MAJOR TECTONIC FEATURES IN THE SOUTHEASTERN BRAZILIAN MARGIN

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Abstract

A regional geophysical and geological dataset has been integrated to analyse the major tectonic elements along the southeastern Brazilian margin, from the Espírito Santo towards the Santos basins, the most prolific oil provinces offshore Brazil. The diverse tectono-sedimentary domains identified along the continental margin are related to the Mesozoic-Cenozoic tectonic reactivations, particularly the syn-rift extensional processes associated with the separation of the West African and South American plates in the Late Jurassic – Early Cretaceous. These processes are responsible for synthetic and antithetic normal faults that formed half-grabens and grabens within the mainland and offshore, which were filled by continental volcanics and siliciclastic rocks in the Neocomian - Barremian. Subsequent to this syn-rift phase, the transitional phase (Aptian age) is associated with siliciclastic and carbonate sediments deposited above a regional unconformity (breakup unconformity) that heralds the continental drift phase and forms a sag basin that underlies the Aptian evaporites. The regionally extensive, thick evaporite layers that occur both along the Eastern Brazilian and West African margins suggest the occurrence of an elongated and shallow gulf that was periodically invaded by sea waters during the first marine ingressions of the nascent Atlantic Ocean. The presence of a highly mobile evaporite layer resulted in the development of a characteristic tectonic style marked by salt diapirs and salt walls associated with extensional and compressional structures. The outermost boundary of the salt layers seem to correlate with the feather edge of seaward-dipping reflectors that correspond to volcanic wedges formed during the inception of oceanic crust, which is related to propagators that advanced northwards by rupturing the crust and upper mantle. Several major tectonic features are associated with syn-rift and post-rift magmatic episodes, particularly in the southern Santos Basin (Florianópolis platform), in the northern Santos and southern Campos basins (Cabo Frio region), and in the Abrolhos region of the Espirito Santo Basin.

Introduction

The study of the sedimentary basins along the passive continental margin of the South American plate has greatly benefited from the results of petroleum exploration and projects from research institutions and government agencies. Earlier works in the 60`s and 70`s characterized the stratigraphic sequences of the onshore and offshore basins along the Eastern Brazilian margin within a template of syn-rift and thermal subsidence phases, each one with different structural styles and sedimentary environments. In the past few decades, new vintage seismic data processed to depths that allow visualization of the crustal architecture of the continental margin illuminated the interpretation of major tectonic features and the proposition of geodynamic models to explain their origin and development. This work will discuss major structural elements in the Southeastern Brazilian margin, from the Espírito Santo, Campos and Santos basins, with emphasis on rift and salt tectonics. The Espírito Santo Basin is characterized by a very thick sag basin or syn-rift II (Barremian to Aptian age) that extends from the plataform towards the deep water region. The northern portion of the basin is characterized by the Abrolhos Volcanic Complex (with basalts dated as Late Cretaceous to Early Tertiary), and the Vitória-Trindade lineament, a major E-W volcanic ridge that separates oceanic crusts with different seismic characteristics and apparently different overburden thickness. The Campos Basin is marked by the Badejo High in the platform, controlled by major antithetic faults, and the outer high in deep waters, which is a volcanic high separating two syn-rift basins with different characteristics in seismic data. The prolific Campos Basin is marked by unusual gravity and magnetic anomalies in the area that concentrates most of the hydrocarbon discoveries. The Santos Basin is marked by the Cabo Frio High in the northern province, which controls the syn-rift depocenters in the Campos and Santos Basins and is also associated with post-rift tectono-magmatic events dated from Santonian to Eocene. The post-salt sedimentary successions in the Cabo Frio fault zone are controlled by a major antithetic fault, which resulted in the Albian gap, a major feature trending NE-SW that extends towards the central part of the basin. Regional highs and fracture zones and propagators are characterized in the southern portion of the Santos Basin. A megaregional gravity and structural high in SE Santos Basin has alternative interpretations as a Precambrian High, a syn-rift high, and a volcanic high associated with the emplacement of oceanic crust.

