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A FAILED SEA-FLOOR SPREADING CENTRE, SANTOS BASIN, BRASIL.

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Abstract

Regional evaluation of the Santos Basin, Brazil, using 2-D seismic and gravity / magnetic data has revealed a linear basement anomaly within the centre of the basin, extending NNE from a large igneous body to the western end of the Santos Fault. This feature coincides with an area of high thermal maturity within potential source rocks and with poor permeability due to intense cementation within clastic reservoirs, indicative of higher heat-flow. Structural reconstruction and modelling indicates a high degree of crustal thinning with raised heat-flows associated with this feature. Integration of the data over this feature with the structural reconstruction suggests it is either a failed break-up basin or an aborted sea-floor spreading centre, both of which could explain the observed geophysical and thermal anomalies. Plate tectonic reconstructions indicate the early South Atlantic sea-floor spreading centre ended at the Florianopolis Fracture Zone in the outer part of the Santos Basin. The linear anomaly in the Santos Basin appears to be a failed attempt to continue this centre north-eastwards towards the Brazilian coast line and was apparently abandoned early in its development. Subsequently, a successful spreading centre developed to the east, continuing the northwards opening of the South Atlantic Ocean.

1. Introduction

Brazil's Santos Basin is the southernmost of the petroliferous chain of basins along the western margin of the South Atlantic Ocean. These basins, the Santos, Campos and Espirito Santo Basins, resulted from rifting of the Gondwanaland "super-continent" in the earliest Cretaceous with break-up and subsequent sea-floor spreading. The Santos Basin is a NE-SW trending basin that covers about 200,000 km^2 of the Brazilian continental margin. The basin is bounded by the Cabo Frio Arch to the north and by the Florianopolis Platform to the south, both features related to magmatic activity associated with the westward prolongation of the ocean fracture zones (Cainelli & Mohriak, 1998). The western limit of the basin is defined by the Precambrian rocks of the Serra do Mar, a coastal range reaching up to 2000m high, while to the east the basin is flanked by the Sao Paulo Plateau.

Rifting in the Santos Basin began around 140 Ma in the Neocomian-Early Aptian, with siliciclastic and coquina deposition, probably interfingering with Lower Cretaceous basalts. Lacustrine, organic-rich shales of the Lagoa Feia Fm. were deposited in the basin centres (Pereira & Feijo, 1994). The rift sequence is overlain by evaporites, comprising intercalations of anhydrite and halite, the latter greatly influencing basin-fill during the later evolution of the basin, with extensive halokinesis producing large salt diapirs and walls within the deep water regions.

The drift phase was initiated around 112 Ma and the post-rift succession consists of coarse sandstones, carbonates and grey shales deposited during progressive deepening of the basin, with the maximum flooding conditions being marked by dark grey shales of Turonian age (Itajai-Acu Fm.). In the proximal areas, a thick conglomerate

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package and shallow marine sandstones were deposited during the Santonian to Maastrichtian in response to the Serra do Mar uplift (dated at 100 - 80 Ma by Lelarge 1993). The Santos Basin evolution during Cenozoic is characterized by a basinward progradation of siliciclastics over platform/slope shales and marls.

Regional evaluation of the Santos Basin, using an approximate 4 x 4 km grid of 2-D seismic data combined with both satellite and ship-bourne gravity and magnetic data has shown that the structure of the basin is complex with several unusual features. One of these features, which is the subject of this paper, forms a linear negative gravity anomaly stretching from the outer southwestern part of the basin north-north eastwards into the basin centre (Figure 1).

