were obtained from Kiang and Kowsmann (1986). The Post-Rift II unit is present but not visible on the right side of the section, since in this area it is only a condensed section, averaging less than 100 m in thickness. See Fig. 5 for location.
phase (the Rift unit). It is clear, however, that they were active before the deposition of Post-Rift I unit, as demonstrated by the way that they affect the isopach distribution, and by the configuration of reflections within the Post-Rift I unit.

Figure 53 is a composite seismic profile, running from onshore to offshore, across the area where the Post-Rift I unit is present in the Northern Domain. Even though the Rift unit was not mapped in this area, it is possible to see that it is cut by the NE trending faults, the faulted blocks being strongly tilted towards the continent. The Rift unit was also heavily eroded at the crest of one of the tilted blocks, and the longitudinal axis of the eroded area follows the same NE direction as the faults (see map in Fig. 20), indicating that the faulted blocks are tilted along the planes of the NE faults. As said before, the effect of these faults on the deposition of the Rift unit, if any, could not be established, but the relationship between the NE faults and the Post-Rift I unit can be understood. The key to this understanding is the area east of the eroded block crest (Fig. 53). Internal reflections in the Post-Rift I unit onlap the fault plane, and the unit gradually thins out upward along the fault plane, evidencing that the fault preceded the deposition. On the western side, it was not possible to verify the existence of a similar situation, that is, onlap against the top of the faulted blocks, but, in the onshore part of the profile, there is indication of a downlap pattern above the base of the Post-Rift I unit, which would indicate progradation from an easterly source, suggesting that the eroded block acted as source area for those sediments. The seismic character is further
Fig. 53 - Location map, interpreted and uninterpreted versions of onshore-offshore seismic profile in the Northern Domain. The Rift unit is faulted and tilted, and has been strongly eroded in the central area. The Post-Rift I unit, to the right, onlaps onto the fault plane, and, in the onshore area, it shows a downlap pattern above the top of the Rift unit (see Figure 54) (see Table I for key to stratigraphic symbols in the wells).
complicated by the presence of the evaporitic sequence of the Post-Rift I unit, deposited as the sea invaded from the south. The base of the Post-Rift I unit is not apparently offset by the faults, but, again, since it was not possible to map the Rift unit, it could not be determined if there is any reactivation of preexisting rift faults.

The crustal thickness map of Kiang and Kowsmann (1986) (Fig. 33) suggests that the continental crust in the Northern Domain also behaves differently from the other two Domains. The crustal thickness gradient expressed in the map is fairly homogeneous, and a schematic cross section across the Northern Domain (Fig. 54) does not show any sharp changes in crustal thickness associated with particular rift structures. It is not possible to identify a point where the crust might have been additionaly stretched during the rift phase, and this is probably the reason why the position of the "Aptian Hinge Line" in this area is controversial.

The contrast in subsiding behavior between the Central and Northern Domains is visible in Figure 23. The seismic profile runs across the transfer fault that separates the two domains, and there is a clear increase in the thickness of the Post-Rift I unit in the Central Domain, indicating a great amount of dip-slip activity in the fault during the Aptian.

A change in crustal behavior could possibly be associated with the change in the nature of the basement itself. As discussed before, the basement in the Northern Domain is composed of gneisses and granites, whereas in the Southern and Central Domains it is formed
Fig. 54 - Schematic cross section in the Northern Domain. Crustal thickness values were obtained from Klang and Kowsmann (1986). See Fig. 5 for location. Depth of basement to the right is not certain. Compare right side of the cross section with Figure 53.
by low grade schists, the overall distribution following the boundaries of the different zones of the Sergipano Folded Belt and the Pernambuco-Alagoas Massif. A tentative hypothesis is that the low metamorphic grade basement would be more easily stretched than the gneissic-granitic one, and the major transfer fault system developed between the two to accommodate the different rates of extension (as discussed before, the transfer faults may be speculatively associated with preexisting structures in the folded belt). Even if that is the case, it still does not explain the presence of the NE oriented faults. Several NE oriented surface lineaments, roughly parallel to the faults, were identified, using radar images, in the basement adjacent to the northern part of the Sergipe-Alagoas basin (Cunha, 1987) (Fig. 11), but other than the coincident orientation, there is no apparent relationship between the lineaments and the faults in the basin (it should also be kept in mind that the lineaments may not express geologic features, as previously observed). Any interpretation of the control of preexisting basement fabrics on this particular set of faults will certainly depend on the determination of both the relationship between the faults and the structures of the rifting phase, and the characteristics of the basement structural fabric itself.

