A GEOLOGICAL AND GEOPHYSICAL STUDY OF

THE SERGIPE-ALAGOAS BASIN

A Thesis

by

BRADLEY MELTON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2008

Major Subject: Geophysics

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Approved by:

Chair of Committee,	Philip Rabinowitz
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ABSTRACT

A Geological and Geophysical Study of the Sergipe-Alagoas Basin. (May 2008)

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Extensional stresses caused Africa and South America to break up about 130 Million Years. When Africa rifted away from South America, a large onshore triple junction began at about 13° S and propagated northward. This triple junction failed and created the Reconcavo-Tucano-Jupato rift (R-T-J), located in northeastern Brazil (north of Salvador). The extensional stress that created this rift was caused by a change in the force acting on the plate during the Aptian.

A series of offshore rifts also opened at this time, adjacent to the R-T-J rift; this series of basins are referred to as Jacuipe, Sergipe, and Alagoas (J-S-A). The basins are separated by bathymetric highs to the north and the south of the Sergipe-Alagoas basin. The Sergipe-Alagoas basin has a Bouguer gravity anomalies more negative than -35 mGal, and the other two basins have values more negative than -100 mGal; the total magnetic intensity is also about 60-80 nT higher in the Sergipe-Alagoas basin than the surrounding basins. The gravity and magnetic values in the Sergipe-Alagoas basin, when compared to the Jacuipe and the Sergipe-Alagoas basins, indicate that the depositional history and/or the formation of the Sergipe-Alagoas basin is different from the other two basins.

This study was done by analyzing the gravity and magnetic anolamies in the region, and comparing these anomalies to the stratigraphy of the basin. This research has allowed the stratigraphy and structures of the Sergipe-Alagoas basin to be better understood—the location of the Sergipe fracture zone will also be outlined. This study provides a comprehensive view of the Sergipe-Alagoas basin and outlines a method for using Gravity and Magnetics to better understand the stratigraphy and structure of the Sergipe-Alagoas basin.

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INTRODUCTION

The geology of the Northeastern coast of Brazil has been extensively studied and reported in the literature (Destro et al. 2003, Mohriak et al. 2000, Campos et. al 1980, Ponte and Asmus 1976, Leyden 1976); figure 1. The continental margin of Brazil was established in the Wealdian Rectivation (110-140 ma), a tectonic episode that was characterized by intense basaltic magmatism; another episode of magmatism occurred 50-80 ma (Campos et al. 1980). The sedimentary basins of NE Brazil are characterized by depocenters separated by basement highs and transfer faults; these features are associated with the opening of a rift system in the NW direction, which are oblique to the general north-south trend of the master faults (Milani and Davidson 1988). The basin fill in the Northeastern portion of Brazil is of Jurrasic through recent age, and consists of a lower clastic marine sequence, a middle evaporitic sequence, and an upper clastic and open marine sequence (Ponte and Asmus 1976).

Though large scale studies have been done for the offshore regions (Campos 1980, Mascle 1976) little has been published with respect to the offshore of Northeastern Brazil. Campos and Ponte (1980) and Mascle (1976) have both discussed the geology of the Brazilian margin, but have not written, in detail, about the Northeastern portion of the continent.

This thesis follows the style of Geophysics.

The faults along the Brazilian coastline tend to parallel to the coastal regions. However, in NE Brazil the faults are oblique to the coastline (Figure 1). The faults are normal and tens of kilometers in length—the faults have variable throws with a maximum of 3.0-5.0 m (Ponte and Asmus 1976). Regional structural highs are determined by west and northwest dipping faults either on the outer edge of the basins or in the interior of the basins. The outer edge faults form barriers to sediments and the interior faults separate the grabens that form the sub-basins. The onshore basin (Reconcavo, Tucano, Jatoba) are bounded by faults that extend to the offshore basins (Jacuipe, Sergipe-Alagoas) respectively (Ussami et al., 1986). This suggests that these onshore and offshore basins formed during the same time period. The onshore basins are filled with 4-5 km of post rift sedimentary material; most of the sedimentary material is alluvial fan deposits. The sediments have been used to define the geological history of the area.

The coastal margin in this area has undergone three major stages of tectonic evolution; a continental interval, an evaporite interval, and a marine interval (Mohriak and Cainelli, 1998a).

Most of this offshore information has been obtained by seismic reflection methods. However, the seismic resolution below the offshore basins (the Jacuipe and the Sergipe-Alagoas) (figure 1) is not understood because seismic resolution below carbonates and salt is usually extremely low.

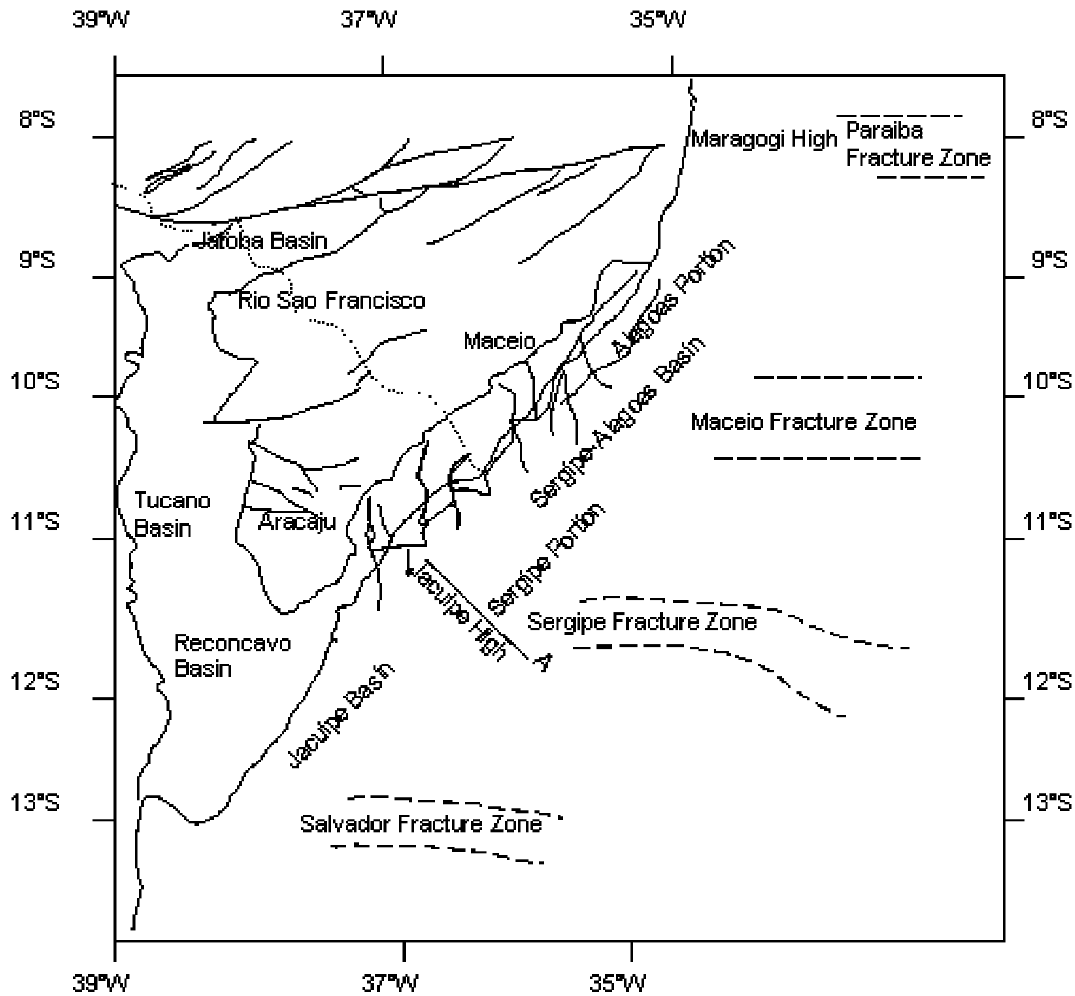

Fig. 1. Composite figure showing the locations of the basins of interest. The Reconcavo-Tucano-Jatoba rift and Jacuipe-Sergipe-Alagoas basins are outlined. The majority of the faults along the coastline are oblique to the coastline (Modified from Mohriak et al. 1998). The fracture zone locations offer an idea of the borders of the basins.

In this study the geology of NE Brazil will be summarized in great detail. Also in this study, we will use the gravity and magnetic anomalies to put constraints on the crustal structures along the coastline. Significant free-air gravity anomalies, in excess of ± 75 mgal are observed bordering the continental margin of NE Brazil and are associated with the offshore basins (Rabinowitz and Cochran 1978). The Sergipe portion of the Sergipe-Alagoas basin has different free air gravity values than the Alagoas and the Jacuipe Basin. These gravity anomalies (corresponding to the Sergipe-Alagoas and Jacuipe basins) along the offshore coastline of NE Brazil are utilized in this study to understand the available, but sparse, seismic data. The magnetic anomalies (Rabinowitz and LeBreque 1979), and published geologic information such as drilling results, well logs, and geologic mapping (Mohriak 1995) have also been used to aid in the interpretation. 3-D geologic models are calculated and used to interpret the offshore anomalies, and help to determine the crustal structure of the basins.

PREVIOUS GEOPHYSICAL STUDIES OF NE BRAZIL

Summerhayes et al. (1976) published the results of a reconnaissance geophysical study of NE Brazil to determine the structure and morphology of the region; he described many gravity and magnetic anomalies that resemble deeply buried dikes of basalt. Summerhayes concluded that the possible deep structure of the seaward part of the Sergipe-Alagoas basin is much like the magnetic anomaly off the eastern coast of the U.S.A, but is somewhat narrower (50 km as against 75-130 km) and more subdued than its North American counterpart. The east coast magnetic anomaly (ECMA) is characterized by a sharp magnetic gradient landward, which decreases in intensity seaward across the transition from a thick oceanic crust to an oceanic crust of normal thickness (Holbrook and Kelemen 1993); this same trend is recognized across the Sergipe-Alagaos and Jacuipe basins. Summerhayes proposes that the anomaly is caused by a deeply buried, nearly continuous, narrow body of relatively uniform magnetization—probably a dike of oceanic basalt emplaced during early fracturing of the South Atlantic. A buried dike or ridge could have served as a dam to trap land-derived sediment during the early history of the South Atlantic, and could have served to restrict oceanic circulation which led to the deposition of evaporates in the Aptian.

Ussami et al. (1986) suggests that all of the basins in the NE region were formed by extension during the rifting of the Atlantic break-up. He suggests that upper crustal extension affected both the onshore and offshore basins, but extension at the deeper lithospheric levels, including the lower crust, would have been concentrated beneath the offshore basins; this relationship is hypothesized due to a large amount of thermal subsidence in the offshore basins. According to Ussami, gravity modeling over the onshore basins, the Tucano basin in particular, shows local negative anomalies. The anomalies indicate that large amounts of sediment are filling the basin. In contrast, modeling over the Jacuipe basin suggests that crustal thinning and upwarp has taken place beneath the offshore basin. To permit coupled differential stretching in the lithosphere, the offshore and onshore regions must have been connected by a low angle crustal detachment surface.

Mohriak et al. (1998) created gravity models from the Sao Francisco craton towards the Sergipe-Alagoas basins using seismic information obtained from Petrobras. He suggests that the crustal architecture of the basins indicate a shifting of the extension axis from the continent (in the late Jurassic/early Cretaceous) towards the offshore region in the Aptian. Mohriak also suggests that Moho depth is in excess of 35 km in the craton, and rises slightly eastward on the Tucano basin depocenter and then rises rapidly beneath the Sergipe-Alagoas basin near the coastline. The models show a general crustal and sediment structure from the coastline to the deep portion of the basins. A free air gravity and magnetic anomaly map of the South America region is shown in figure 2 (Rabinowitz and Cochran, 1978).

Karner et al. (1992), as a result of kinetic modeling constrained by Bouguer and free-air anomaly maps, suggest that the offshore basins (Sergipe-Alagoas and Jacuipe) are genetically linked in space and time. Karner et al. (1992) also hypothesizes that the ocean/continent boundary formed to the east of the Sergipe-Alagoas basin because of non-uniform extension with depth beneath the basins. If extension with depth was uniform beneath the basins, he hypothesizes that the ocean/continent boundary would have formed in the Tucano basin.

