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From oceanic crust to exhumed mantle: a 40 year (1970-2010) perspective on the nature of crust under the Santos Basin, SE Brazil

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Abstract: The first comprehensive geological and geophysical surveys of the Brazilian continental margin during the 1970s recognized the crust in the SE Brazilian basins as 'anomalous' but models for the opening of the South Atlantic proposed at that time invoked a very narrow continent–ocean transition. Nevertheless, such studies established the presence of a thick sedimentary prism, including an extensive salt layer under the São Paulo Plateau. The earliest reconstructions for the South Atlantic invoked a seaward shift of the spreading axis to account for the asymmetric widths of the salt layer between the Brazilian margin and its conjugate in offshore Africa.

Although our understanding of continental–oceanic transition has progressed since then, direct seismic imaging at crustal scale has only been possible recently through long offset (10 km), deep recording (18 s), pre-stack depth migrated ((PSDM) to 40 km) seismic-reflection data. These data allow us to generally image the Moho from under thick continental crust (>30 km) to thin oceanic crust (*c*. 5 km). Although the nature of the transitional crust is still contested with various different proposals, these data allow for constraints on various models for continent–ocean transition. Future integrated studies utilizing PSDM and refraction seismic data will further refine these models.

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The purpose of this paper is to review the crustal architecture of the area underlying the Santos Basin, offshore SE Brazilian margin, and the evolution in understanding the crustal structure of this basin from the 1970s until today. Although improvements in all geological and geophysical technologies have contributed to this advancement, this paper will show that the seismic technology holds the key to understanding the nature of the continent–ocean transitions in conjugate margins.

As the need for multidisciplinary studies became clear for understanding continental margins, the 'International Decade of Ocean Exploration (IDOE, 1971–1980)' (Intergovernmental Oceanographic Commission 1974) was launched to create a vehicle for such large-scale studies. Brazil took an early lead in this effort and various Brazilian agencies, in co-operation with institutions around the world, particularly in the United States, launched 'Reconhecimento global da margem continental brasileira (Projeto REMAC)' (Petrobras 1979). This effort led to a variety of publications, maps and reports that mark the beginning of systematic geological and geophysical investigations of the Brazilian margin. These studies show that key problems in understanding the evolution of continental margins have been with us for some time. However, modern seismic technology now enables us to image those regions of the crust that could not be imaged before, thus allowing us to restrict the possibilities for the nature of the continent–ocean transition.

Study area

The study area extends more or less between 18° and 28°S latitudes and 38° and 47°W longitudes, occupying the offshore extents of the Espirito Santo, Campos and Santos basins (Fig. 1). However, this paper primarily deals with seismic data from the Santos Basin, which underlies the São Paulo Plateau (Figs 2 & 3). This plateau is a morphological feature, which extends at least 300 km beyond the 1000 m-isobath to water depths of 3000 m or more. The conjugate basins on the African margin for the Brazilian basins mentioned are the Kwanza, Benguela and Namibe basins, located to the north of the Walvis Ridge (Fig. 1) (Mohriak 2004).

As shown in Figure 1, the margins to the south of the study area are characterized by thick wedges of seaward-dipping reflectors (SDRs) (Hinz *et al.* 1999; Mohriak *et al.* 2002). These are conjugate to the region south of the Walvis Ridge on the African side (Bauer *et al.* 2000). Although Hinz *et al.* (1999) mapped a zone of SDRs in the Santos Basin area, subsequent authors (e.g. Mohriak *et al.* 2002)