Method

The methodology used in the interpretation of the megaregional structural features is based on integration of geophysical and geological datasets, mainly seismic, gravity and magnetics. Several regional seismic profiles with deep resolution (processed up to 18 s TWT) have been employed to constrain the models derived from potential field data. Analogies with areas where deep reflection and refraction data is available (example, western margin of Africa) have also been used in the

palinspastic reconstructions of conjugate margin segments and are often useful tools to constrain the alternative interpretations (example, Mohriak et al., 2002).

GEOLOGICAL AND GEOPHYSICAL INTERPRETATION

The rift system that formed the sedimentary basins along the eastern Brazilian and West African continental margins is a consequence of extensional processes dated as Late Jurassic to Early Cretaceous (Chang et al., 1992). The climax of the rifting in SE Brazil is dated as Early Cretaceous (Mizusaki et al., 2002), coincident or soon after the formation of basaltic lavas, and just preceding the formation of the South Atlantic oceanic crust in the Early Cretaceous, which propagated from Argentina towards the northern Brazilian margin according to magnetic isochrons (Mohriak, 2001).

The Southeastern Brazilian margin, the most prolific oil province in Brazil, encompasses the Espírito Santo, Campos and Santos basins, which lie almost entirely offshore the states of Espírito Santo, Rio de Janeiro, São Paulo and Paraná. Figure 1 shows a regional topographic and bathymetric map illustrating some of the main geomorphological features along the margin, particularly the highlands adjacent to the Campos and Santos basins, and the Tertiary depressions along the Rio Paraíba do Sul River, which are related to the Cenozoic tectonic reactivation of the continental borderland adjacent to the offshore basins (Cobbold et al., 2001).

These basins are characterized by basement-involved normal faults in the basement, and a syn-rift to post-rift sequence that thins towards the west, onlapping volcanic or Precambrian basement rocks. Structural maps for the Precambrian basement onshore and volcanic basement offshore (Fig. 2) indicates that there are several highs controlling the distribution of the syn-rift depocentes, particularly the Cabo Frio High, which separates the Campos from the Santos Basin, and is also associated with different styles of salt tectonics (Mohriak et al., 1995). Figure 2 also shows the location of the interpreted continental – oceanic crust boundary (COB) as interpreted by the Leplac project along different segments of the margin (e.g., Gomes et al., 1993). Figure 3 shows the top of the upper mantle that was obtained by inversion of gravity data constrained by seismic data (Petrobras, Leplac and spec surveys datasets) and spectral analysis of Petrobras and Geosat gravity datasets (Paula and Vidotti, 2001). The continental crust in the onshore region is quite thick (exceeding 35 km), and there is an abrupt change in crustal thickness due to lithospheric stretching that affected the continental margin, particularly along the area near Cape São Tomé in the Campos Basin (Mohriak et al., 1990). Deep crustal anomalies along the margin are expressed as gravity highs along the rift border faults that may be associated with Moho uplift (Mohriak et al., 1990; Cobbold et al., 2001; Meisling et al., 2001).

The Brazilian Eastern margin is marked by different episodes of magmatism (Mohriak, 2001). The beginning of the Wealden reactivation was triggered by the uplift of the Ponta Grossa Arch in the Paraná Basin, which is marked by a series of NW-trending diabase dikes onshore. These dikes have been dated as Early Cretaceous (133-129 Ma) using the Ar-Ar method (Misuzaki et al., 2002) , and are approximately contemporaneous with the tholeiitic basalt lava flows in the Paraná Basin (Serra Geral Fm.). They occur offshore as continental margin basalts of the Camboriú Fm. (Santos Basin) and Cabiúnas Fm. (Campos Basin). These basalts may constitute the basement for the subsequent rift structures that resulted in the formation of troughs which accumulated continental sediments deposited in fluvial to lacustrine environments.