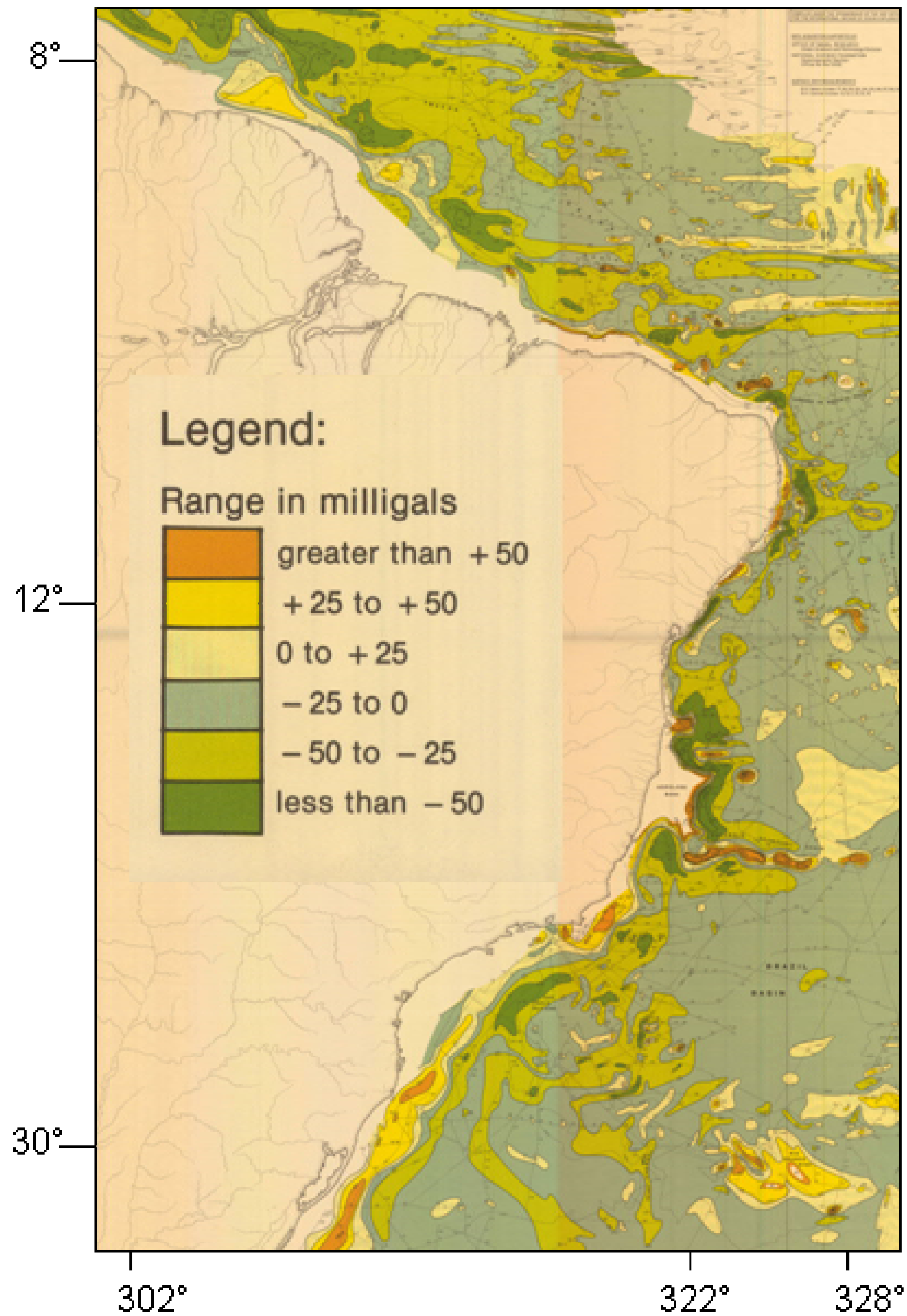

Fig. 2. Free air gravity map of Brazil (modified from Rabinowitz and Cochran 1978).

GEOLOGY

EVOLUTION OF THE SOUTH ATLANTIC

The Breakup of Gondwana started during the Valangenian in the southern portion of the South American Plate and propagated northward (Rabinowitz and LaBreque, 1979). Rifting led to the separation of South America and Africa and created compression in the northern portion of Brazil. Next, continental crust and upper mantle thinning took place due to asthenospheric uplift and lithospheric stretching (Mohriak and Cainelli, 1998a). This stage coincides with large faults affecting the continental crust, extrusion of continental flood basalts in the southern basins, and the formation of half grabens. By the end of the episode, lithospheric extension increased and large faults rotated the rift blocks and sedimentary layers that were previously deposited. By comparing gravity and magnetic anomalies on both sides of the southern South Atlantic, Rabinowitz and LaBrecque (1979) conclude that the margins have linear magnetic anomalies that can be modeled as edge effect anomalies separating oceanic from continental basement; gradients in the isostatic gravity anomaly are also coincident with these magnetic anomalies.

Toward the end of the rifting episodes steady state sea floor spreading commenced. Continental and oceanic volcanism, reactivation of large faults, and erosion of the rift blocks evidenced by a regional unconformity occurred during this time period (that leveled topography). This event is often referred as the Breakup Unconformity because it separates the continental from transitional to marine environments of deposition. Above this unconformity and below the evaporite layer, some basins register a substantial thickness of Aptian siliclastic and carbonate rocks. This sequence also marks the first marine incursion and could contain hydrocarbon source rocks. Sedimentation was predominantly carbonitic in the Aptian, before the salt deposition (Mohriak, 1998a).

REGIONAL BRAZILIAN GEOLOGY

Brazil contains about 32 main basins with the sedimentary area totaling 4.5 million sq. km. (Mello et al., 1990). The Brazilian coast is divided into two main regions; the north-northeastern coast shelf and the east-southeastern coastal shelf (Ponte and Asmus, 1976) (Figure 3).

The east-southeastern coastal shelf extends from the Pelatos to the Recife-Joao Pessoa Basin. The tectonics of this region are the result of tensional stress in the Late Jurassic-Early Cretaceous that parallel the basement. The basin fill of Upper Jurassic through recent age consists of a lower clastic non-marine sequence, a middle evaporitic sequence, and an upper clastic paralic and open marine sequence (Ponte and Asmus, 1976).

The Northern Province extends from the Potiguar Basin to the Amazon Submarine Basin. This region displays both tensional and compressional tectonics of Upper Jurassic to Upper Cretaceous in age that parallel or cut transversely to basin alignment (Damuth, 1976). Figure 3 shows the faults in the eastern-southeastern region and the faults in the northern-northeastern region.

The Sergipe-Alagoas and the Jacuipe basin are located along the east-southeastern portion of the coastline. This portion of the coastline is long and narrow (the shelf is about 980 km long and varies from about 11 to 100 km in width). The topographic surface is comprised of many volcanic features, calcareous algae, and stone reefs (Asmus, 1980).

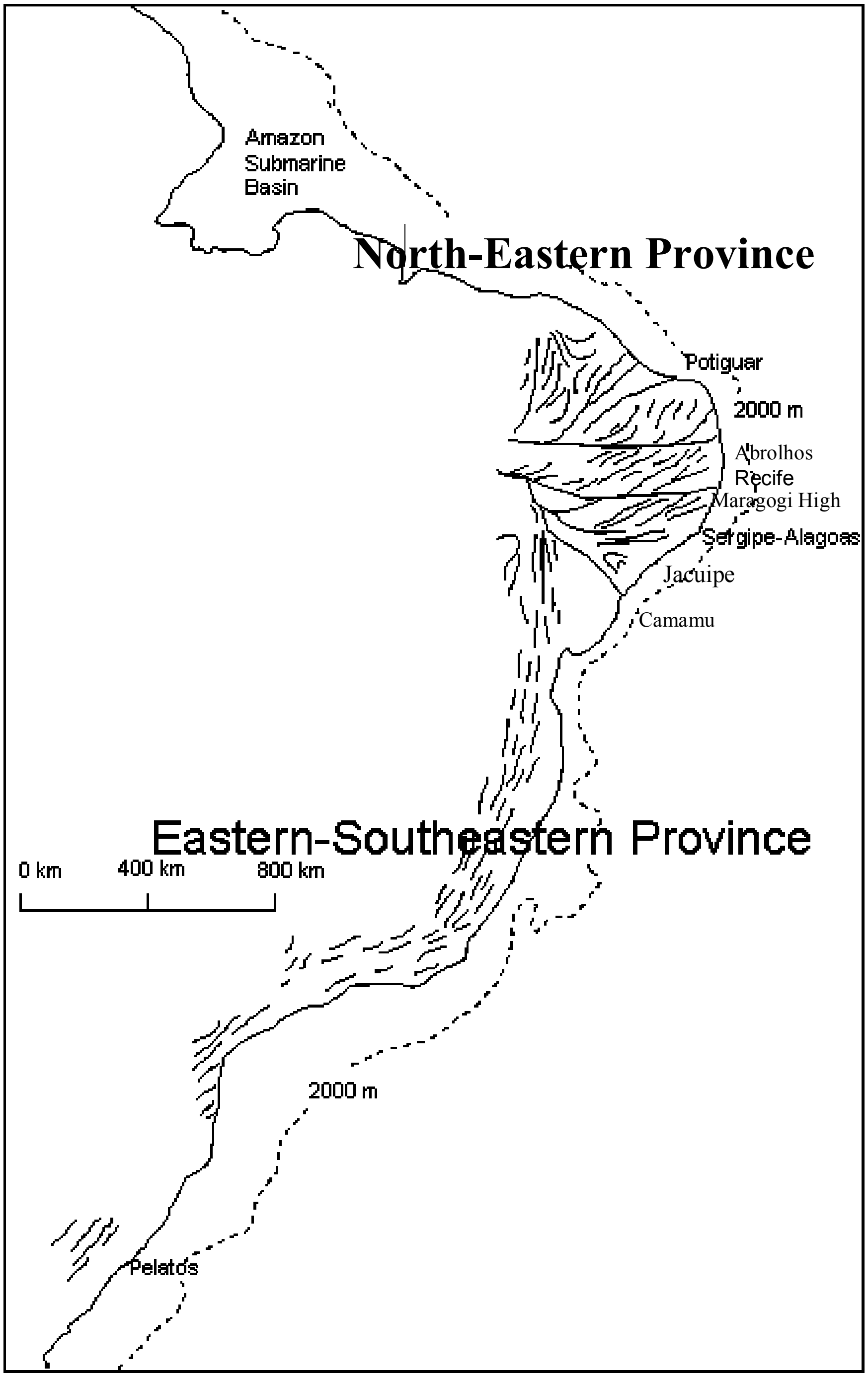

Fig. 3. Brazilian province map. Amazon-Maranhao continental shelf, north-northeastern coast shelf, and the east-southeastern coastlines of Brazil. (Modified from Asmus, 1980).

The tectonic structure of the continental margin in this region was first established during the Wealdian Reactivation (a large igneous event) around 110-140 Ma; another large igneous event took place around 50-80 Ma in the Early Tertiary (Asmus, 1980). Several submarine seamounts are seen adjacent to the Abrolhos Volcanic complex near Sergipe-Alagoas basins. These features trend toward the Sergipe-Alagoas basins, and could be related to features found around these basins (Mohriak et al., 1998).

Rift depocenters are located on the Brazilian platform (mainly on the southern to eastern part of the margin). Salt tectonics is one of the most important controls on the evolution of the offshore basins. The amount of salt in the offshore basins decreases northward, and the basins become mainly dominated by volcanic plugs. The rift tectonics are mostly synthetic faults; SDR wedges were created by the post rift volcanism (Guimaraes, 1988).

CONTINENTAL BASIN GEOLOGY OF NE BRAZIL

Three main basins are located onshore from the offshore Sergipe-Alagoas and Jacuipe basins; the Reconcavo, Tucano, and Jatoba basins (Figure 1). The Reconcavo Complex consists of a series of half-grabens formed throughout the Reconcavo, Tucano and Jatoba basins. The basins are located between latitude 13° and 8° 30’ S. These three basins, discussed below, are similar in makeup, and were formed from the arm of a failed triple junction (Silva et al., 1998).

The Reconcavo basin (Figure 4) is bounded by the Salvador Fault on the east and the Margopipe Fault on the west; the basin is bounded on the north by the Apora high. 6000 m of Upper Jurassic to Lower Cretaceous sedimentary material bounds the basin to the north and south (Figueiredo, 1994). The sediment overlies Archean granulites and slightly metamorphosed Proterozoic rocks. The basin contains a large number of faults, mainly due to differing rates of crustal stretching during rifting. Two main sedimentary sequences outline the basin; a pre-rift sequence composed of an arid alluvial fan system and a post-rift sequence composed of alluvial, fluvial, and deltaic lacustrine sediments (which represent the infilling a lake basin) (Figueiredo, 1994).

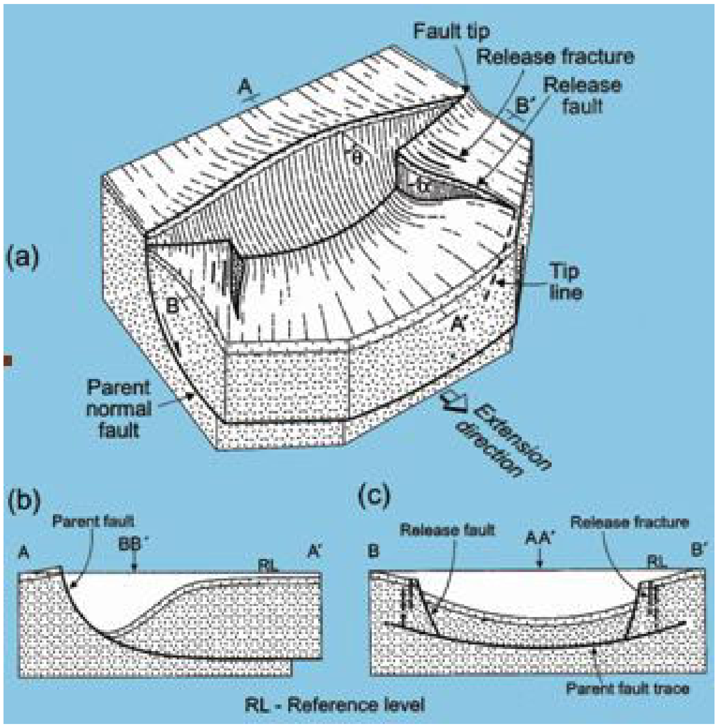

Fig. 4. The structural makeup of the Reconcavo basin (Destro, 2003).