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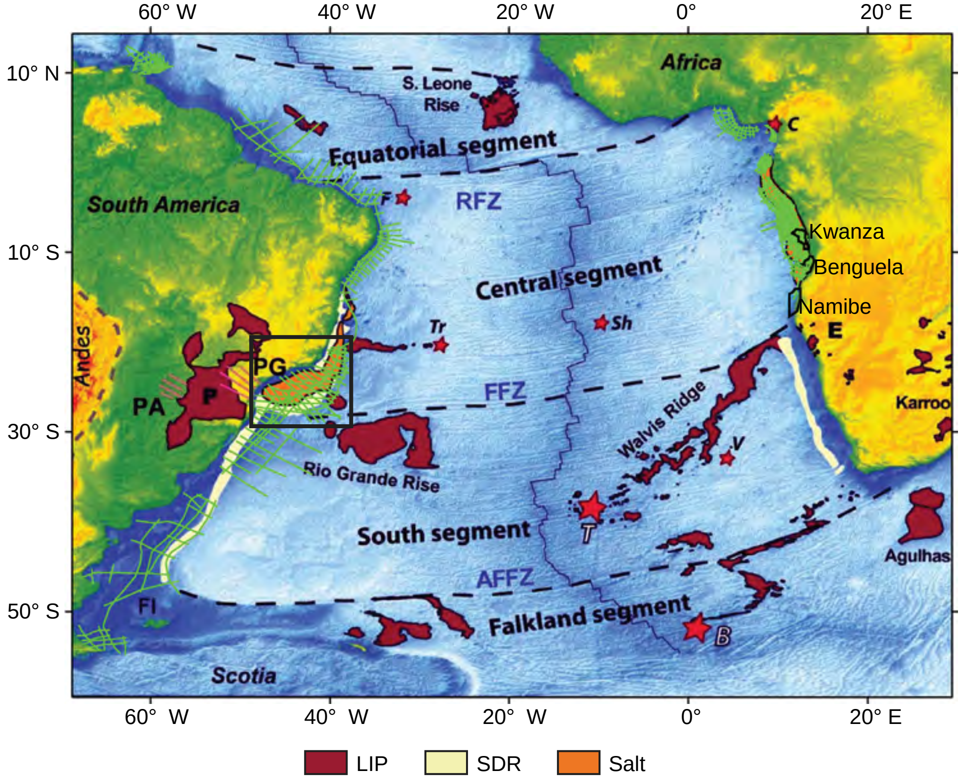

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Fig. 1. Regional map of the South Atlantic (modified from Torsvik *et al.* 2009) showing the locations of regional seismic data (green lines) in the Brazilian and African margin. The map shows the topography on land and bathymetry offshore. Some of the abbreviations used are as follows: SDRs, seaward-dipping reflectors; LIP, large igneous province (E, Etendeka; P, ~~Parana~~). Stars mark 'hot spots': T, Tristan da Cunha; PG, Ponta Grossa Dyke System; PA, Paraguay Dyke System; FFZ, Florianópolis Fracture Zone. The box marks the location of the study area. Some of the conjugate basins on the African margin are also labelled. Other explanations are in the original reference.

terminate the SDR zone at the Florianópolis Fracture Zone (FFZ) (Fig. 1). In almost all of our seismic data in the São Paulo Plateau, we have not seen convincing evidence of the presence of SDRs. In addition, Jackson *et al.* (2000) mapped large igneous provinces (LIPs) in the Atlantic Ocean extending from the Argentine margin to the south of the São Paulo Plateau (terminating at the FFZ, Fig. 1). These authors mapped another region significantly north of the study area near 12°S latitude.

Figure 2 shows the locations of seismic lines that form the basis of interpretations presented in this paper. Figure 3 shows the seismic grid on a free-air gravity anomaly map of the region (Sandwell & Smith 1997), with the same three seismic lines highlighted. Most of the lines in the area start at the shelf edge (>200 m); short extensions were added to some of the lines to water depths of 20 m.

These extensions have been merged with the longer lines crossing the Santos and Campos basins. As a reference, we have shown the boundaries of basins in the study area from the IHS database, used by many companies in the oil and gas industry. These boundaries may not represent the 'true' boundaries of these basins for all the readers of this paper. As shown on Figure 2, there are small rift basins in the onshore region of the study area; the largest of these is the Taubaté Basin, formed in ~~Late~~ Tertiary time (Asmus 1984). The large Paraná Basin in SE Brazil developed in Palaeozoic times, and was strongly affected by magmatic events during the formation of the South Atlantic Ocean in the Early Cretaceous (Torsvik *et al.* 2009).