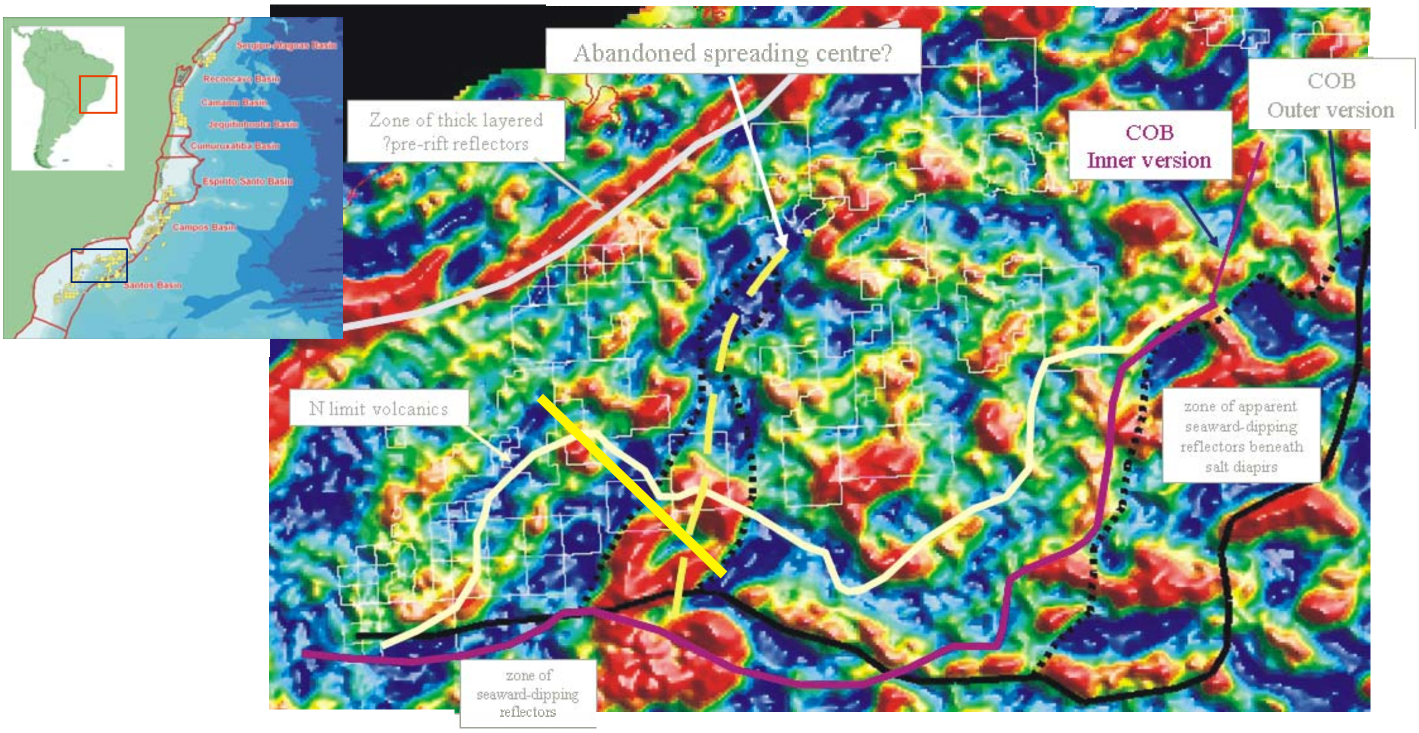


Figure 1. Satellite Bougeur gravity anomaly map (200km high pass filter) over the central area of Santos Basin showing linear feature with strong negative gravity anomaly. Yellow line is seismic section in Figure 2.

On the seismic data a feature within the pre-salt basement section can be seen on data crossing the same alignment (Figure 2), extending from an igneous feature within the basement at the southwestern end and terminating in the basin centre beneath the so-called Santos Fault. Associated with this feature are anomalies in the regional thermal maturity of overlying source rocks within the early Cretaceous Lagoa Feia Formation, concurrent with greatly reduced reservoir properties in overlying late Cretaceous turbiditic sandstones. These anomalies in the sediment cover suggest the feature was associated with considerably higher palaeo-heat flows than the surrounding basin areas and could be related to the rifting and formation of the South Atlantic Ocean. A regional study of satellite gravity data and seismic data was undertaken, followed by back-stripping and modeling of the crustal rifting and extension across the Santos Basin.

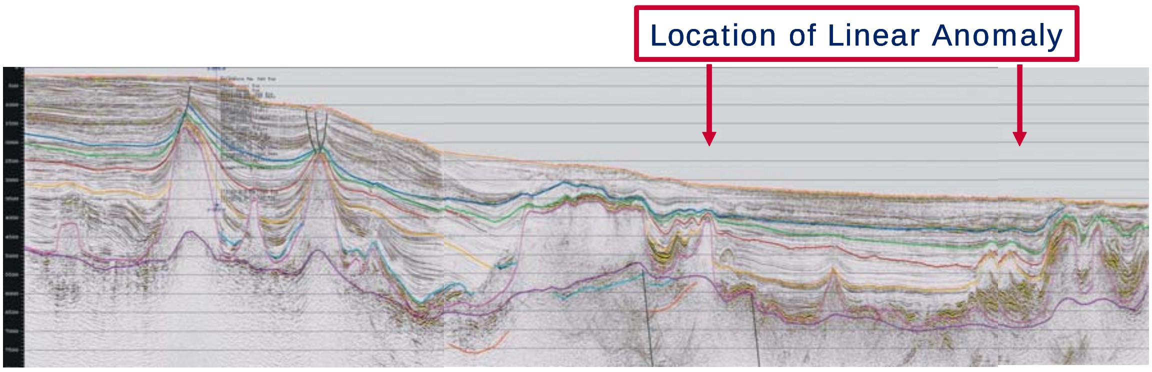


Figure 2: Seismic Line across centre of linear anomaly. Line located on Figure 1.