The Tucano basin is approximately 100 km wide, and forms an asymmetric half graben trending N-S. The basin is filled with non-marine sediment, late Jurassic to Aptian in age (Karner et al., 1992). The maximum rift sediments (of about 10-12 km) occur in the Northern Tucano basin and the western Jatoba basin, and are associated with a free air gravity anomaly of about -120mgal. No significant sediment accumulation occurred in the region after the Aptian; Karner (1992) suggests that the post rift phase of sediments was never deposited, and therefore subsidence in the Tucano basin is limited to the period over which extension of the lithosphere occurred. Karner believes that the lack of post-rift sediments have thermal and mechanical implications for the reaction of the lithosphere with extensional forces because lithospheric extension is usually proceeded by a phase of post-rift sedimentation with a cumulative thickness approximately equal to that of the rift section (McKenzie, 1978). Karner believes that since significant post rift subsidence is engendered by lithospheric mantle extension, its absence can be interpreted as extension limited to the crust. An intracrustal detachment is required to disconnect the crust from the lithospheric mantle mechanically. Another explanation of the lack of post Aptian sediments could be small rates of extension that allow the lithosphere to cool during rifting; Karner diffutes this explanation because forward modeling demonstrated that finite rifting rates over a 20-25 m.a. period are not enough to cool the lithosphere to a point where post rift subsidence fails to develop.

ONSHORE OIL EXPLORATION

The Reconcavo sub-basin is in the mature stage of exploration. The Tucano sub-basin has been is lightly explored, but has a thick sedimentary section, similar to Reconcavo, with possible source rock. The Jatoba basin is a relatively unexplored, shallow basin (less than 3,000 m of sediment); (Van de Ven et al., 1989).

Regional shear components resulted in complex faulting in the Reconcavo basin following deformation of organic rich lacustrine shales in early Neocomian (Guthrie et al., 1996). Hydrocarbon migration into Jurassic Sergi sandstones in adjacent fault blocks by the end of Candeias deposition resulted from high thermal gradients, (2° F/100 ft) due to thin crust. Continued continental clastic deposition through the Aptian resulted in Ilhas shale diapirism with subsequent trapping opportunities. In the late Aptian, major continental separation shifted to the Salvador-Recife transform fault and the Reconcavo Rift system was abandoned (Mello et al. 1988).

OFFSHORE BASIN GEOLOGY

The offshore basins (J-S-A) are characterized by transfer faults and about five relatively thin layers of sediment. Salt diapirs exist close to the coastline, in a water depth of about 200 m, and are less prevalent in the deep water areas. The offshore regions contain several volcanic mounds and plugs which extend along approximately 15° S latitude off of the coast (Leyden, 1976).

Differing stretching rates between the basins were accommodated by transfer faults trending N-W or E-W. This phase started when the stretching and rifting of the continental crust ceased with the inception of the oceanic crust (Mohriak et al., 2000). Listric growth faults were created by the salt in evacuation zones, sub-basins surrounded by salt domes, salt walls, and thrust faults.

SERGIPE-ALAGOAS GEOLOGY

The Sergipe-Alagoas basin is located offshore Brazil between latitude 9° and 11° 30’ S. The Sergipe-Alagoas basin has an approximate area of 26,000 km^2 offshore and onshore, and extends offshore to a water depth of about 1 km (Figure 1). Core samples taken from the Sergipe-Alagoas basin reveal that the basement in the Sergipe part of the basin is mostly composed of schist, quartzite and marble; the Alagoas portion of the basement is mostly gneiss, migmatite and granite (Guimaraes, 1988).

During the rift sequence, alluvial fan deposits and fluvial-deltaic sands were deposited in the Sergipe-Alagoas basin (Figure 5). After this event, a small retrogradation occurred and oceanic sediment was deposited in the system. During the Albian, the rifting reactivated and a progradation occurred, leading to renewed alluvial fan deposition. During the last episode, a large transgression took place and deep water sediments dominated the system.

The southern limit of the Sergipe-Alagoas basin is the Jacuipe High; the northern limit is the Maragogi High (Figure 1). The sedimentary deposits in these basins can be divided into rift phase and drift phase (Mohriak, 1998). The rift phase is characterized by down-stepping synthetic faults that trend NE or N-S and are sometimes crossed by antithetic faults; the system creates a network of half graben structures.

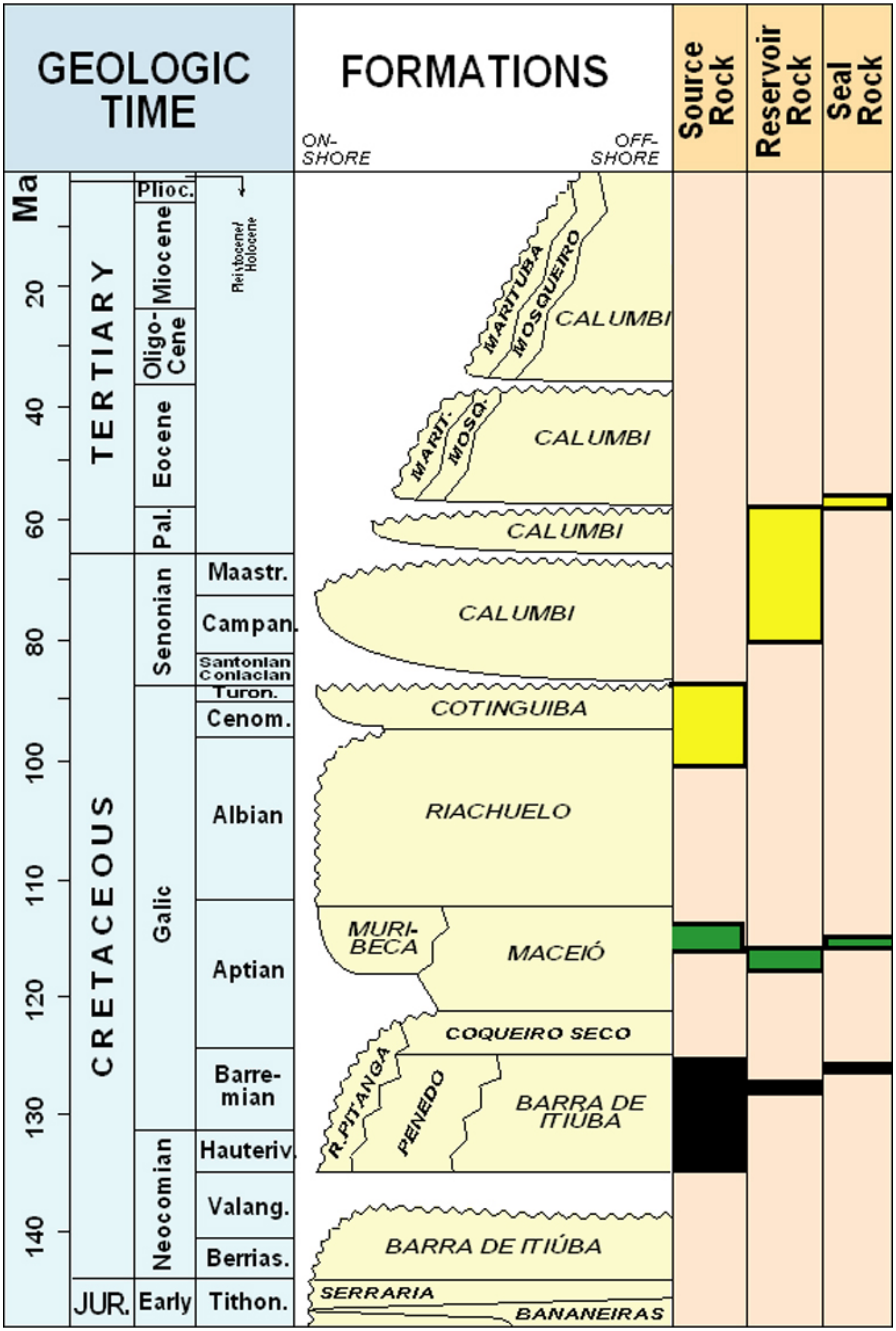

Fig. 5. Straigraphic column of the Sergipe-Alagoas basin (Modified from Feiji 1994).

There are two major fault systems present in the Sergipe-Alagoas basin; a N to NNE-trending fault system and an ENE-trending fault system (Figure 1). The N to NNE-trending fault system developed during the Neocomian rift phase, and is mostly a listric fault system with growth of strata towards the fault plane. The ENE-trending faults are strike slip faults that connect the early rift stage N to NNE-trending fault systems (Guimaraes, 1988). Salt tectonics and growth faults begin developing during the Aptian in the same style as the N to NNE and ENE-trending fault systems.

The same type of low angle detachment faults seen in the Reconcavo basin (figure 4) are recognized in the Sergipe-Alagoas basin; these faults are related to rifting. The Neocomian strata and the basement material in the hanging wall of the detachment surfaces are tilted westward in a half graben configuration. This configuration suggests that the hanging wall rotated during rifting along the detachment surface (Guimaraes, 1988).

The Sergipe-Alagoas basin can be broken up into two major areas of structural development; the Aracaju high and the Sao Francisco (Mosqueiro) Low (Figure 6). These two areas are separated by the Aptian hinge line (AHL). The AHL is a major tectonic hinge zone that consists of a series of short segment, en-echelon blocks. The blocks are sub parallel to the Brazilian margin, and demarcate the western limit of

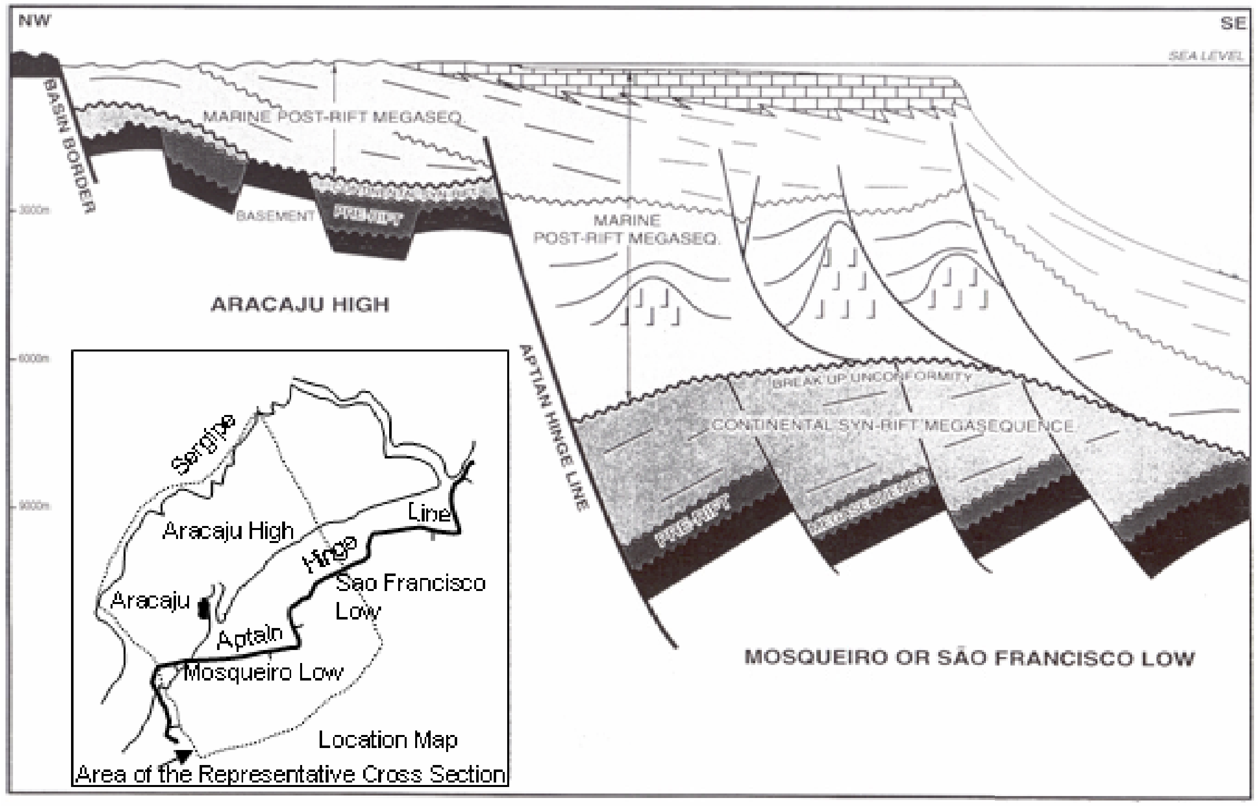

Fig. 6. Sergipe –Alagoas basin, dip oriented. This figure displays the two major areas of the basin and the Aptian hinge line. Also shows the low angle detachment faults in the Mosqueiro Low (Modified from Mohriak).

significant continental extension (Karner, 1992). The Aptian hinge line is responsible for the distribution of salt related structures in the basin (Guimaraes, 1988).