Early studies (1970–1980)

Multidisciplinary studies carried out in the Brazilian margin during the 1970s included seismic reflection

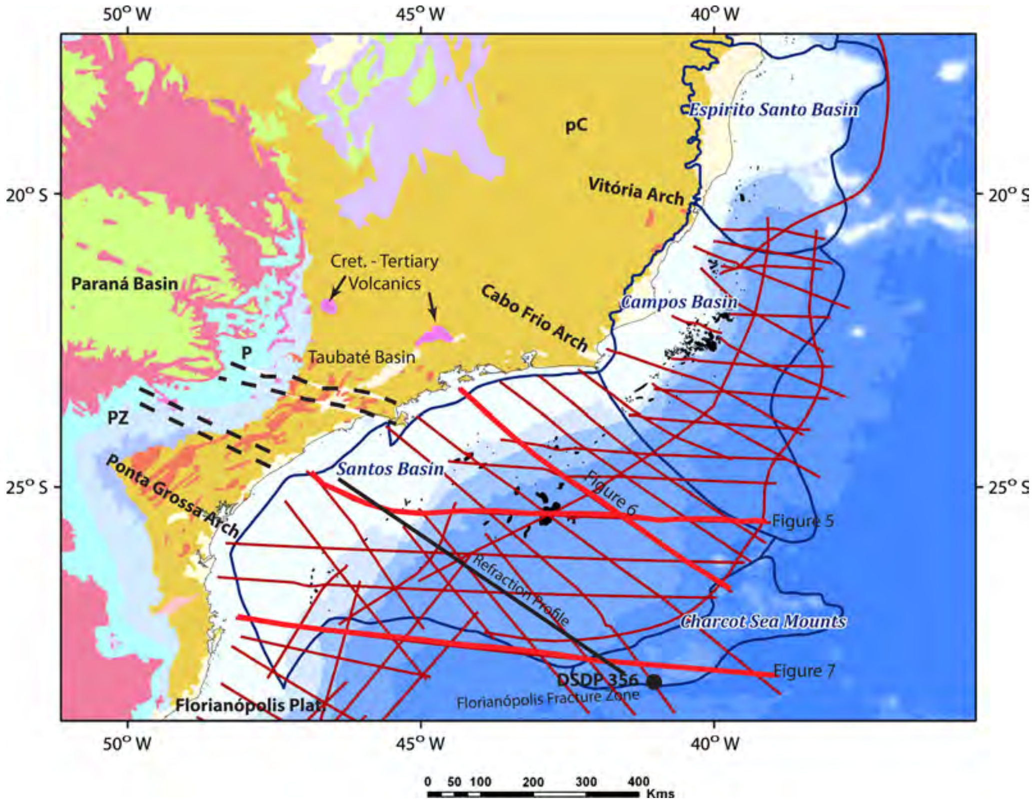

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Fig. 2. Bathymetric map of the study area showing the locations of seismic lines shown in this paper. The location of the refraction profile from Leyden *et al.* (1971) is shown as a black line (Fig. 4). Simplified land geology from the Geologic Map of Brazil (CPRM 2004). pC, Precambrian; PZ, Palaeozoic; P, Permian. Black dashed lines represent lineaments with dyke swarms. Bathymetric contours shown are 200, 1000, 2000, 3000 and 4000 m. Oil and gas fields in the area are shown in black, and the Deep Sea Drilling Site 356 is marked as a large black dot.

and refraction surveys, shipboard gravity and magnetic measurements, sea-floor sediment sampling, and integration with onshore and shallow offshore well information available at that time (see the discussion in Mohriak 2004). Among the papers and reports, there was a set of maps for the entire continental margin of Brazil: free-air gravity anomalies (Rabinowitz & Cochran 1979), magnetic anomalies (Cande & Rabinowitz 1979), bathymetry (Moody *et al.* 1978) and sediment isopachs (Kumar *et al.* 1979). These maps formed the basis for many publications that were published in the 1970s and 1980s.