Recent regional studies of the Santos Basin for the Brazil 7th Licence Round in 2005 have indicated that the Santos Basin has had a much more complex geological history and this paper aims to illustrate a feature discovered during this evaluation and the subsequent work undertaken to understand its significance to the geology and prospectivity of the basin.

2. Methodology

Regional mapping of the Santos Basin on 2-D seismic data allowed the areal extent and nature of the feature to be mapped. A loose grid of long composite 2-D sections where chosen to characterize the feature and these were depth converted and used as a basis for the reconstruction and modeling of the basin. A grid of eight regional cross-sections (Figures 3 and 4), based on the regional seismic lines, was to reveal information on the subsidence history and the magnitude of crustal/lithosphere stretching in the Santos Basin. Each profile was backstripped independently and then the results for the full grid have been converted to map form to provide a basin-wide model for subsidence and stretching. Independently, determination of Moho depth and crustal thickness was made using satellite gravity anomaly inversion.

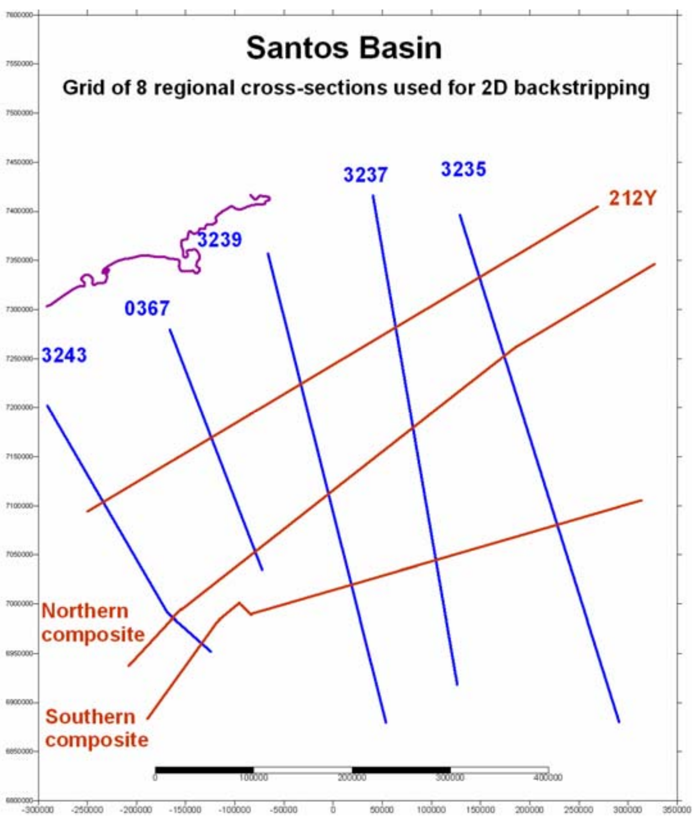


Figure 3. Location of composite regional seismic lines used for 2-D backstripping

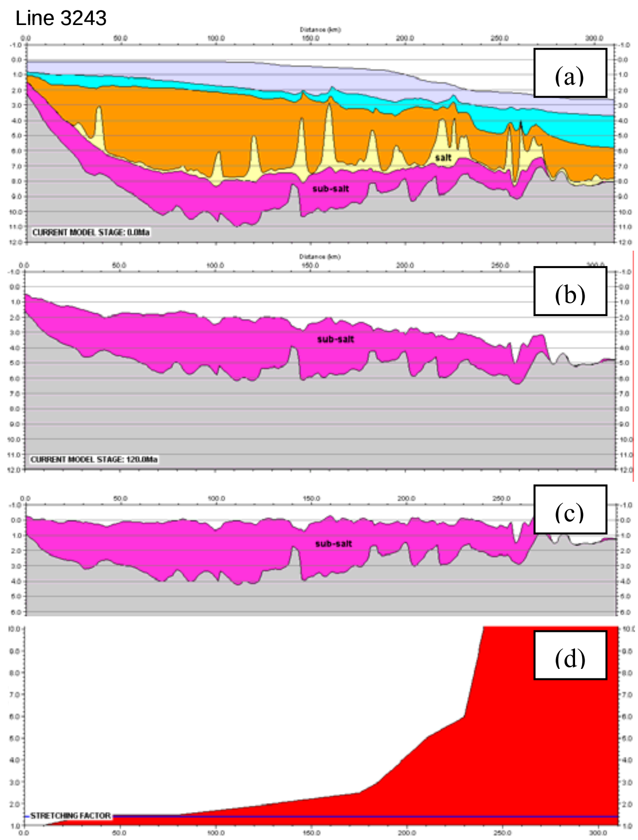


Figure 4: 2-D Backstripping of line 3243.