The Espírito Santo Basin shows a narrow strip of syn-rift sediments along the coast, whereas the Campos Basin extends a few kilometers onland as indicated by the penetration of Early Cretaceous basalts in the only onshore borehole drilled in the São Tomé Cape, and the Santos Basin lies entirely offshore. The western limit of the syn-rift sediments corresponds to a major fault affecting and offsetting the basement, or locally, to a hinge line marking the erosional limit of the Neocomian and Barremian sequences (Guardado et al., 1989). Towards the east, the crustal limit (COB on Figure 2) marks the end of the syn-rift sequences, and it often coincides with the salt scarp at the seaward edge of the salt diapir province (Chang et al., 1992; Demercian et al., 1993).

The maximum total sediment thickness in the Campos Basin is about 8,000 m, where as in the Santos Basin it may reach more than 10,000 m, and in the Espírito Santo Basin, the basement may be as deep as 12,000 m, particularly along the southern edge of the Abrolhos Volcanic Complex, landwards of the Vitória Trindade Ridge. This thick depocenter is marked by a major gravity low trending NW-SE (Fig. 2).

Rifting in the South Atlantic began during the Late Jurassic - Early Cretaceous, advancing from Argentina to south Brazil by propating N-S spreading centers (Mohriak, 2001). There is a gradual crustal thinning with a consequent Moho uplift from unstretched continental regions in the west, towards the pre-Aptian limit or border faults of the Pelotas, Santos, Campos and Espírito Santo basins (Fig. 3). An abrupt change in crustal architecture is observed near the platform, with a rapid rising of the Moho, and a gentle, smooth Moho topography towards the basin depocenters, as evidenced in deep seismic profiles along the margin (Mohriak et al., 1990). Figure 4 shows a transect along the Espírito Santo basin with the main structural horizons (including the Moho, which was obtained by gravity inversion) interpreted based on Petrobras regional grids. It is questionable whether the syn-rift sequence thickens below the salt walls in the deep water region or pinches out towards the crustal limit. There is growing evidence in the South Atlantic margin that the outermost limit of the salt layers is underlain by volcanic rocks (Mohriak, 2001).

The sedimentary successions observed in geoseismic transects along the Campos and Espírito Santo (Fig. 4) are charaterized by three megasequences with different environments of deposition and tectonic control. These include:

(1) the non-marine syn-rift megasequence, comprising lacustrine Neocomian to Barremian sediments may overlie Late Jurassic – Early Cretaceous basalts or Precambrian rocks. The playa lake environment is characterized by alluvial fans grading into mudflats with shallow lakes in the centre during arid periods. Deeper stratified lakes in the central part of the basin are characterized by euxinic sediments with excellent source rock characteristics.

(2) The transitional megasequence extends from late Barremian to late Aptian, and was deposited during a period of little tectonic activity, above a megaregional erosional surface known as the breakup unconformity, which marks the beginning of the post-rift or drift phase in the basin. It is associated with two major sedimentary units: the lower, mostly composed by shales, carbonates, sandstones and conglomerates, and the upper represented by halite, anhydrite, carbonates and other evaporite rocks. The evaporite layer may form huge salt diapirs in the deep water region, and locally, evidence for allochthnous salt tongues is evidenced near the São Paulo Plateau Escarpment (Demercian et al., 1993).

(3) The marine megasequence was deposited following the inception of oceanic crust (drift phase with thermal subsidence), and was greatly influenced by salt tectonics. It comprises and Albian to Cenomanian carbonate sequence, with shallow environments at the base and grading upwards into deeper marine environments. This sequence is overlain by Upper Cretaceous to Early Tertiary platform to bathyal sedimentary successions consisting of carbonates, shales, and marls with intercalations of sandstone turbidites. A typical passive margin progradational carbonate to siliciclastic sequence characterizes the present day depositional pattern of these basins.