The overall picture presented by the Post-Rift I unit, of an evaporitic sequence deposited above an unconformity not affected by rift-phase faults is similar to the situation as seen in other South Atlantic basins. Published seismic data from the Campos basin, in Brazil (Figuiredo, 1985) and the Cabinda basin, in Africa (Brice et
al., 1984), indicate that in these basins the base of the evaporitic sequence is only very slightly, if at all, affected by rift faults (Figs. 55, 56). In the Gabon basin, Brink (1974) presented schematic cross sections which indicate that the base of the evaporitic sequence is structured by rift faults (Fig. 57), but a later report by Reyre (1984) presented interpreted seismic profiles indicating otherwise, that the base of the evaporitic sequence is not structured by rift faults, in a situation similar to that of the Sergipe-Alagoas, Campos and Cabinda basins (Fig. 58).

DRIFT PHASE - ALBIAN TO PRESENT

- Basin Subsidence

From the Albian to the Present two characteristic types of sedimentation were prevalent. The first is essentially carbonatic, typically of a shallow platform-slope system, with subordinated fan-delta clastics (the Post-Rift II unit). The second type is essentially clastic, characterized by thick sequences of shales with interbedded sandstones, sediments being deposited in slope and deltaic systems, with associated platform carbonates (the Post-Rift III unit). The essentially carbonatic sediments are interpreted to be deposited in a shallow, but permanent, sea that was formed when oceanic waters gained free access to the area, before the onset of massive subsidence. Along the eastern Brazilian margin, the upper limit of the carbonatic sequence has been recognized to be
Fig. 55 - Seismic profile in the Campos Basin. The base of the evaporitic section is flat, not affected by rift faults (from Figueiredo, 1985).
Fig. 56 - Seismic profile from the Cabinda Basin. Similarly to the Campos Basin (Fig. 58), the base of the evaporitic sequence is flat, not affected by rift faults (from Brice et al., 1982).
Fig. 57 - Schematic cross section across the Gabon Basin, as presented by Brink (1974). Note that the base of the evaporitic section is indicated to be, to some extent, affected by rift faults.
Fig. 58 - Seismic profile across the Gabon Basin, as presented by Reyre (1984). The base of the evaporitic section is shown not to be affected by rift faults, in a style similar to the Campos and Cabinda basins (compare with Figures 55 and 56).
increasingly younger towards the north, the carbonates extending
from the Albian to the Cenomanian in the Santos and Campos basins,
from the Albian to the Turonian in the Espírito Santo basin, and from
the Albian to the Santonian in the Sergipe-Alagoas basin (Asmus,
1984; Emery and Uchupi, 1984), indicating that the coastal
subsidence was progressive from south to north.

In the Sergipe-Alagoas Basin, the sedimentation of the Post-Rift
II and Post-Rift III units was preceded by an erosional period, that
created an unconformity visible in seismic profiles in different
areas of the basin (Figs. 26, 27). This unconformity indicates that
the change from a restricted marine environment (represented by the
Post-Rift I unit) to open marine conditions was not gradual, but
rather happened in individualized tectonic stages. Such tectonic
differentiation has not been reported in other basins to the south,
which could indicate that the Sergipe-Alagoas Basin went through an
additional evolutionary step before the final consolidation of sea
floor spreading. Reyre (1984) reported the presence of an
unconformity separating Upper from Lower Albian strata in the
Lower Congo-Gabon basin, and he associated this unconformity with
the final decoupling between Brazil and Africa. The correlation
between the unconformities in the African and the Brazilian side is
uncertain, because no Albian sediments have been found below the
unconformity in the Sergipe-Alagoas Basin, and also because the
paleontological dating available in the basin are not detailed enough
to restrict the age of the Albian sediments to Late Albian. At this
point, all that can be done is to suggest the possibility of a
correlation, based on the assumption that the development of the opposing continental margins, although following the same general sequence of events through time, could be affected by local characteristics or events in specific segments of the margin (e.g., on a purely speculative basis, it could be suggested that eventual Lower Albian sediments in the Sergipe-Alagoas Basin were completely eroded, or even that they were not deposited at all).