Most offshore portion of the Sergipe-Alagoas basin, that lies east of the AHL, is referred to as the Mosqueiro Low. The Mosqueiro low has about 10 km of sediment above the pre-rift sequence in the downthrown block of the AHL. Salt tectonics strongly influence sedimentation in the platform by creating depocenters for the sediments. Volcanic mound-like features and igneous plugs are found past a water depth of about 200 m (Leyden, 1976).

LOWER CREATACIOUS UNCONFORMITY

The uppermost portion of the Sergipe-Alagoas basin is referred to as the Aracaju high. The Aracaju High is located at the mouth of the Sao Francisco River (Figure 6). This High marks a change in the Sergipe Basin and is related to a Lower Cretaceous unconformity. Below the conformity, Carboniferous to Lower Cretaceous beds are nonmarine; Lower Cretaceous to Tertiary beds are dominantly marine. Preceding the Unconformity, Intense Normal Faulting tectonic activity created uplift and erosion, exposing Precambrian rocks in the area of North Aracaju. During this time, in adjacent grabens, thick wedges of syntectonic conglomerates were deposited over older sediments (Silva et al., 1998). The Irregularities on this surface were infilled by the Carmopolis conglomerate and coarse sandstone member of the Muribeca Formation. The Ibura

Member evaporates, also of the Carmopolis Formation, also covered areas where the basement was still exposed (Mohriak, 1995).

STRATIGRAPHY

Metamorphic rocks of Precambrian age constitute the floor of the Mesozoic basin, with remnants of Carboniferous Batinga and Permian Aracare sedimentary rocks preserved mainly in the North Eastern part of the studied area (Cainelli, 1992). In the Late Jurassic or Early Cretaceous, nonmarine red shales of the Bananeiras Formation and coarse grained, poorly sorted, kaolinitic sandstones of the Serraria Formation were extensively and blanketwise deposited in most of the basin. Early Cretaceous Neocomian time is represented by the Barra de Itiuba Formation consists of greenish-gray shales and siltstones and fine to very fine-grained lenticular sandstones indicative of low energy indicative of low energy, fluvatile to lacustrine deposition (Milani and Davidson, 1988). In the late Neocomian, while the Barra de Ituba sediments were being deposited in parts of the basin, the survey area is considered to have been covered by red to green polymictic conglomerates and breccias of the Rio Pitanga Formation or by poorly sorted sandstones of its lateral equivalent Penedo Formation, there is an areally restricted occurrence of chalky and coquinoidal limestone included in the Morro do Chaves Formation.

A widespread hiatus in the southern part of the Sergipe-Alagoas basin, which followed deposition of the Neocomian sediments, is known as the Muribeca (pre-Aptian) unconformity (Castro, Jr., 1987). The oil productive Muribeca Formation, which overlies this surface is composed of three distinct superposed members, from base to top—Carmopolis, Ibura, and Oiteirinhos. The Carmopolis Member is a coarse clastic sequesnce with grayish-green organic shale interbeds; it becomes finer upward and grades into the overlying unit. The evaporitic Ibura Member consists, at the base, of bituminous shales with locally abundant fish and plant remains, dolomitic limestones, dolomites, and some anhydrite, which gives way to locally thick bodies of anhydrite (or halite), carnallite, and more subtle salts. The uppermost Oiteirinhos Member contains alterations of gray to dark shales, limestones, and siltstones (Mello et al., 1990).

The first entirely marine sediments in the basin belong to the late Aptian to late Albian Riachelo Formation, subdivided into four members named Angico, Taquari, Maruim, and Aguilhada. The Angico Member lies mainly near the present basin border and is characterized by fine grained to conglomeratic sandstones interbedded with siltstones, shales, and coquinoidal limestones. The Taquari Member is represented by rhythmic alterations of grayish limestone and shale with abundant benthonic fauna, representative of a shallow open-marine environment. The Maruim Member contains predominantly oolitic to pisolitic limestones and some algal patch reefs, whereas the Aguilhada Member is saccharoidal dolomite sequence with some sandstone shale.

The Turonian to Santonian Cotinguiba Formation lie unconformably on the Riacheluelo, and contain some massive to stratified marine shaly limestones and marls, with local chert. Some shales and siltstones are present at the southeastern wedge of the formation. The Campanian to Eocene Piacabucu Formation is essentially clastic: thick, gray, marine shales and some sandstones and limestones of the Calumbi Member that grade upward to the sandstone and calcarenite of the Marituba Member (Cainelli, 1992).

MAJOR OIL FIELDS OF THE SERGIPE BASIN

CARMOPOLIS FIELD

The main producing reservoirs of the Carmopolis Field are the sandstones, conglomeratic sandstones, and conglomerates of the Carmopolis Member. Some minor production is obtained from the lenticular, fine grained sandstones of the Barra de Itiuba Formation and medium grained, poorly sorted sandstones of the Serraria Formation. The oil is found from depths of 550 to 800m, and the maximum net oil producing sandstone thickness is 106m (Mohriak et al., 2000).

The reservoir rocks of the Carmopolis oil Field are subdivided into eight productive zones on the basis of detailed log correlations, shale interbeds, and lithology. The upper six zones belong to the Carmopolis Member; the other two are represented by the Barra de Itiuba and Serraria sandstones, respectively (Cainelli, 1992).

The structure of the Pre-Aptian rocks is represented by a complex assemblage of normal fault blocks successively downthrown north and north-east. This structural interpretation is based mainly on geophysical data indicating the field to be on one of the first step-fault blocks between the Aracaju regional high and the Japaratuba graben. The structural behavior of post-unconformity sediments is completely different; on top the Carmopolis Member the structure is a well defined, east-west elliptical dom. The oil closure of as much as 250m is provided by dips, small displacement normal faults and pinchout of the Carmopolis Member. The gradational oil-water contact is 800m at subsea (Candido and Wardlow, 1985).

SIRIRIZINHO

Discovered in August 1967 in the west-central part of the Sergipe basin, about 30 km north of Aracaju. The discovery well was drilled on a north-south basement high indicted by gravity near the basements margin, and detailed by seismic determinations. The proved area is 18 sq km with 82 extension and development wells; 13 have been abandoned.

Oil production comes from conglomerates, conglomeratic sandstones, and sandstones of the Carmopolis Member at a depth range of 400 to 650m, lying directly on basement. Maximum net oil-producing sandstone thickness is 74m. Reservoir rocks are grouped into 5 productive zones (based on vertical variations in interbedded shales). The zones are easily identified on gamma ray logs (Mello et al., 1990).

The gradational nature and irregular nature of the tilting oil-water contact from northwest to southeast are attributed mainly to varied permable-porosity conditions of the reservoir rocks. Influence of hydrodynamic factors must also be considered.

The structure in the basement is north-south trending high between the Siriri-Divina Pastora and Japaratuba grabens. The structural map of the top of the Carmopolis Member shows a northeast-southwest anticline associated with a south-dipping nose on its northern end. Several small-displacement normal faults, observable only in a highly detailed map, contribute to the present structural features (Candido and Wardlow, 1985).

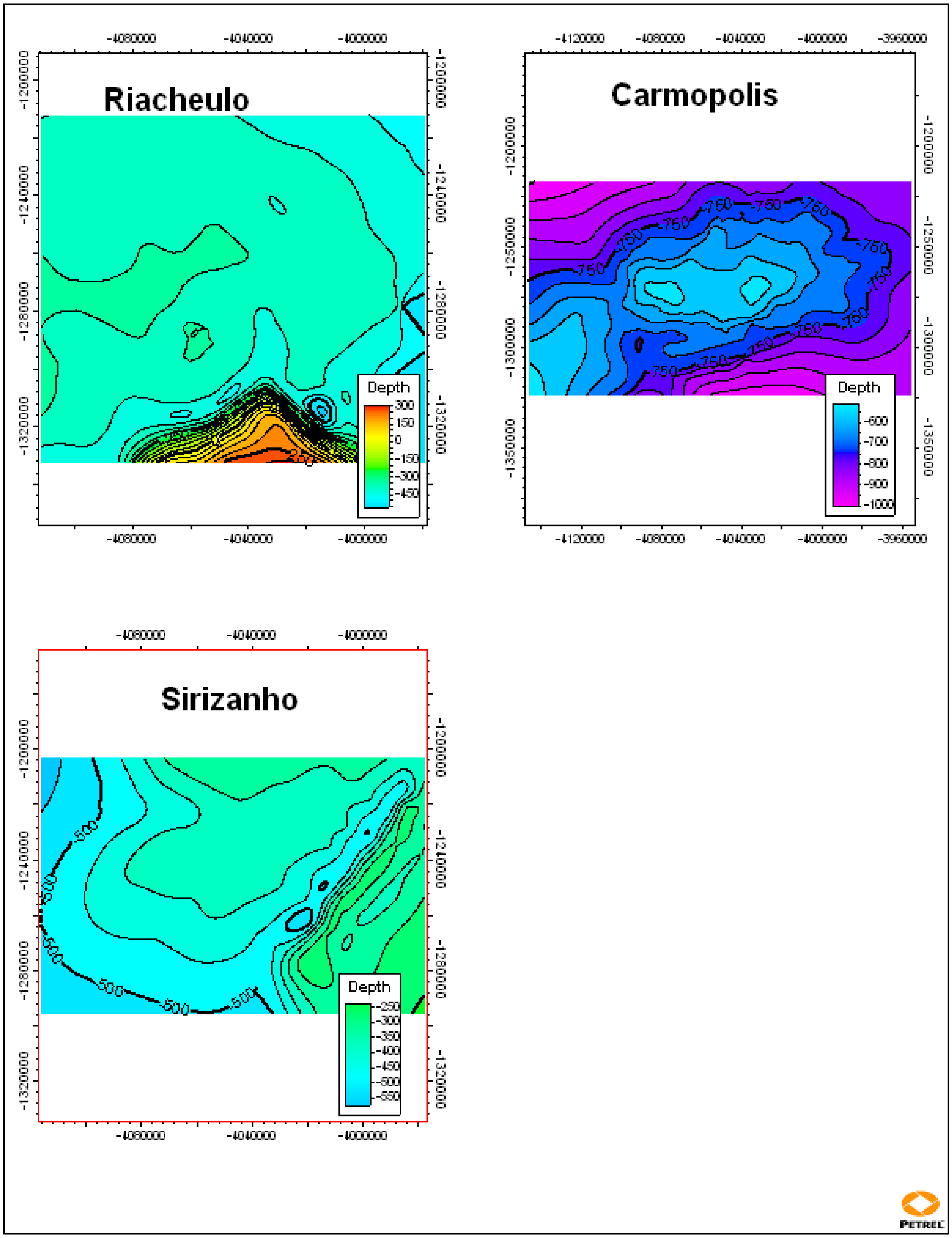

Fig. 7. Example Sergipe-Alagoas oil fields. The Riacheulo, Carmopolis, Sirizanho fields are displayed.

OFFSHORE OIL EXPLORATION

SERGIPE-ALAGOAS BASIN

The Riachuelo-Siririzinho and Vassouras-Carmopolis oil trends resulted from a combination of northwest subsidence of the basin-margin grabens and a regional southeastward tilting which started at a later period of time.

Oil production in the basin comes from the Carmopolis, Siririzinho and Ricachuelo fields; mostly from the Carmopolis Member in the southern onshore part of the basin. The Lower cretaceous reservoirs that come in contact with the unconformity also attribute to some of the oil production (Mohriak and Cainelli, 1998a). The depth range of all of the reservoirs is about 400-800m.

Adequate structural evolution during the Late Cretaceous, the presence of evaporates and organic shales at the top of the reservoirs, and younger conformities not reaching down to the trap create good conditions for oil accumulation (Guthrie et al., 1996).

RESERVOIR ROCKS WITHIN THE BASIN

The Carmopolis Member of the Muribeca Formation is the most important oil-producing section of the Sergipe basin. This section, in the Carmopolis, Riachuelo, and Siririzinho fields, contributes more than 90 percent of the oil produced in the basin.

Small production also is obtained from limestones and sandstones at the base of the Ibura Member (Riachuelo field), from sandstones of the Barra de Itiuba and Serraria Formations (Carmopolis field), and from fractures in basement subcrops at the pre-Muribeca unconformity (Carmopolis and Riachuelo fields). Producing zones of the Carmopolis Member are conglomerate sandstones, and sandstones, which are consistently interbedded with shales (Cainelli, 1992). These coarse clastics grade upward from hard conglomerates with sand-clay matrix, to fine grained, friable, argillaceous sandstones.

Because of varied clay content and grain size, each producing zone displays lateral facies changes which, in places, severely alter the permeability-porosity characteristics of the reservoir rocks. Porosity values range from 5 to 33 percent; the increase consistently occurs from the base to the top of the producing section (Frota et al., 1994). Depending on the clay content. Permeability ranges from 0.1 to 1000 md. Such lithologic characteristics, associated with the great number of shale interbeds, contribute to the presence of irregular and gradational oil-water contacts (Hunt, 1979).