The development of halokinesis in the Espírito Santo, Campos and Santos basin is related to sediment progradational episodes, overburden extension, gravity gliding, gravity spreading and locally, to the underlying rift architecture. Salt mobilization started in the Albian and continued throughout the Late Cretaceous, reaching a climax in the Tertiary. Early salt movement formed growth-fault structures which controlled the distribution of shallow-water carbonates that were preferentially deposited in structural highs (Guardado et al., 1989). The Early post-rift sequences above the Aptian salt is represented by the Albian-Cenomanian Macae Formation in the Campos Basin, the Guarujá Fm. in the Santos Basin, and the Regência Fm. in the Espírito Santo Basin. Sedimentation at this time was strongly controlled by growth-fault structures generated by salt tectonics, mainly due to gravity spreading and gravity gliding down the slope of the basin. Roll-over fold anticlines with faulted crests (crestal grabens) are common in the platform and in the deep water region. The amplitude and wavelength of these anticlines increases seawards and upwards, indicating an influence of the sedimentary thickness above the salt during compressional stresses. Continued salt movements occurred throughout the Tertiary, and some salt features continued to grow by passive diapirism and down-building, but locally they form plugs that may pierce sediments very close to the present day sea bed.

The salt tectonics styles along Atlantic-type continental margins are typically associated with 5 domains summarized as follows (Mohriak, 2001):

I, incipient salt tectonics, which may occur in areas with small quantities of original or residual evaporites;

II, extensional salt tectonics, usually associated with overburden extension and basinwards salt flow;

III, diapir province with compressional tectonics, usually basiwards of a hinge line that offsets this compartment from the previous one;

IV – strongly compressional salt tectonics near the boundary between continental and oceanic crust,

V – oceanic crust, which may be overlain by allochthonous salt tongues or by the feather edge of the original salt layers that advanced beyond the COB.

The Santos Basin (Figure 1) occupies the continental shelf off the southeast coast of Brazil adjacent to the states of Santa Catarina, Paraná, São Paulo and Rio de Janeiro, and extends offshore along the São Paulo Plateau. The São Paulo Plateau is a vast physiographic feature with bathymetry ranging from 2,000 m to 3,000 m and is associated with a thickening of the salt sequence and intense halokinesis in a very wide ultradeepwater region. The more distal portion of the southern parts of the São Paulo Plateau is marked by E-W lineaments which may correspond to the prolongation of fracture zones such as the Florianópolis Fracture Zone (FFZ), and by basement highs, for example, the Santos Basin SE High (Fig. 3). This regional high has alternative interpretations for the substratum: (1) continental crust with syn-rift sequences, affected by later uplift; (2) Precambrian High; and (3) extrusive complex of igneous rocks related to the breakup of the continental crust and emplacement of oceanic crust (Mohriak, 2001; Mohriak et al., 2002; Modica and Brush, 2004).

Figure 5 corresponds to a SW-NE regional seismic profile extending from the oceanic crust in the south towards the continental crust in the north. The profile shows that the crust in southern Santos Basin – northern Pelotas basin is intruded by igneous plugs associated with the propagation of oceanic spreading centers (Abimael Ridge, Fig. 2) advancing from the Pelotas Basin towards the southern Santos Basin (Mohriak, 2001). A major structural high in southern Santos Basin has been active from the beginning of the rift towards the end of the salt deposition, which indicates a probable relationship with the formation of oceanic centers, and thus would have a volcanic origin (Mohriak, 2001; Meisling et al., 2001). Uplift of the syn-rift sequences or volcanic layers is still observed after deposition of the evaporite layers, suggesting compressional events. Alternatively, Modica and Brush (2004) interpreted this megaregional high (which appear even on Geosat gravity data) to correspond to an uplifted block of Precambrian rocks.

The styles of salt tectonics in the the Campos and Santos Basin have been discussed by several authors (e.g., Demercian et al., 1993; Cobbold et al., 1995; Mohriak et al., 1995). One of the most intriguing features in the northern Santos Basin corresponds to the Cabo

Frio antithetic fault zone and the Albian gap, which is associated with massive clastic progradation and salt expulsion towards the deep water region (Mohriak et al., 1995), resulting in piling up of thick sedimentary wedges that become younger basinwards, towards a major listric fault that dips landwards. This fault, which soles out in the salt, is unique to the Santos Basin, both in length (about 300 km) and in width of the half-graben (50 km), and has no counterparts at the same scale in other segments of the Brazilian or West African margin. The expanded stratigraphic sequence is restricted to the Upper Cretaceous through Early Tertiary sediments that lies above the salt, but locally there is evidence that basement-involved faults may be controlling small pods of Aptian evaporites.