2.1 Analysis of subsidence and stretching by 2D backstripping

Each profile was backstripped twice, following the 2D flexural-backstripping methodology of Roberts et al (1998). The first backstripping iteration involved sequential removal of the stratigraphy (Fig.4a) down to the base salt (120Ma), accompanied by sediment decompaction and flexural-isostatic unloading, but without reverse thermal-subsidence modelling. This results in a backstripped profile with the base-salt restored to seabed (Fig. 4b). Assuming the base-salt surface to be a palaeo-sealevel marker at the time of deposition then the residual bathymetry of the backstripped restoration (above the base salt) represents the backstripped water-loaded subsidence to have affected the base salt over the 120Ma period since deposition. Figure 5 shows the mapped distribution of water-loaded subsidence from all eight profiles, which (unsurprisingly) increases oceanwards, away from the Brazilian coast. Close to the

Brazilian coast water-loaded subsidence is <1km, increasing to ~5km in more distal areas of the basin close to the ocean margin (Fig.4b).

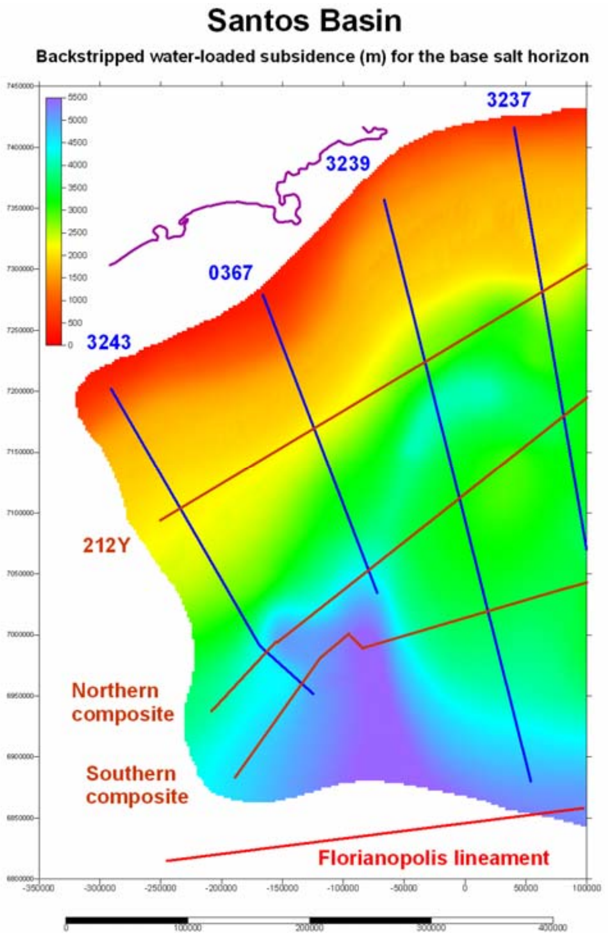


Figure 5: Backstripped water loaded subsidence (m) for the base salt horizon

The second backstripping iteration included reverse thermal-subsidence modelling, with the specific aim of recovering the water-loaded subsidence of the initial model (Fig.4b) and restoring the base salt to its correct palaeogeographic position at sea-level (Fig.4c). In the inboard area of the basin this involves applying moderate beta factors to recover the required subsidence, but in the outer areas of the basin high-to-extreme beta factors must be applied (Fig.4d). In the most outboard areas of the basin, close to the ocean margin, even oceanic beta factors will not restore the base salt back to sea-level, which leads to some questioning of the backstripping methodology applied. Restoration by 2D backstripping (Roberts et al 1998) specifically implies that all backstripped subsidence is modelled as post-rift thermal subsidence, rather than as syn-rift tectonic subsidence. It is very likely, however, that the base salt of the Santos Basin has experienced both syn-rift (Atlantic break-up) tectonic subsidence at ~110-120Ma, followed by continued thermal subsidence to the present day. If this is the case then treating the water-loaded subsidence as post-rift only will lead to an overestimate of the beta stretching factors required to model the subsidence.