At the same time, the Deep Sea Drilling Project (DSDP) drilled several locations in the eastern and SE Brazilian margin during its Leg 13 (Perch-Nielsen *et al.* 1977). One of these, Site 356, was drilled at the SE periphery of the São Paulo Plateau (Figs 2 & 3) and provided key information for reconstructing the early evolution of this feature (Kumar *et al.* 1977; Kumar & Gambôa 1979).

Key results related to the SE Brazilian margin from the investigations carried out during this period are summarized below.

- The sedimentary wedge in deep water (beyond the 200 m-isobath) in the Espirito Santo, Campos and Santos basins was at least 4–6 km thick, and contained local thins over basement highs (Kumar *et al.* 1977).
- An extensive field of diapiric structures, ‘previously speculated to be composed of salt’, was Q2 surveyed in 1974 and, on the basis of thermal anomalies associated with these structures and on high salinities in interstitial waters recovered from overlying sediments, were deemed to be salt diapirs (Leyden *et al.* 1978). Leyden *et al.* (1976) also proposed an Albian reconstruction of the South Atlantic by matching the seaward boundaries of the salt layer on both sides of the Atlantic, suggesting a single salt basin of Aptian age.

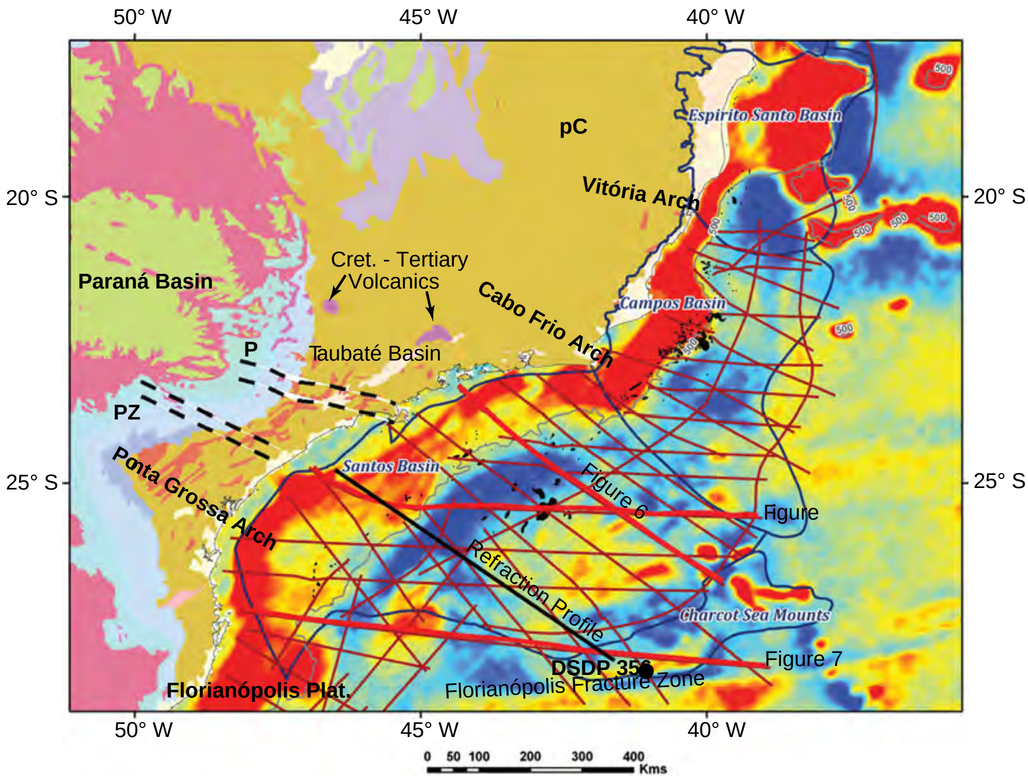

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Fig. 3. Free-air gravity map (Sandwell & Smith 1997) of the area with locations indicated of seismic lines shown in this paper. The location of the refraction profile from Leyden *et al.* (1971) is shown as a black line (Fig. 4). Simplified land geology from the Geologic Map of Brazil (CPRM 2004). pC, Precambrian; PZ, Palaeozoic; P, Permian. The black dashed lines represent lineaments with dyke swarms. Oil and gas fields in the area are shown in black, and the Deep Sea Drilling Site 356 is marked as a large black dot. Some of the tectonic features are after Meisling *et al.* (2001). The large gravity anomaly parallel to the coastline in the inner shelf is interpreted as 'near shore Moho uplift' by Meisling *et al.* (2001); it marks the 'hinge line' for abrupt thickening of sedimentary wedges in these basins.