The deep water salt diapir province in the Santos Basin is characterized by salt walls affected by compression, locally with recumbent folding (Cobbold et al., 1995). There is a regional reflector with strong impedance contrast at the top of the salt diapirs that also occurs in the mini-basins, above a sequence of layered reflectors, which might correspond to Albian to Late Cretaceous sediments or to the top of a layered sequence of evaporites (Demercian et al., 1993; Modica and Brush, 2004). This enigmatic reflector that occurs above the salt layer advances oceanwards towards the area identified to be underlain by volcanic basement.

Conclusions

This work discussed major structural elements in the Southeastern Brazilian margin, from the Espírito Santo, Campos and Santos basins, some of which are imaged even in large scale maps such as the ones derived from the Geosat dataset, such as the Vitória-Trindade Ridge in the Espírito Santo Basin, the Badejo High and the Outer High in the Campos Basin, and the volcanic highs and fracture zones in the southern Santos Basin.

Major tectonic features in the Espírito Santo Basin are the Vitoria-Trindade Ridge, an east-west lineament probably associated with a hot spot, and the Abrolhos Volcanic Complex, which marks the eastern part of the Espirito Santo Basin and is associated with a thick sedimentary sequence and basalts dated as Late Cretaceous to Early Tertiary. The southern portion of the Espirito Santo Basin corresponds to a reentrant of the bathymetry, approximately westwards from the prolongation of the volcanic features imaged as seamounts in the oceanic crust. The Vitória-Trindade lineament, a major E-W ridge that separates oceanic crusts with different seismic characteristics and apparently different overburden thickness. The Espírito Santo Basin is characterized by a very thick sag basin or syn-rift II (Barremian to Aptian age) that extends from the plataform towards the deep water region.

The Vitória High separates the Espírito Santo from the Campos Basin. The Cabo Frio High bounds the Campos Basin to the south, separating it from the Santos Basin depocenters. The Cabo Frio High is associated with post-rift tectono-magmatic events dated from Santonian to Eocene. The Campos Basin is marked by the Badejo High in the platform, controlled by major antithetic faults, and the Outer High in deep waters, which is a volcanic high separating two syn-rift basins which show different characteristics in seismic data. There is a marked inflection of this high towards a northerly direction from Campos to Espírito Santo. The platform region of the Campos Basin is characterized by an abrupt crustal thinning near Cape São Tomé, with underplated rocks forming an antiformal shape in the lower crust, and a similar feature is imaged in the platform of the Espírito Santo Basin, with deep seismic reflectors interpreted to correspond to Moho uplifts or to emplacement of underplated rocks.

The analysis of regional deep seismic lines indicates that the outer limits of the Aptian salt basin and the syn-rift sequence in the Santos Basin may be characterized by a post-rift extrusive complex, related to the genesis of the proto-oceanic crust. The region between the salt basin and the Florianópolis Fracture Zone may be underlain by volcanic rocks rather than by sedimentary siliciclastic rocks as previously interpreted.

The transitional stage is characterized by the decay of extensional activity and by the first marine incursions into the grabens formed during the rifting. The Transitional Megasequence can be divided into a lower terrigenous sequence (alluvial/fan delta and sabkha environments) and an upper sequence which may contain different cycles of evaporites locally forming stratified salt layers.

The development of halokinesis along the margin is related to sediment progradational episodes, overburden extension, gravity gliding, gravity spreading and are locally influenced by underlying rift architecture. Salt mobilization started in the Aptian and had a major influence on the development of the Albian structures. Salt tectonics along the margin formed several tectonic compartments characterized by extensional to compressional domains. Near the coast there is an upper domain, with a suite of structures attributable to down-dip extension. Towards the deep basin there is a lower domain where the structures can be attributed to contraction, forming several structures such as growth folds of various wavelengths, thrust faults and nappes that may advance basinwards as salt tongues. Salt pillows occur mainly in the platform and evolve into large salt diapirs and salt walls by passive diapirism and down-building.