The pattern of thickness variation of the CArmopolis Member suggestd that its deposition was controlled by the general morphology of the Early Cretaceous unconformity surface.

PROBABLE SOURCE AND MIGRATION PATHS

In the area most, if not all, of the petroleum generating potential is attributed to the Muribeca Formation. Up to 50m of Bituminous, dark to brown shales, with locally numerous plant and animal remains, have wide areal distribution at the base of the evaporitic Ibura Member. They constitute the first signs of a basin restriction which, although ephemeral, led to the extreme local precipitation of sodium, potassium, and even magnesium salts (Frota et al., 1994). Environmental conditions, therefore, were adequate for the preservation of organic matter. Another line of evidence consists of the fact that wherever the Ibura Member lies upon the basement, fractures are found to contain oil. Therefore, it seems safe to attribute numerous petroleum indications in the Carmopolis Member, as contrasted with an almost complete absence of shows int other lithologies of the studued sequence, to the good source rock potential of the basal shales in the Ibura Member (Cainelli, 1992).

Proximity between source and reservoir rocks greatly favored primary migration processes, allowed the expelled fluids to be displaced directly downward into the reservoirs. Movement of oil into the structural-stratagraphic traps of Carmopolis, Riachuelo, and Siririzinho also must have involved migration from the adjoining Jaratuba, Siriri-Divina Pastora, and Treme grabens (Guthrie et al., 1996).

METHODS AND MATERIALS

GRAVITY AND MAGNETIC DATA

Marine free air gravity data used for this experiment was derived from ERS-1, Geosat, and Seasat radar altimeter data (Sandwell and Smith, 1997), and data from ship cruises (Rabinowitz and Cochran, 1978). The satellite altimeter data is collected from several satellites that orbit the earth. The satellite transmits a microwave pulse—the two-way travel time for the microwave pulse is reflected from the sea surface, and the signal is transmitted back to the satellite. Altimeter data approximates the marine geoid by measuring the height of the sea surface. Depressions in the geoid are created by mass deficiencies, such as in trenches and sedimentary basins. Geoid highs are created by mass excesses, such as seamounts or basement highs (Haxby et al., 1983). The satellite measurements are compared and combined with measurements made by ships to get high resolution gravity anomaly maps of the seafloor; the accuracy of the satellite altimeter method is about ±5 mgal (Sandwell and Smith, 1997).

The accuracy of shipboard gravity measurements is generally about ±5 mgal (Talwani and Ewing, 1960), and errors in absolute measurements may be much greater depending on sea conditions, navigation system, etc. Shipboard gravity shows significant short wavelength anomalies that are not resolved by satellite gravity (Small and Sandwell 1992). Shipboard gravity measurements can provide a ground truth for satellite measurements.

Rabinowitz et al. (1985) notes that the resolution of shipboard gravity data (with wavelengths shorter than 22 km) is better than the resolution of satellite gravity data (specifically, the SEASAT satellite); satellite data is more useful than shipboard data, however, because the data points are more evenly spaced and the readings cover more areas than shipboard reading.

The magnetic data used in this experiment were taken using a proton precession magnetometer (Talwani and Ewing, 1960). Magnetic total field anomaly is determined by subtracting the total observed magnetic field intensity from the regional field (Peddie, 1985).

SEISMIC MAPPING

Paper 2D lines were used to map the study region; the line depths were listed in two way time. Interval velocities were used to depth convert the structures. The interval velocities, based on regional analysis of borehole sonic logs, are assumed as follows: water = 1500 m/s;

Late Tertiary sedimentary section: 2000 m/s;

Middle Tertiary sedimentary section: 2500 m/s;

Early Tertiary-Late Cretaceous sedimentary section: 3000 m/s;

Late-Middle Cretaceous sedimentary section: 3500 m/s;

Early Cretaceous sedimentary section: 4000 m/s;

upper crust layer: 6000 m/s; lower crust layer: 7000 m/s.

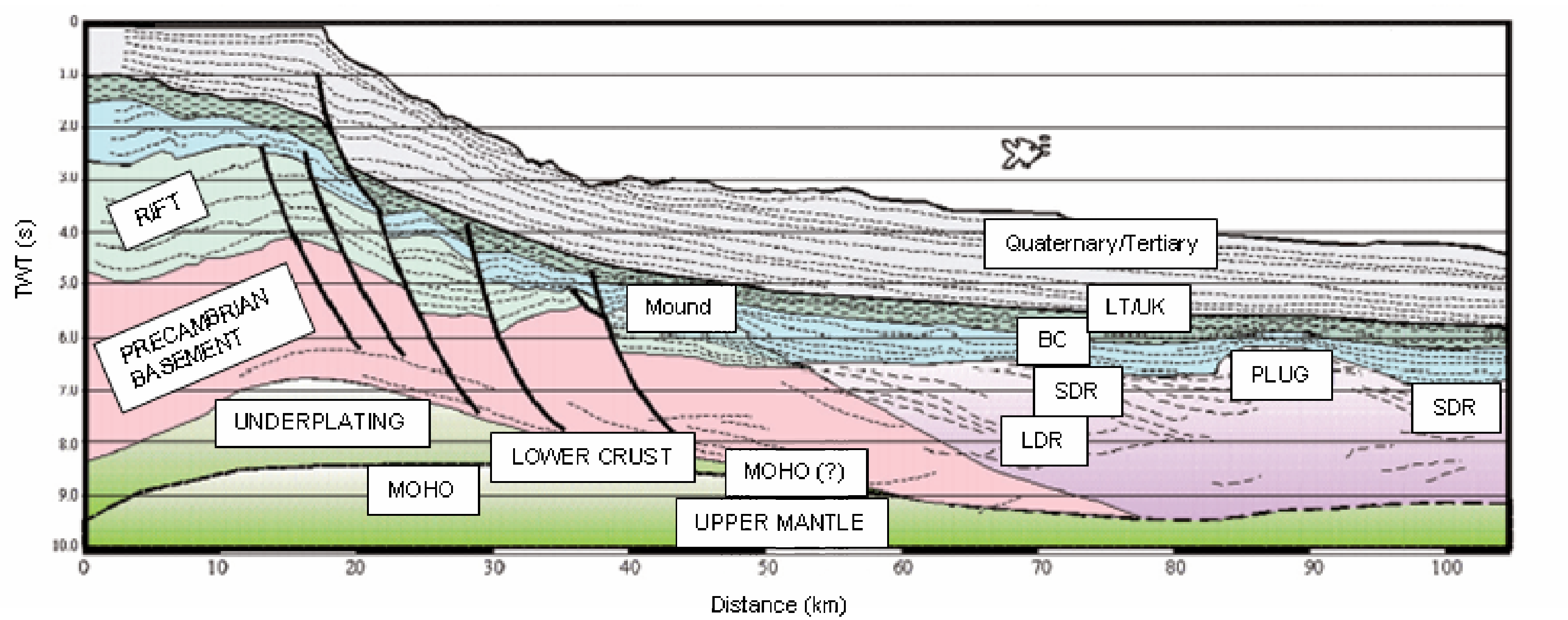

Fig. 8. Interpreted seismic section across the Sergipe-Alagoas basin. The interpretation is across the Sergipe portion of the Sergipe-Alagoas basin. The distances are in km and the two way time is in seconds. (Modified from Mohriak et al. 1995).

3D MODELING

Three dimensional structural models of the Sergipe-Alagoas basin were created from the mapped horizons, and the models were then populated with the potential field data from the region. This was performed to understand the change of different attributes across the region. The modeled Magnetics, Free-Air gravity, Bouguer gravity, and thickness of the bottom zone (the Calumbi section) were modeled for the basin.

BOUGUER GRAVITY

The gravity anomalies observed in the Bouguer field are caused by lateral density contrasts within the sedimentary section, crust and sub-crust of the earth. The gravity field obtained after latitude, elevation, and Bouguer corrections have been applied to the measured gravity data to obtain a Bouguer Anomaly Map.

DATA ANALYSIS

GRAVITY MAP

Free air gravity maps, obtained from satellite and shipboard data from the study region, are displayed in figures 9 and 10 (lines have been drawn across the basins for reference). The satellite and shipboard gravity maps have comparable free air gravity values; the satellite map shows better resolution near the coastal basins, and the shipboard map shows better resolution seaward from the coastal basins. A free-air gravity high ranging in values from 0 to 70 mgal is seen along the coastline for all three offshore basins of interest. The Jacuipe basin has gravity lows peaking about 5-10 km from the shelf break. A portion of this trend seen across the basins may be due to the 'edge effect'. The edge effect is caused by juxtaposition of thin oceanic with thick continental crust (Worzel, 1968). If the region was in perfect Airy Isostatic compensation, then the resulting isostatic anomaly would be zero. However, if resulting isostatic anomalies exist then deviations from the Airy model are implied; these deviations could be due to changes in crustal thickness, crustal density, or a combination of the two.

The Alagoas portion of the Sergipe-Alagoas basin has free-air gravity highs in the range of 30 -70 mgal at the shelf break. The free-air anomalies attain values more negative than 30 mgal 10-15 km from the shelf break.

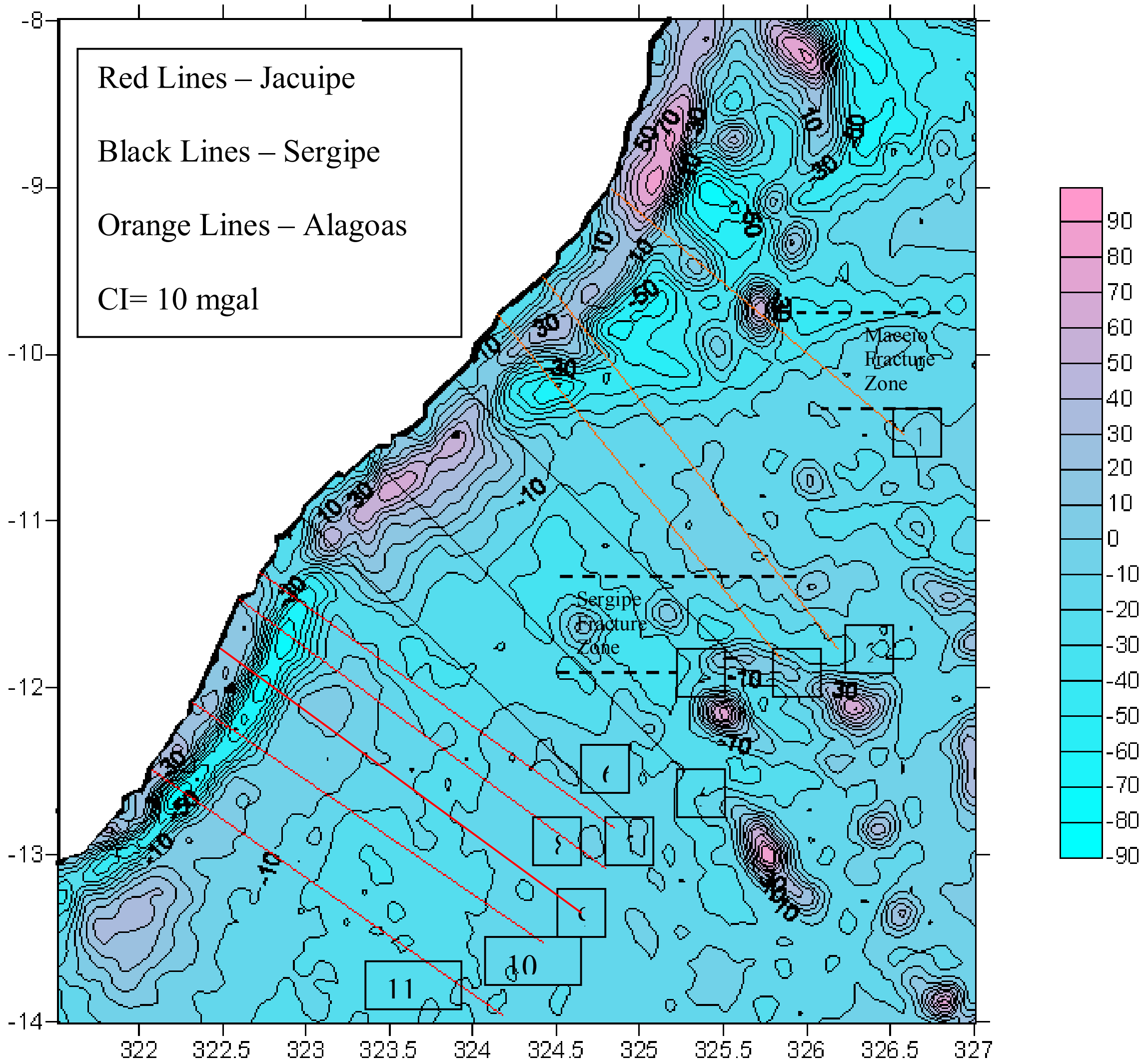

Fig. 9. Free air gravity plot of the offshore study region. 2-D gravity extraction lines are displayed. Lines are drawn across the basin for reference.