- Sonobuoy measurements made on the São Paulo Plateau by Leyden *et al.* (1971) suggested that the underlying crust was oceanic, although the measured thickness was almost 10 km compared to about 5 km further seaward. Their transect is shown in Figure 4 (location of the transect in Figs 2 & 3). It shows a Moho at a depth of about 15 km in the middle of the São Paulo Plateau, rising to about 10 km near the seaward edge of the transect. The total crustal thickness varies from approximately 9 to 5 km from NW to the SE. To the best of our knowledge, these data remain the only published seismic-refraction information to date.
- Based on drilling results from DSDP Site 356 (Figs 2 & 3) and seismic data, Kumar *et al.* (1977) and Kumar & Gambôa (1979) correlated the post-salt stratigraphy across the plateau to the edge of the continental shelf. In order to account for the width of the plateau, they also invoked an eastward ridge jump at the end of Aptian time.

Follow-up research and current models (1980s–today)

Although a comprehensive review of literature is beyond the scope of this paper, the concepts regarding ocean–continent transition in general, and regarding the evolution of the SE Brazilian margin in particular, have evolved significantly since the 1970s. Ever since the classic publication by McKenzie (1978) proposing that the continental-crust 'stretched' during break-up, and hence the continent–ocean transition was not a sharp boundary, various authors have further elaborated or proposed modifications to this model. However, a review of the literature suggests that concepts that are labelled