The post-salt sedimentary successions in the Cabo Frio fault zone are controlled by a major antithetic fault, which resulted in the Albian gap, a major feature trending NE-SW that extends towards the central part of the basin.

The Cabo Frio antithetic fault is associated with massive clastic progradation episodes in the platform that resulted in mobilization of the salt layer basinwards. The successive progradation episodes between the Late Cretaceous and Early Tertiary resulted in loading of the evaporite layers and salt being expulsed towards the deep basin. The sediment accumulation was controlled by an antithetic fault (probably triggered by basement-involved faults), that resulted in expansion and younging of the stratigraphy basinwards. This process resulted in submarine fans that are highly rotated due to the expulsion of the underlying salt, and created immense

gaps of sedimentary strata, the largest of which is known as the Albian gap.

The presence of an high-impedance contrast reflector extending throughout a large area of the salt diapir province in the Santos Basin suggests the possible occurrence of stratified evaporites within mini-basins separated by a more mobile and transparent halite facies (Cobbold et al., 1995; Modica and Brush, 2004). This reflector extends towards the outermost salt diapir province, near the crustal limit.

The southern portion of the Santos Basin is marked by E-W fracture zones (example,. the Florianópolis FZ), and by regional highs along a N-S direction. A megaregional gravity and structural high in the southern portion of the Santos Basin has been alternatively interpreted as syn-rift high, a Precambrian High, and a volcanic high associated with the emplacement of oceanic crust (Mohriak, 2001; Meisling et al., 2001; Modica and Brush, 2004).

Some of the themes that are still under debate and constitute topics for further research include: (1) position and nature of the the crustal limit (boundary between continental and oceanic crust) in areas underlain by thick evaporite layers; (2) delimitation of the outermost syn-rift blocks that probably are present below the thick salt layers in deep waters; (3) differentiation between rifts with siliciclastic infill and rifts with volcanic infill; (4) characterization of volcanic ridges and transform or hotspot lineaments; (5) identification of the mechanisms of formation of the wedges of seaward-dipping reflectors that commonly occur in the transition from continental to oceanic crust; (6) identification of features associated with normal faults in oceanic crust domains; (7) characterization of heat flow patterns in different tectonic domains and implications on source rock maturation; and (8) identification of the basement-involved tectonic controls on the development of different styles of salt tectonics.

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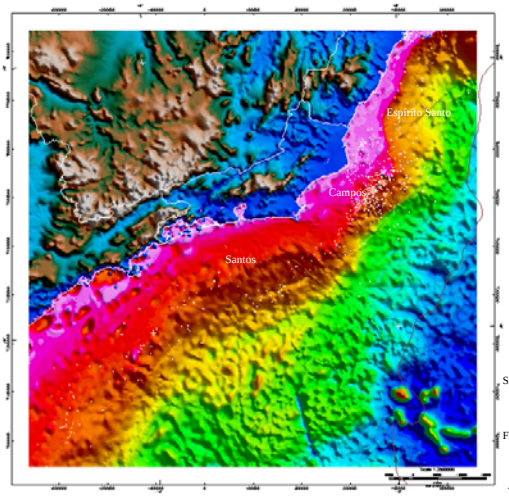

Figura 1 - Topographic - bathymetric map of SE Brazil.