As discussed before, the Post-Rift II and Post-Rift III units reach great thickness in the Southern and Central Domains, but are absent in the Northern Domain, except for a thin cover of Post-Rift III unit sediments. This distribution is undoubtfully associated with the differences in basement behavior that previously defined the geometry and development of the initial rift, and thus controlled the later evolution of the basin. The stratigraphic information from the wells was utilized to date seismic stratigraphic sequences identified in the Post-Rift III unit, and it was then possible to verify that the Late Cretaceous and Paleocene sequences get progressively thinner to the north, and eventually pinch out completely before reaching the transfer fault zone (Fig. 23), thus suggesting increased subsidence towards the south. As discussed in the preceding sections, it is interpreted that the continental crust underwent a lesser amount of extension and thinning in the Northern Domain than in the others; and, therefore, was substantially less affected by the thermal and loading processes that induced and maintained subsidence in the rest of the basin. The seismic profile shown in Figure 59 runs across the transfer fault, and it is clearly
Fig. 59 - Offshore seismic profile in the Central and Northern Domains (see Fig. 5 for location), across the main transfer fault.
separated in two distinct areas. Even though the position of the basement could not be determined, the change in water depth and the position of stratigraphic units on both sides of the fault are interpreted to illustrate the different subsiding behavior in different Domains.

Sediments of both the Post-rift II and Post-rift III units have been partially eroded onshore, and the limit of occurrence of the marine portion of the Post-Rift III unit (the Pia)abu)u Formation) is roughly parallel to the coast line (Figs. 29, 30, 31, 32). These features are interpreted to represent the effects of crustal flexure, and lateral heat flow from the center towards the sides of the basin, causing uplift and erosion along the flanking regions of the basin (Steckler and Watts, 1982). Structures in the post-rift units are mainly those caused by the gravity-induced mobilization of evaporites (Kehle, 1972; Schaller and Dauzacker, 1986), which create pillows, small to large faults, and piercing salt domes and ridges (Figs. 22, 25, 26).

- Relation with the ocean floor

It is interesting to note that if we follow the same NE direction of the transfer fault system, it coincides with the southern border of the Pernambuco Plateau (Fig. 60). The Pernambuco Plateau is a shallow submarine platform off the coast of northeastern Brazil, where sedimentation and erosion over a basement high have alternated since the Late Cretaceous (Kowsmann and Costa, 1976;
Fig. 60 - Physiographic map of the ocean floor adjacent to northeastern Brazil. (A) Paraiba Seamounts; (B) Pernambuco Plateau; (C) Sergipe-Alagoas Basin; (D) Pernambuco-Paraiba Basin; (1) Fernando de Noronha Lineament and Fracture Zone; (2) Paraiba Lineament; (3) Pernambuco Lineament (offshore); (4) Maceió Lineament; (5) Sergipe Lineament; (6) Pernambuco Lineament (onshore); (7) transfer fault system between the Central and Northern Domains in the Sergipe-Alagoas Basin. (modified from Gorini and Carvalho, 1984). There is no evidence that the onshore Pernambuco Lineament (6) is tectonically related to the offshore lineament of the same name (3).
Guazelli et al., 1977). Fainstein and Milliman (1979) suggested that the sediments were underlain by continental crust, and this interpretation was apparently confirmed by the recovery of Precambrian and Paleozoic quartz-monzonites and biotite gneisses from the escarpment at the northern border of the Plateau (Emery and Uchupi, 1984). The onshore area adjacent to the Pernambuco Plateau is the Pernambuco-Alagoas Massif, which is itself the basement of the northern part of the basin, suggesting that the Pernambuco Plateau and the Northern Domain of the basin belong to the same crustal block, bounded on the north by the Pernambuco Lineament. The overall picture suggests that this crustal block remained essentially stable since the Cretaceous.

A relationship between structures in the Sergipe-Alagoas Basin, and those in the oceanic floor has not been definitely established. Figure 60 shows a physiographic map of the ocean floor adjacent to the northeastern South American margin. To the south of the Fernando de Noronha Lineament and Fracture Zone there are numerous seamounts, collectively known as the "Paraiba Seamounts", of uncertain tectonic origin. The east-west orientation of some of the seamounts has led to the identification of two sea floor lineaments - the Paraiba Lineament and the Pernambuco Lineament. In spite of the fact that the Pernambuco Lineament, on the ocean floor, is aligned with the major onshore fault zone also known as Pernambuco Lineament, Carvalho and Franciscon (1981) have suggested that the seamounts are oriented northwest-southeast, rather than east-west, questioning the validity of the individualization of the
submarine lineaments.