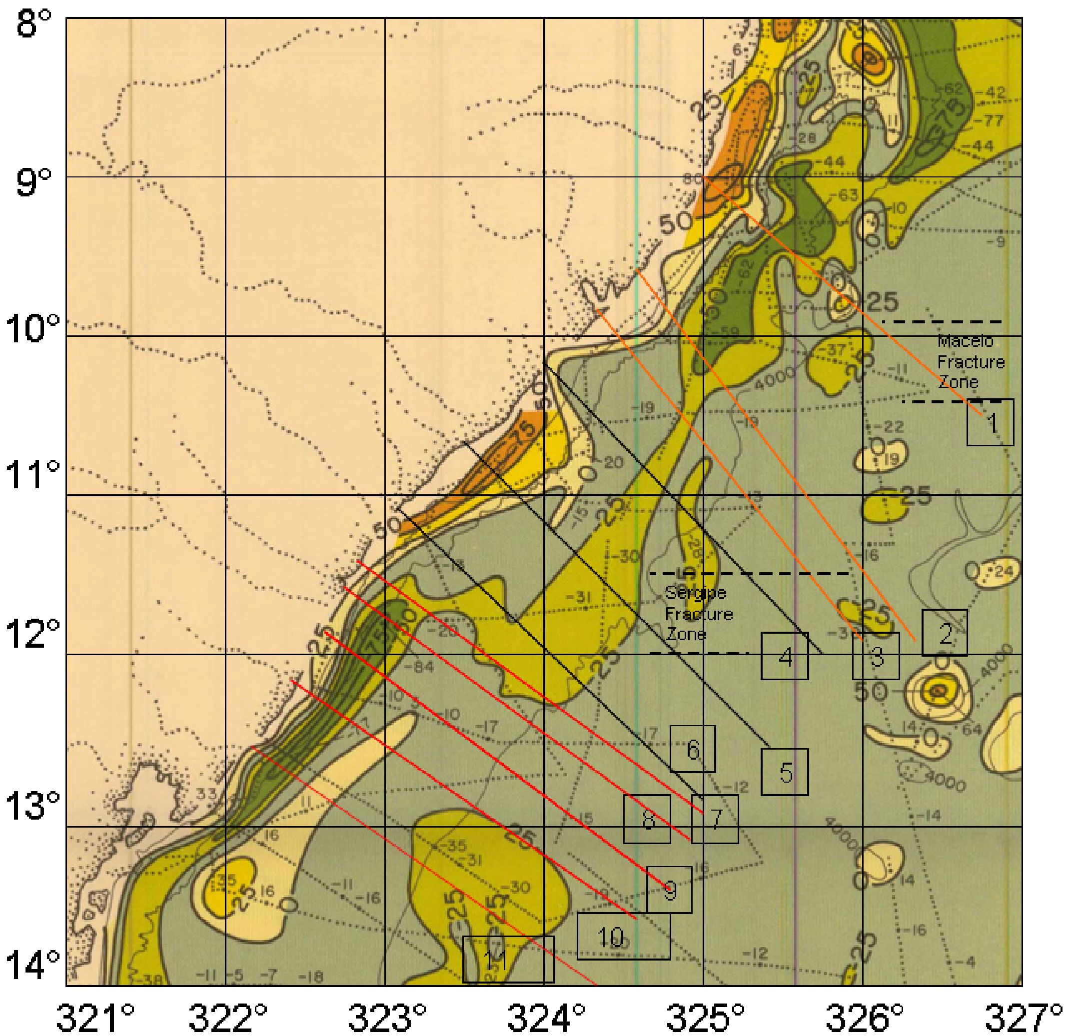

Fig. 10. Free air gravity map of the study region. The map was plotted from ship track information (modified from Rabinowitz and Cochran 1978).

The region around the Sergipe portion of the Sergipe-Alagoas basin free-air has gravity highs in the range of positive 60-75 mgal at the shelf break; these free-air gravity values attain values more negative than -10 mgal about 60 km eastward from the shelf break. The Jacuipe basin displays free-air gravity anomalies in the range of 30 mgal at the shelf break, which become negative than 30 mgal 10-20 km eastward from the shelf break.

Several seamounts are recognized on the map. A chain of seamounts exists near the Sergipe fracture zone, and extend off of the map to the south-east. Another large seamount exists near the Maceio fracture zone (10° latitude and 325.5°longitude), near the Alagoas basin. These seamounts have free-air gravity values in excess of 60 mgal.

MAGNETIC MAPS

Figure 11 displays a residual magnetic map of the study region with the reference line locations shown. Magnetic values in the Sergipe region of the Sergipe-Alagoas basin are positive in the range of 200 gammas landward of the shelf break for lines 4 and 5, but the magnetic values are more negative landward of the shelf break of line 6. The magnetic values in the Alagoas portion of the Sergipe-Alagoas basin are negative landward of the shelf break, but become more positive near the shelf break. The magnetic values around the Jacuipe basin are negative landward of the shelf break and become near zero at the shelf break.

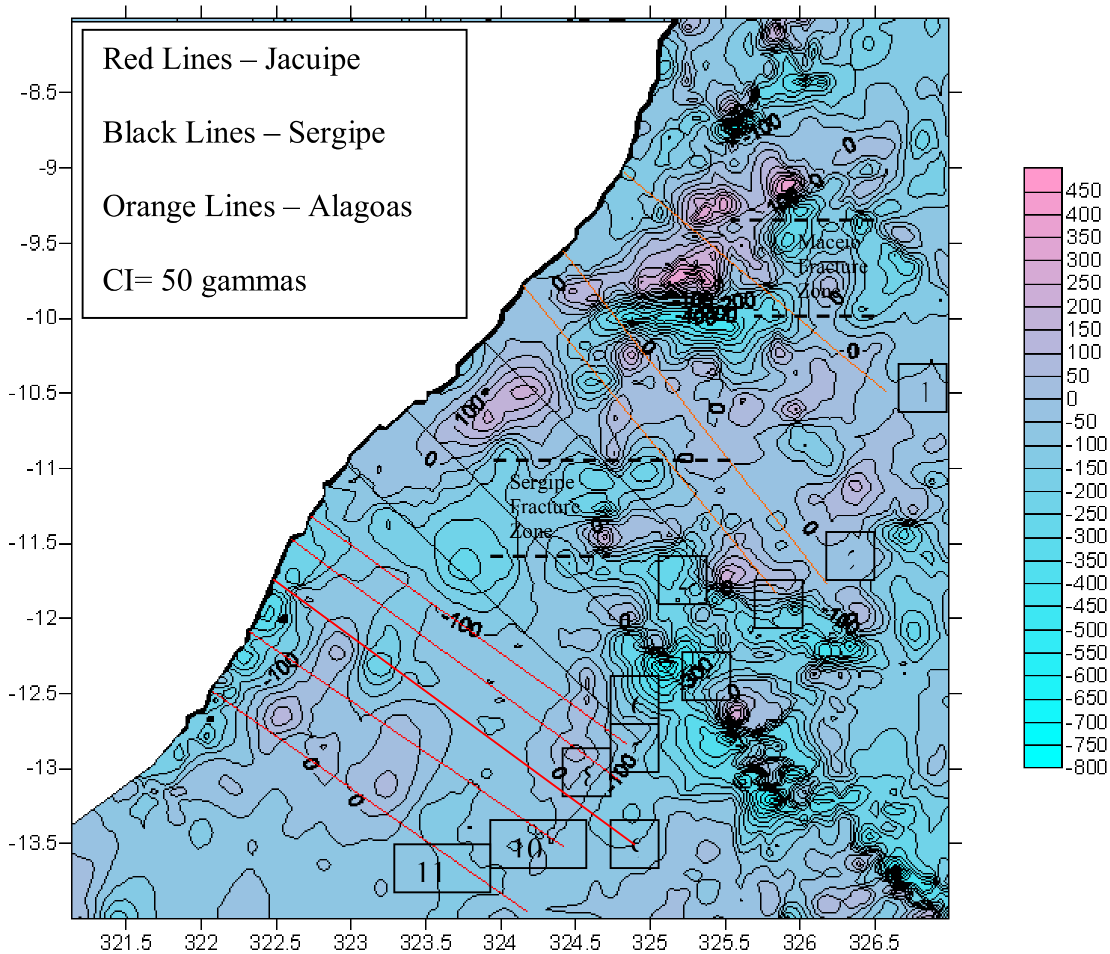

Fig. 11. Residual magnetics plot of the offshore study region. The Maceio and Sergipe fracture zones are also displayed.

Figure 12 shows the magnetic profiles along the ships tracks' in the study region. Large positive anomalies are seen trending from line 2 to line 4; it can also be assumed that line 1 and line 5 also contain these magnetic anomalies. The anomaly seems to be most positive in line 4, at the shelf break. Lines 7-11 are mostly surrounded by negative magnetic values. A few positive peaks occur near line 11, about 15 km seaward from the shelf break and extend for about 100 km.

Two fracture zone regions are seen in the study area; the Maceio fracture zone (10° latitude and 325.5°longitude) and the Sergipe fracture zone (11.5° latitude and 324° longitude) on figure 11. The fracture zones trend toward the coastline, and divide the J-S-A basins—the Maceio fracture zone divides the Alagoas and Sergipe portions of the Sergipe-Alagoas basin, and the Sergipe fracture zone divides the Sergipe basin from the Jacuipe basin.

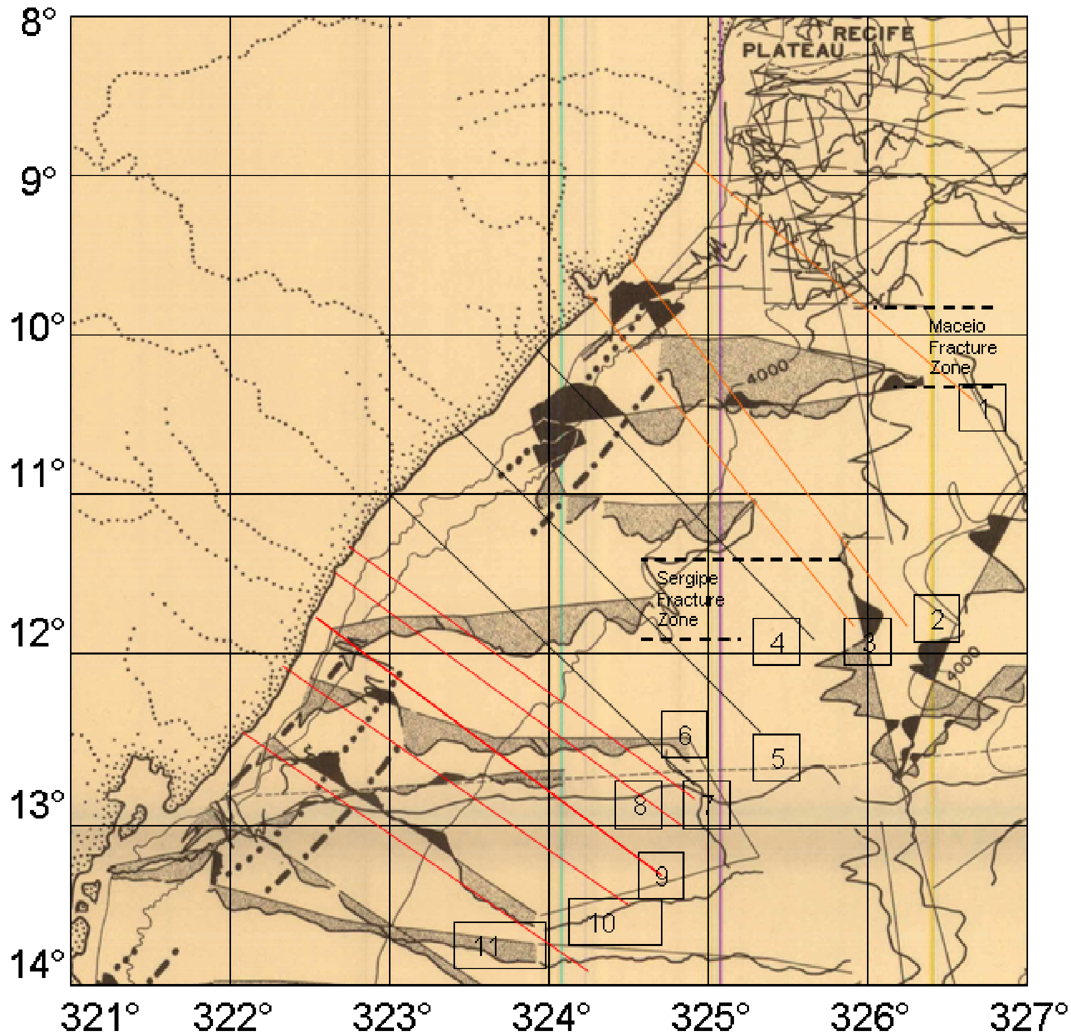

Fig. 12. Magnetic map of the study region. The map was plotted from ship track information (modified from Cande and Rabinowitz, 1979).