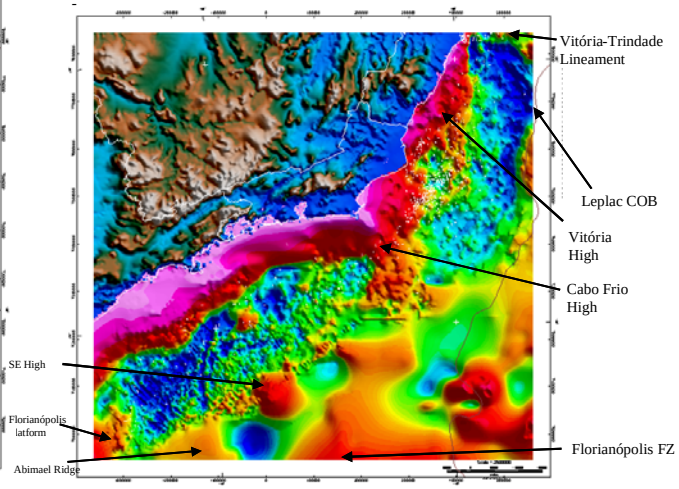

Figura 2 - Structural map (depth-converted) for the top of the basement reflector.

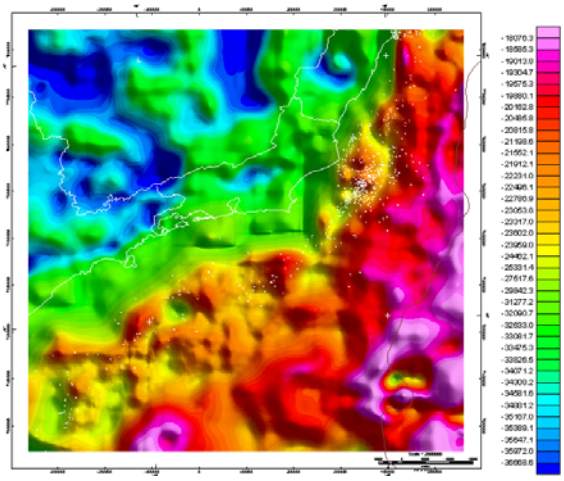

Figura 3 -Structural map (depth-converted) for the Moho discontinuity obtained by gravity inversion.

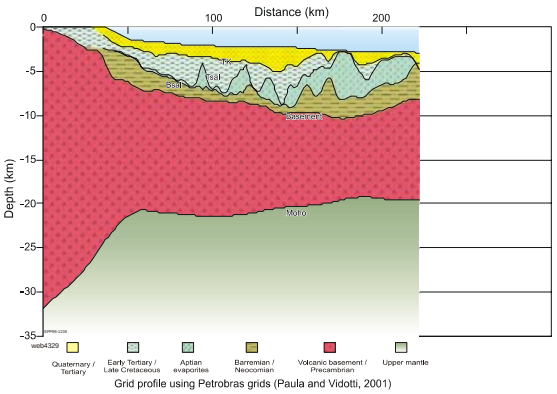

Figura 4 Regional geoseismic profile (depth-converted) with stratigraphic horizons and Moho topography obtained by grid profile and gravity inversion.

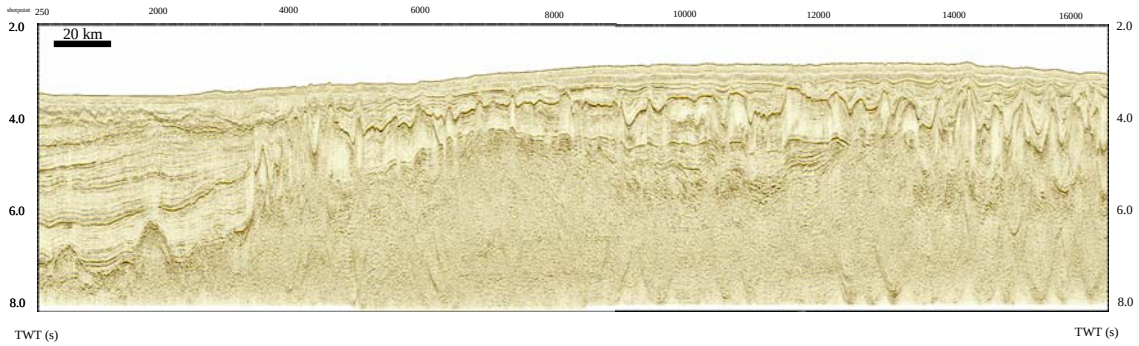

Figura 5 Regional seismic profile in the southern part of the Santos Basin, across the SE High.