Further south is the Maceió Lineament, a continuous submarine mountain chain, covered by 540 to 1,000 m of acoustically transparent sediments, contrasting with the highly reflective sediments on the adjacent sea floor, both to the north and to the south of the lineament (Gorini and Carvalho, 1984). The Maceió Lineament constitutes the southern limit of the Pernambuco Abyssal Plain. Asmus and Carvalho (1978) identified the Maceió lineament as a fracture zone extending into the Sergipe-Alagoas continental shelf, and this extension coincides with the position of the transfer fault system mapped between the Central and Southern Domains in the basin (Fig. 60). Asmus and Carvalho (1978) also proposed that vertical displacement along the fracture zone caused uplift and erosion of the northern part of the Sergipe-Alagoas and the Pernambuco-Paraiba basins, from the Albian to the Santonian. As we have previously discussed, the transfer fault system in the basin has indeed had a great amount of vertical activity, but we have been able to verify that the major activity happened during the Aptian. Since the Albian Post-Rift II unit is not significantly offset by the fault (see, for example, Figure 23), the conclusion is that the relatively thinner post-rift sedimentation north of the transfer fault is due to less subsidence in this area, rather than being directly related to contemporaneous activity in the fault. The eastward continuation of the Maceió Lineament into the central ocean is not known, and the existing data do not show any connection between the lineament and lateral shifts in the mid ocean ridge (Gorini and Carvalho, 1984).
The Sergipe Lineament (Fig. 60) is constituted by a series of seamounts and buried basement highs. Its extension into the central ocean is not known, but there is no apparent connection between the lineament and lateral shifts in the mid ocean ridge (Gorini and Carvalho, 1984). Guimarães (1988), observing the overall orientation of the Sergipe Lineament, suggested that it is connected with a transfer fault in the Sergipe-Alagoas basin, which was identified, in this study, as being the fault separating the Southern from the Central Domain in the basin. The data available, however, are not sufficient to verify the validity of this assumption.
7. CONCLUDING REMARKS

The evolution of the Sergipe-Alagoas basin can be summarized as follows: the basin originated as a rift bounded by N-S oriented normal faults, during the Neocomian. The rift formed in response to crustal extension oriented obliquely to the direction of propagation of the rift. Transfer faults developed to accommodate both the oblique extension, and the different rates of attenuation of the heterogeneous continental crust. Thus the basin was divided into separate Domains. This crustal segmentation, created during the rift phase, will be the principal controlling factor for the later evolution of the basin. During the Aptian, after the end of the rifting phase, vertical displacement occurred along the transfer faults, to accommodate the contrasting rates of subsidence between the Southern and Central Domains (with highly attenuated crust), and the Northern Domain (with less attenuated crust). This led to great differences in sediment thickness on each side of the faults. The deposition of large amounts of evaporites during the Aptian marks the initial marine incursions in the basin. From the Albian to the Santonian, the basin was covered by a shallow but permanent sea. Great thickness of carbonates were stacked on high areas, whereas in the distal portions of the basin only a thin, condensed section was deposited. The subsidence in the Northern Domain was still considerably less than in the other two domains, but the difference was accommodated by a basinwide tilting to the south, rather than by movement along the transfer faults. Towards the end of the
Cretaceous, during the Campanian and Maastrichtian, open oceanic conditions were fully installed, and a prograding clastic wedge started to be deposited. The Northern Domain remained an essentially stable area through the rest of the evolution of the basin, this stability determined by the same crustal configuration that supports the Pernambuco Plateau.

This is an apparently simple rendition of the evolution of the basin, but beneath the apparent simplicity there are a number of complex problems to be solved: the influence of structures of the Sergipano Folded Belt on the structural framework of the basin; the existence of crustal detachment surfaces and their geometry; the development of the NE oriented normal faults in the Northern Domain; the precise timing of initiation of sea floor spreading; a detailed stratigraphic correlation with the Gabon basin, especially around the Aptian-Albian boundary. These are some of the key issues that will have to be addressed in any attempt for a better understanding of the evolution of the basin. Further analysis of these problems, however, will depend on the existence of appropriate data, such as good quality deep seismic profiles, to image deeper horizons in the basin, eventual discontinuities within the crust, as well as the continental-oceanic crust boundary, regional seismic profiles in the basement around the basins in the region, and a considerable refinement of the paleontological information.

In spite of being one of the more explored basins in Brazil, it is clear that there is much yet to be learned about the Sergipe-Alagoas basin. Hopefully, this study will contribute to the identification of
future research objectives, and will bring new insights for the evaluation of daily exploration problems.
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