A new methodology has been derived which will convert total backstripped water-loaded subsidence into the appropriate syn-rift and post-rift components and from this derive estimates of beta factor which acknowledge both contributions to the subsidence history. This methodology uses a pure-shear (unfaulted) implementation of the 2D flexural-cantilever model (Kusznir et al 1995) to produce a highly-stretched, water-loaded basin which is forward modelled through a syn-rift and 120Ma post-rift history subsidence history. The water-loaded subsidence experienced by this model can then be used to convert the mapped water-loaded subsidence to a map of beta stretching-factor which incorporates both the syn-rift and post-rift contributions to subsidence.

2.2 Determination of Moho Depth and Crustal Thickness

Moho depth and crustal thickness were using satellite gravity anomaly inversion (Figure 6). Satellite derived gravity anomaly data (Smith & Sandwell 1997), bathymetry data (Gebco 2003) and a correction for the gravity anomaly contribution from sediments using thickness estimates from seismic reflection data are used to derive the mantle residual gravity anomaly which is inverted in the 3D spectral domain (Parker 1972) to give Moho depth. Density depth variation within sediments is predicted assuming compaction.

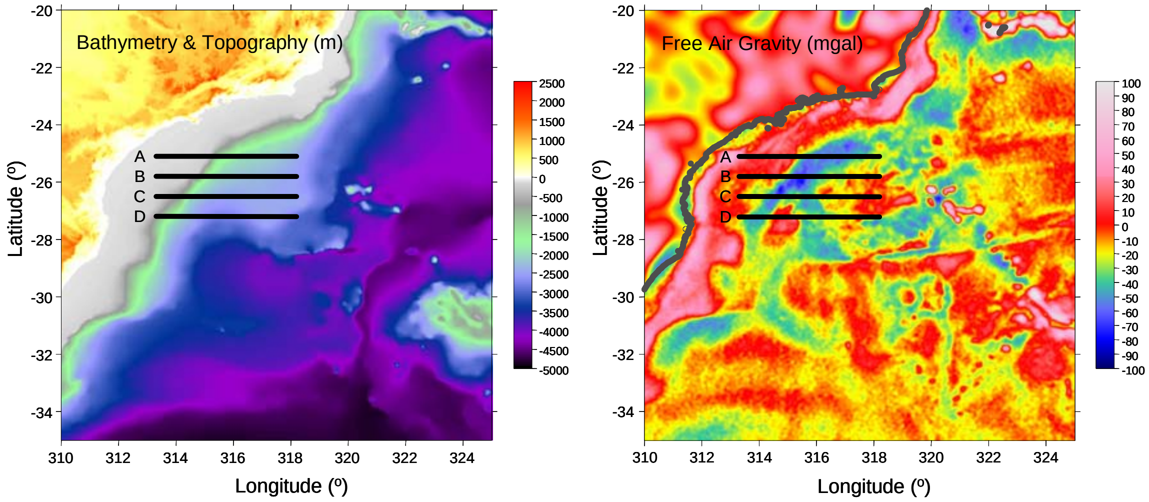


Figure 6. (a) Bathymetry and topography (Gebco 2003), and (b) free air gravity anomaly (Sandwell & Smith 1997) for the Santos Basin and adjacent segments of the Brazilian continental rifted margin. A-D denotes the location of the 4 crustal cross-sections.

Moho depth and crustal thickness have been determined for the Santos Basin, offshore Brazil, using satellite gravity anomaly inversion (Figure 6). Satellite derived gravity anomaly data (Smith & Sandwell 1997), bathymetry data (Gebco 2003) and a correction for the gravity anomaly contribution from sediments using thickness estimates from seismic reflection data are used to derive the mantle residual gravity anomaly which is inverted in the 3D spectral domain (Parker 1972) to give Moho depth. Density depth variation within sediments is predicted assuming compaction.

Oceanic and rifted continental margin lithosphere have elevated geothermal gradients as a consequence of continental breakup and sea-floor spreading. As a consequence both oceanic lithosphere and stretched continental margin lithosphere have a large negative lithosphere thermal gravity anomaly (up to -380 mgal at the ocean ridge). The inversion of gravity data at rifted continental margins to map crustal thickness variation and predict the location of the ocean-continent transition (OCT) requires the incorporation of a lithosphere thermal gravity anomaly correction (Hurst & Kusznir 2005). The gravity inversion using the thermal gravity correction predicts oceanic crustal thicknesses consistent with seismic observations (Hurst & Kusznir 2005), while that without the thermal correction predicts much too large oceanic crustal thicknesses.