3D MODELING

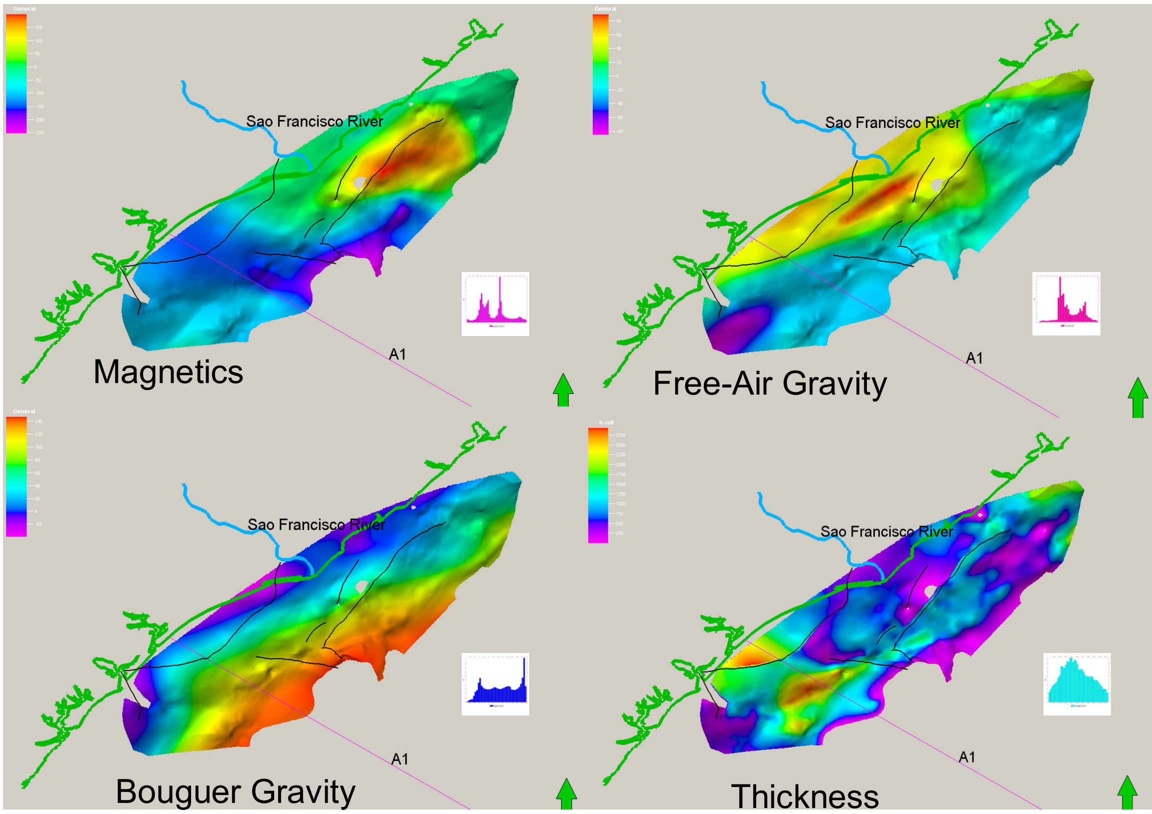

Fig.13. 3D properties of the basin. Magnetics, Free Air Gravity, Bouguer Gravity, and Thickness between the Turonian and Neocomian (the Calumbi Section) are displayed, along with histograms of the data ranges. Line A1 is displayed for reference.

MAGNETICS MODEL

A strong positive magnetic anomaly can be seen in the Northwest region of the map (figure 13); the greatest positive values are seen about 36 km seaward from the coastline. The character of this positive anomaly becomes more negative southeastern-ward, where the most negative values occur about 75 km from the coastline.

FREE AIR MODEL

The histogram of the Free Air Gravity model (figure 13) is dominated by negative values, which mostly exist away from the coastline; positive gravity values are seen near the coastline. A large positive anomaly is seen directly southeast of the Sao Francisco river.

THICKNESS

The thickness for the interval between the Turonain and Neocomian (Calumbi section) is shown in figure 13. The thickness seems to be greatest in the southern portion of the model (across line A1).

An isolated structure with large thickness values, created by a large normal fault, exists on the southwestern border of the map. Also, a series of normal faults are seen near the middle of the map. Regions of thickness seem to be created on the downthrown side of the faults.

BOUGUER GRAVITY WITH TREND REMOVED MODEL

This model was created in order to understand the gravity anomalies in the region (figure 14). Due to the principle that Bouguer gravity normally increases with distance away from the coastline, this effect was removed from the Bouguer gravity map to obtain the anomaly map. The Bouguer gravity was plotted as a function of distance from the coastline to obtain a trend map. After the trend map was created, the map was subtracted from the original Bouguer map to obtain the trend removed Bouguer map. The histogram plot of the trend corrected map shows that the map now has a normal distribution.

Negative gravity values are seen in the northeastern portion of the trend corrected Bouguer map. A strong positive anomaly exists about 49 km southeast of the Sao Francisco river. This anomaly decreases in value as it trends southwest into the coastline.

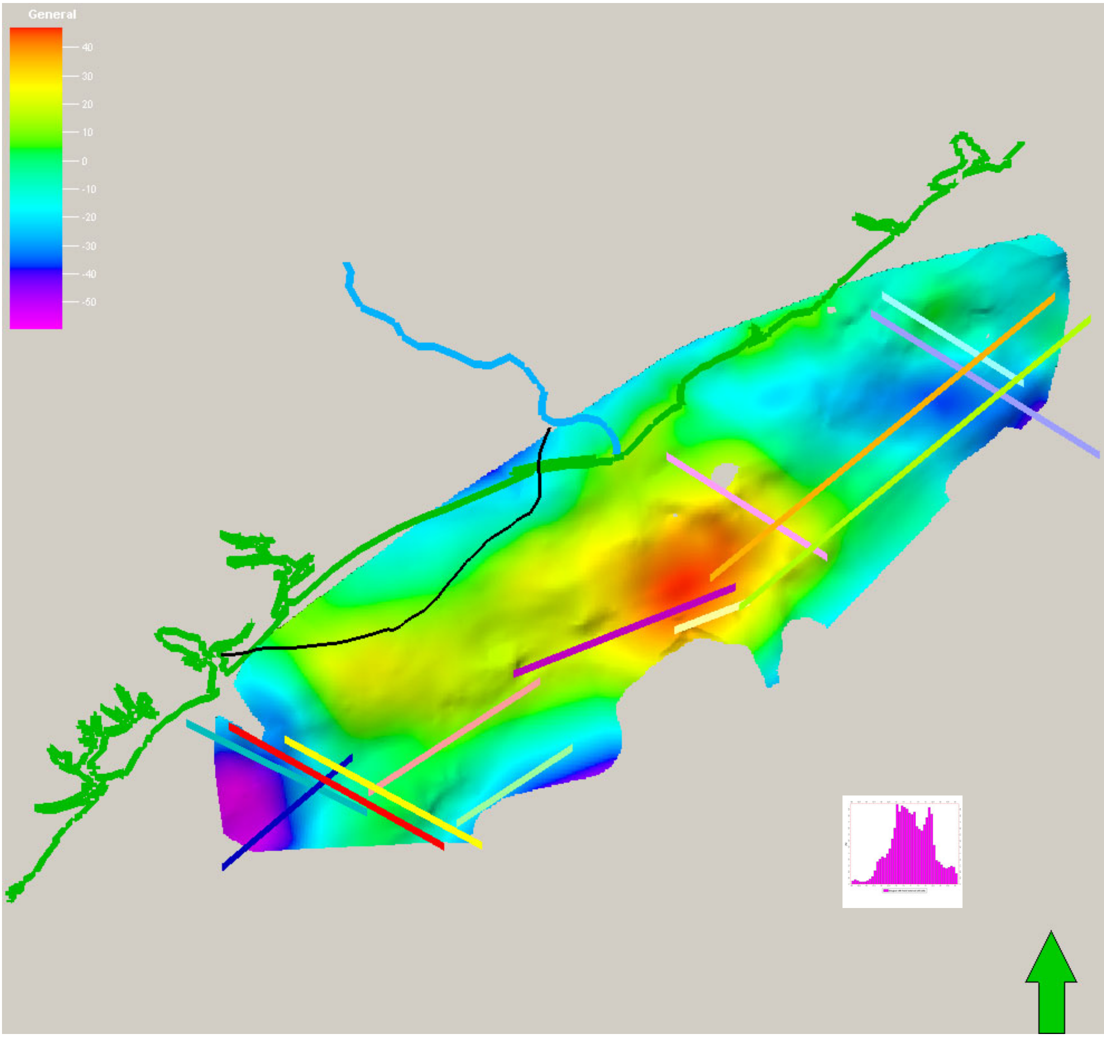

Fig. 14. Bouguer gravity map with the Trend Removed. This figure displays the Bouguer Gravity map with the trend removed; the locations of the 2D seismic lines are displayed.

BATHEMETRY TO NEOCOMAIN

A thickness map was created between the Neocomain and the Seabottom in order to represent the distance from the top of the rift surface (Neocomain) to the seafloor

(Figure 15). The greatest thicknesses are seen on the southwest portion of the map, with a band of thick values trending away northwestward.

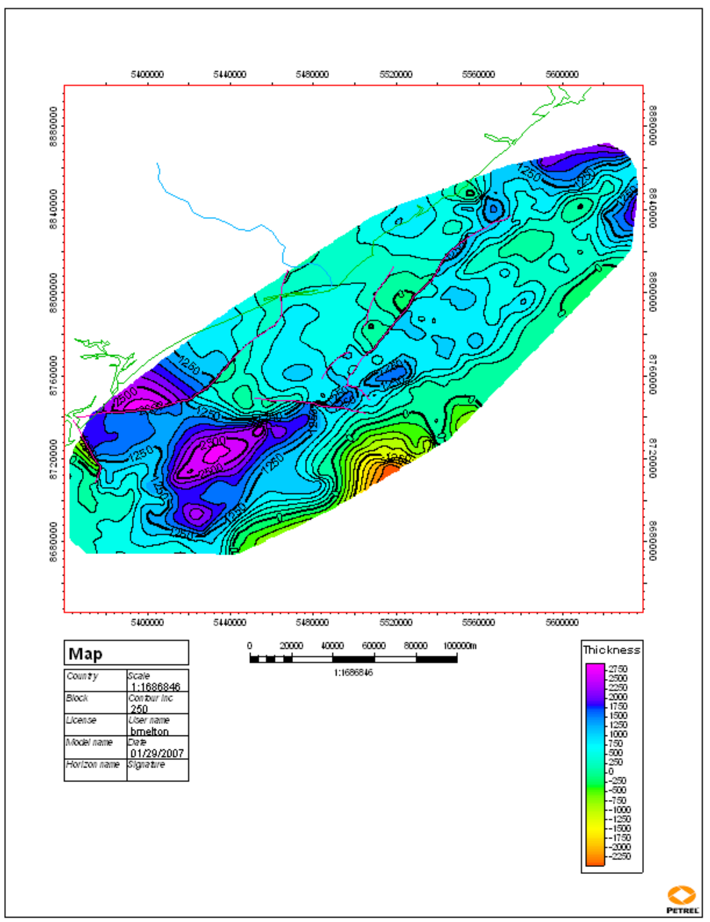

Figure 15. Thickness map between the seabottom and Neocomian.

CROSS SECTIONS

Cross sections were created across the study region to understand the relationship between the Neocomian and other layers in the model.

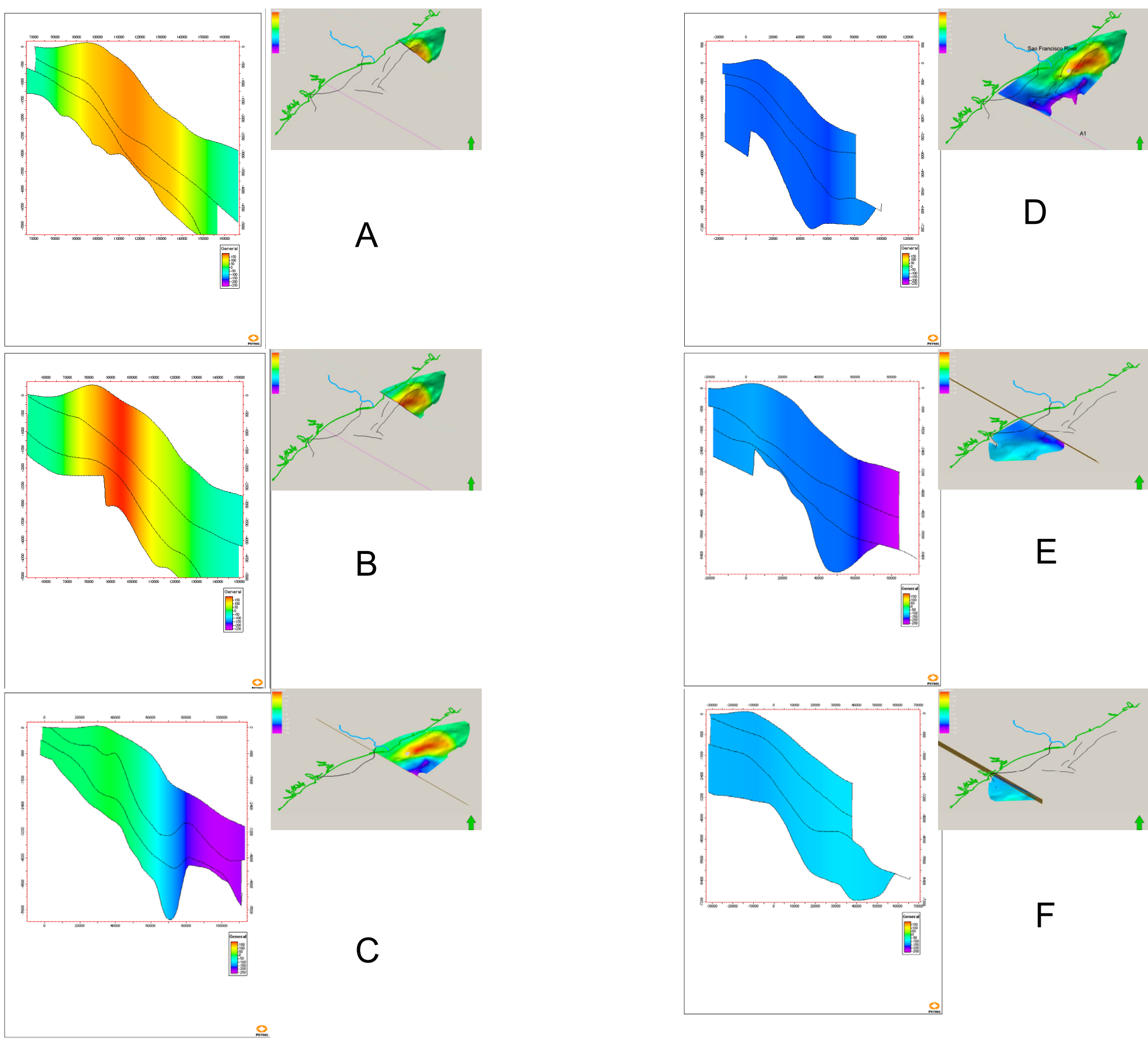

Figure 16. Cross sections taken perpendicular to the coastline. Magnetic values are posted onto the cross lines.