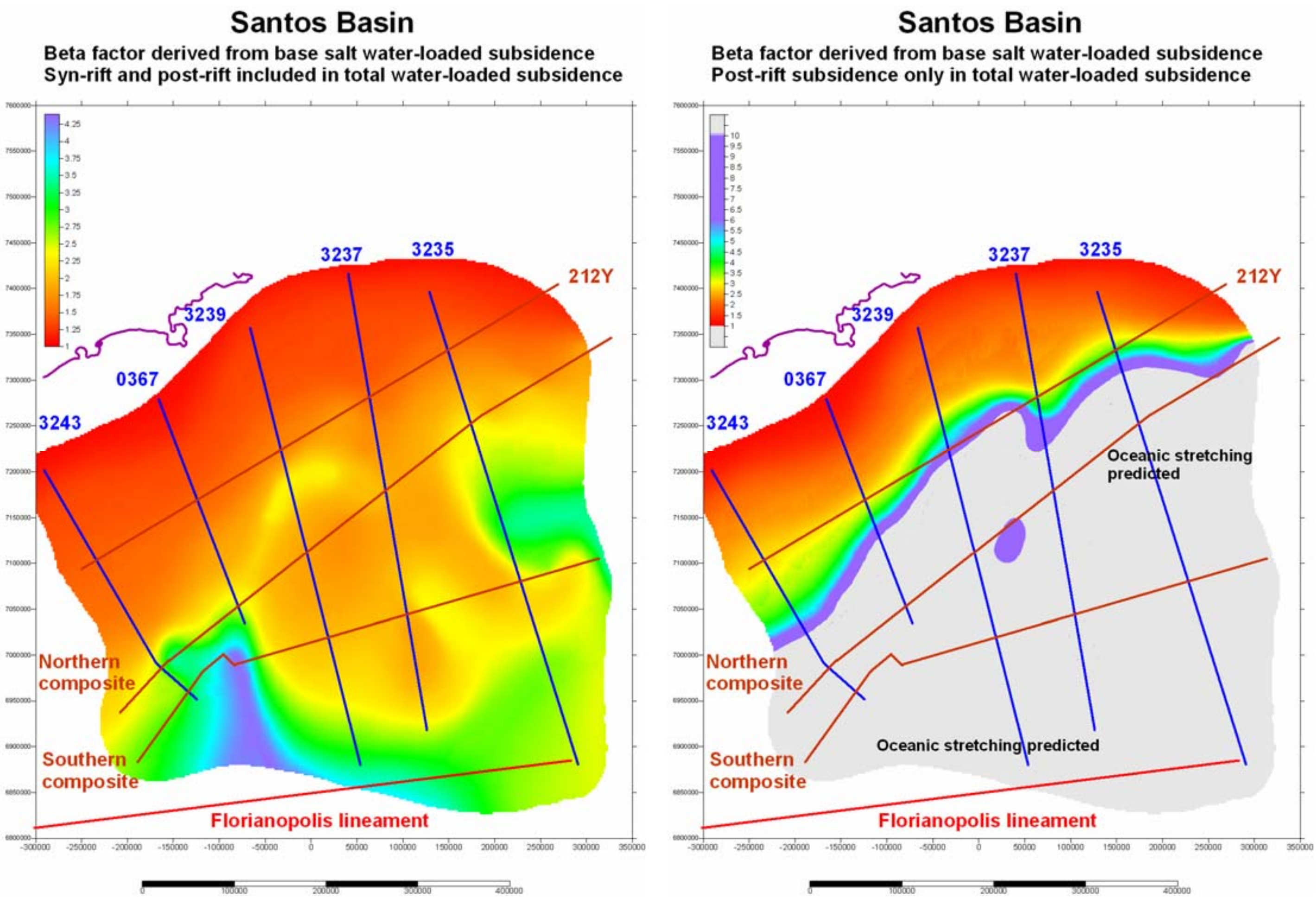
The lithosphere thermal model used to predict the gravity anomaly correction may be conditioned using magnetic isochron data to provide the age of oceanic lithosphere (e.g. Müller et al. 1997). The resulting crustal thickness determination location is however sensitive to errors in the magnetic isochron data. An alternative method of inverting satellite gravity at rifted continental margins to give crustal thickness, incorporating a lithosphere thermal correction, has been developed which does not use a priori information of the location of the OCT using magnetic isochron data (Hurst & Kusznir 2005). This new modified form of gravity inversion with embedded thermal correction provides an improved estimate of rifted continental margin crustal thinning and an improved (and isochron independent) prediction of OCT location.

Where oceanic isochrons are believed to be reliable, the lithosphere thermal gravity correction may be determined for oceanic lithosphere from ocean lithosphere age, and for the thinned continental margin lithosphere using margin rift age and β stretching estimates (McKenzie 1978) iteratively derived from crustal basement thickness determined from the gravity inversion. Where ocean isochrons are unknown or unreliable, all lithosphere is assumed to be initially continental and a uniform lithosphere stretching age is used corresponding to the time of continental breakup. The lithosphere thinning factor (1-β) produced by the gravity inversion is used to predict the thickness of volcanic addition (and oceanic crust) using an empirical relationship, which is used to improve the estimate of β stretching factor from crustal thinning determined from the gravity inversion.

Results

This new map of beta factor for the Santos Basin is shown in Figure 7. Beta factor increases from <1.5 in coastal areas to >3 (locally >4) in the areas of the basin close to the ocean margin. We can be fairly confident that this map provides a low-end estimate of beta factor, because it does not incorporate the possible buoyant effects of any igneous underplating which would lead to an increase in estimated beta factor (see discussion in Roberts et al 1997, p553). In the outer areas of the basin the interpreted fault-controlled extension does not match the high stretching estimates from backstripping and thus we can be reasonably confident that the process of depth-dependent stretching (Roberts et al 1997, Davis & Kusznir 2004) has operated in the Santos Basin, adjacent to the Atlantic continental margin.

If Figure 7 provides a considered low-case estimate of beta factor then Figure 8 provides the high-case alternative. This map of beta stretching-factor has been produced by assuming that all water-loaded subsidence of the base salt (Figure 5) is post-rift only (no syn-rift contribution) and is thus analogous to the beta profiles applied during the second 2D backstripping iteration (Figure 4d). This map shows large areas of the Santos Basin to have experienced oceanic magnitudes of stretching and on geological grounds this is considered an almost-certain overestimate of the stretching in these areas. Figure 7 is a more reliable estimate of the likely stretching experienced.



Figures 7 and 8: Beta Factor derived from Base Salt water-loaded subsidence, Figure 7 including both syn and post rift in the total water-loaded subsidence, Figure 8 including only post-rift subsidence.

The new gravity inversion method of crustal thickness and OCT mapping has been applied to the Santos Basin segment of the Brazilian continental rifted margin. The predicted crustal basement thickness and lithosphere thinning factor ($1-1/\beta$) from the satellite gravity inversion using the lithosphere thermal gravity anomaly correction is shown in

Figure 9.The volcanic addition thickness predictor used in the gravity inversion is tuned for a volcanic margin. Crustal cross sections (located in Figure 6), in which Moho depth has been determined using the new gravity inversion method, are shown in Figure 10. Crustal basement thinning in the Santos Basin is shown to thin southwards. The low crustal thicknesses shown on cross-section D, located to the north of the Florianopolis Fracture zone, suggest that the southern Santos Basin is underlain by oceanic crust.

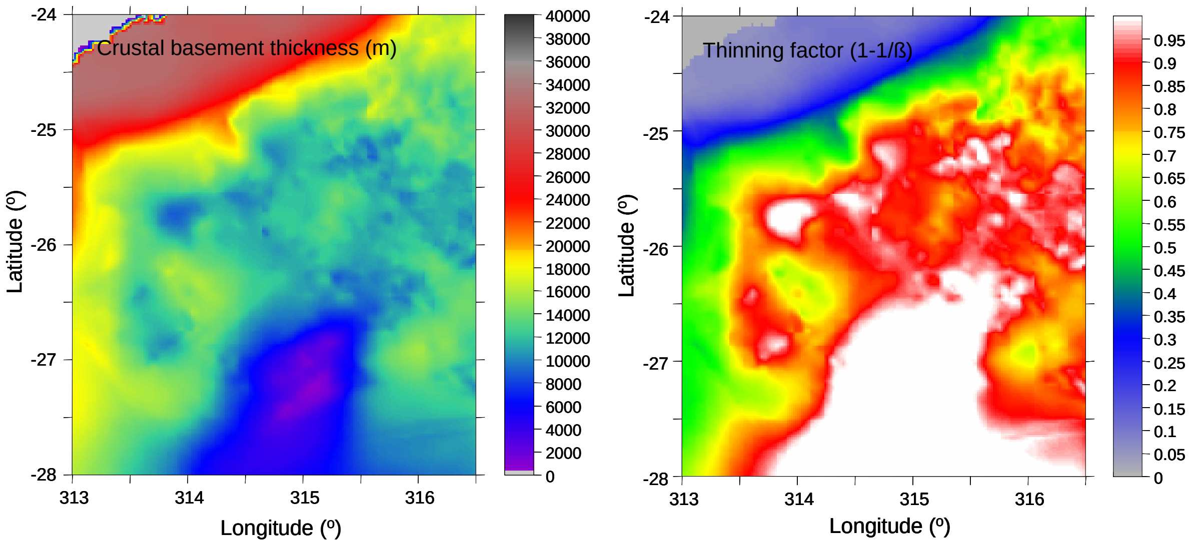


Figure 9: (a) Crustal basement thickness and (b) lithosphere thinning factor (1-1/β) for the Santos Basin segment of the Brazilian margin predicted by the gravity anomaly inversion with lithosphere thermal gravity anomaly correction