Figure 16 displays cross sections of the study area along dip. Cross section A shows that the Calumbi section (bottom layer) thins ocean-ward in the Northern portion of the model. Travelling southwest, the Calumbi section tends to have greater thicknesses ocean-ward than near the coastline. Mound-like features are seen near the middle of cross section A and toward the end of cross sections C and E.

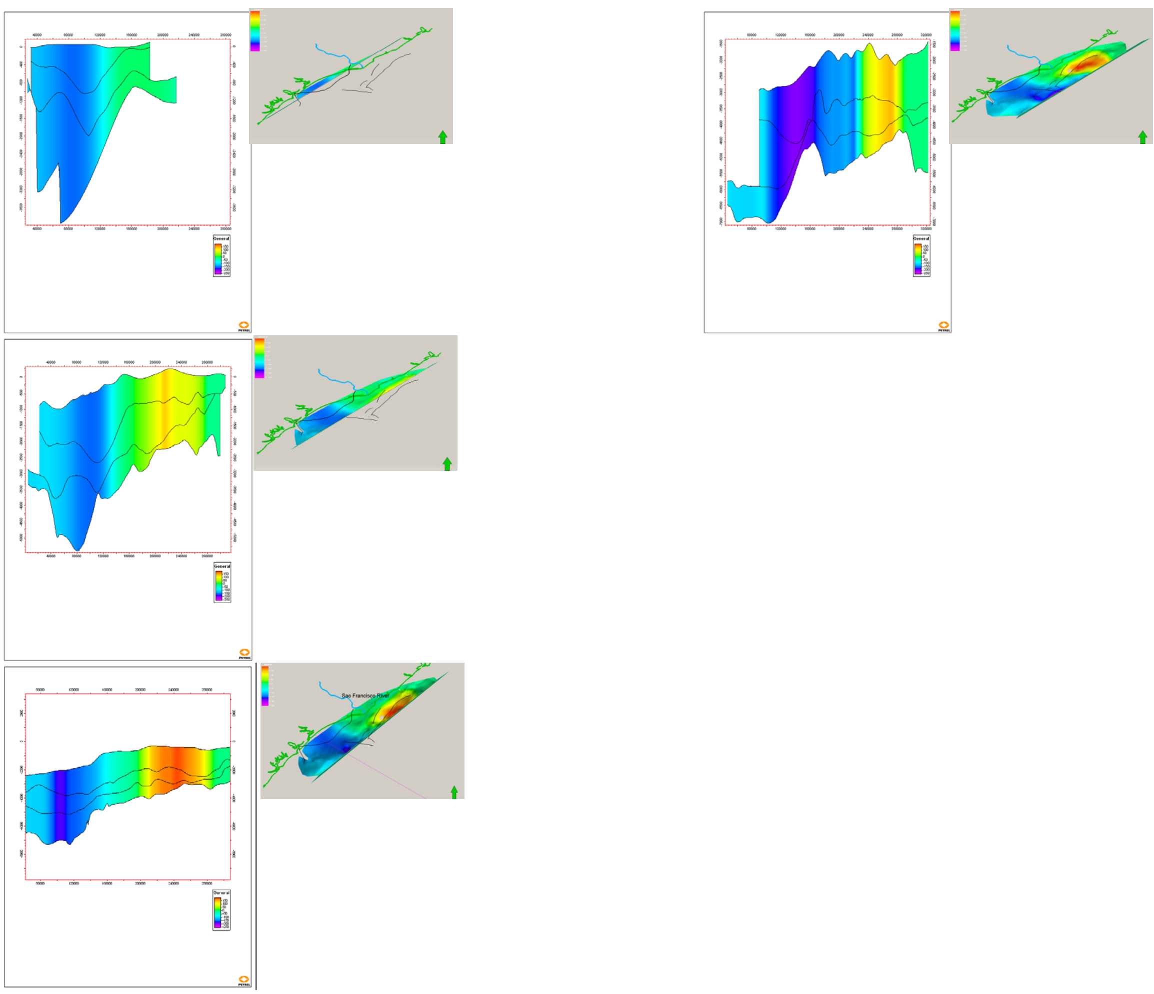

Fig. 17. Cross sections parallel to the basin. Magnetic values are posted onto the cross lines. This figure shows that the rift is deepest in the SE portion of the basin.

Figure 17 displays cross sections in the study area along strike. The cross sections demonstrate that the rift is higher (up to 4 km in some cases) in the Northern portion of the model. Cross Section D displays a possible uplifted feature in the middle of the section.

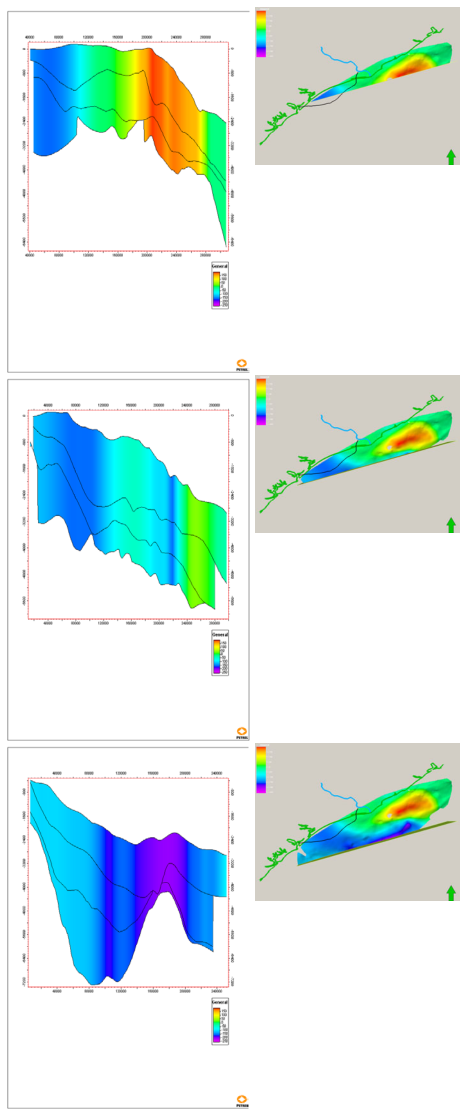

Fig. 18. Cross sections taken parallel to the suspected rift zone. Magnetic values are overlain onto the cross sections.

Figure 18 displays cross sections parallel to the suspected rift zone. The sections tend to thin westward, with the thickest areas lying near the coastline. Section A exhibits uplift across the middle of the section, including an unconformity at about 200 km. Section C also displays uplift near the end of the section, and displays an unconformity at about 100 km.

CONCLUSION

The onshore and offshore basins of NE Brazil (North of Salvador) were created by the same large rifting event. Negative gravity anomalies (-100 mgal) are found beneath the onshore R-T-J rift and extend toward the offshore J-S-A basins, where they become more positive in magnitude. The onshore and offshore basins may also be connected by large fault systems. The Sergipe-Alagoas basin is separated from the Jacuipe basin to the south by a regional bathymetric high, which may be due to interruption by a fracture zone.

The study region contains various magnetic, gravity, and thickness anomalies. The various anomalies tend to differ across the middle of the study region; the line across which the values change character may be associated with the Sergipe Fracture zone.

Generally, the rift is closer to the seabottom on the northern portion of the fracture zone than the southern portion of the fracture zone. Also, the zone between the Turonian and the Neocomian tends to thin away from the coastline north of the fracture zone and thickens away from the coastline south of the fracture zone.

The positive magnetic anomaly north of the fracture zone (figure 19) was created by the large amount of uplifted rift material in the area, and may be accentuated by the large normal fault that exists north of the fracture zone.

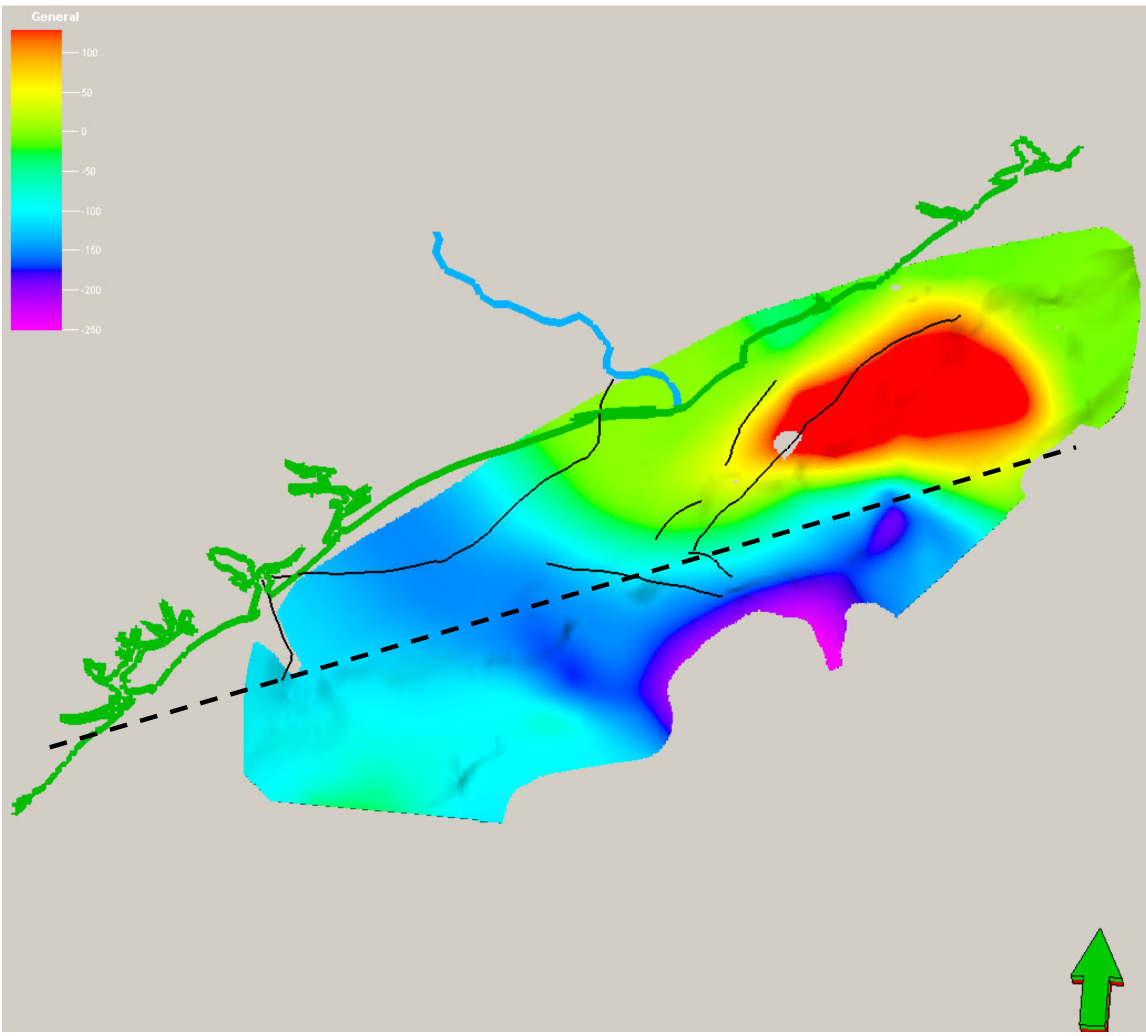

Fig. 19. Hypothesized location of the Sergipe fracture.

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