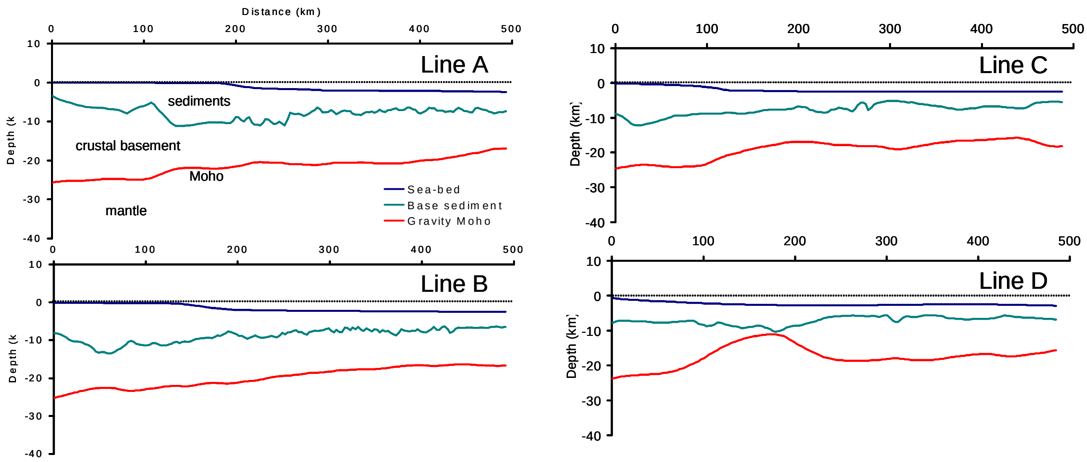


Figure 4: Crustal cross-sections across the Santos Basin along 4 profiles located in figure 1. Moho depth has been determined by gravity inversion using a lithosphere thermal gravity anomaly correction. Crustal basement thickness increases southwards. Very thin crustal basement for profile D in the south of the Santos Basin is interpreted as oceanic crust and implies that sea-floor spreading occurred to the north of the Florianopolis Fracture Zone

Conclusions

The results of these studies indicates the linear seismic and gravity anomaly is a zone of very high extension and likely emplacement of oceanic crust. This suggests that the feature represents either a failed break-up basin generated by unsuccessful rifting or an abandoned sea-floor spreading centre, resulting from an early attempt by the incipient South Atlantic Ocean to extend opening north of the Florianopolis Fracture Zone (Figure 11).

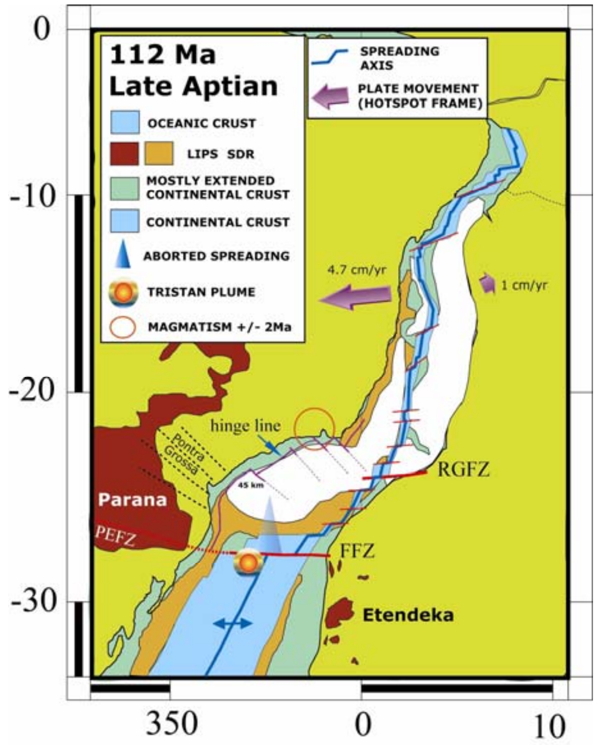


Figure 11: Postulated failed extension of sea-floor spreading into the Santos Basin (After NGU)

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