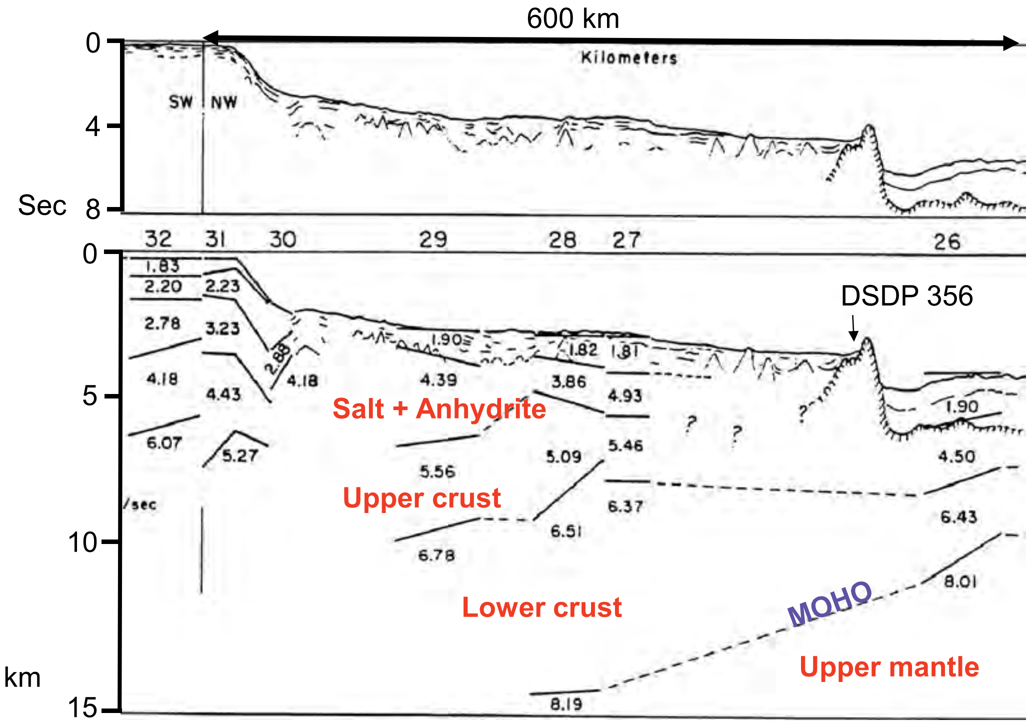

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Fig. 4. The tracing of seismic reflection and refraction profiles from Leyden *et al.* (1971). Locations shown in Figures 2 & 3. Depth to Moho is interpreted to be approximately 15 km in the middle of the profile, supporting a thinned continental crust. Velocities are shown in kms^{-1}. To date, these are the only refraction data available in the area.

as 'new' tend to have their roots in much earlier work. A prime example being the idea of 'extension of the continental crust along oceanward-dipping normal faults leading to the exhumation and submarine exposure of mantle rocks and mafic intrusives, the associated basalts forming a new seabed covered with products of submarine eruptions' that Q3 was suggested by Bailey (1936, p. ~~??~~) (see the discussion by Bernoulli & Jenkyns 2009).

Modifications to the McKenzie (1978) model (pure shear or uniform stretching) have been offered in the literature to account for local geometries and subsidence patterns in continental margins (e.g. Wernicke 1985: simple shear or asymmetric stretching). Further elaboration to account for margin subsidence has been provided for the Brazilian margin by Karner (2000) ~~and~~ Karner & Driscoll (1999), who introduced the concept of 'depth-dependent stretching' in the context of sag-basin development.

One of the key motivations for studies carried out in the Brazilian margin has been the quest of hydrocarbons in the offshore basins. In the 1980s, the LEPLAC Project (Plano de Levantamento da Plataforma Continental Brasileira) was initiated by various Brazilian agencies to establish the base of the continental slope (for the purpose of adding territory to Brazil's Exclusive Economic Zone, as permitted by the United Nations Charter), resulting in a large amount of bathymetric and seismic data (Gomes 1992; Gomes *et al.* 2000). The recent giant discoveries in the pre-salt section in SE Brazil only accelerated the pace of additional work in the area (GeoExpro 2008). With the acquisition of high-quality deep-penetration data in ~~the late 2000s~~, many of the ideas related to continent–ocean transition can now be ~~put to the test~~ because the geometry of the ocean–continent transition can be imaged on seismic profiles in a level of detail that was not possible earlier. Q4

A number of comprehensive papers have been published in recent years regarding the South Atlantic. A large proportion of these papers deal with the 'best fit' and opening history of the oceanic basin (Moulin *et al.* 2005, 2009; De Wit *et al.* 2008; Aslanian *et al.* 2009; Torsvik *et al.* 2009; Blaich *et al.* 2011). Although selected seismic data have been available to most of these authors, the results are mostly based on non-seismic data. Recent work by Zalán *et al.* (2009, 2011) has basically utilized the same two-dimensional (2D) data set that we discuss in this study. ~~Their~~ data were depth processed to 25 km, and additional data not utilized in their study were acquired in 2009 ~~at~~ water depths of between approximately 20 and 200 m (shallow extensions) to tie the earlier acquired lines in deeper waters. These extensions were merged with deep-water lines and reprocessed. Some of these lines were depth migrated to 40 km. Images from this most recent generation of processed data are displayed in this paper.

At this time, there appear to be two primary groups of ideas on the nature of the continent–ocean transition in SE Brazilian margin.

- That the segment is a 'volcanic passive margin', as evidenced by the Paraná basalts and oceanic seamounts along the eastern margin of the São Paulo Plateau. In addition, hot spots, such as Trinidade, St Helena and Tristan da Cunha (Fig. 1) (Torsvik *et al.* 2009), have been active in this area, stressing the 'volcanic' nature of this segment of the South Atlantic. As mentioned earlier, definitive SDRs, comparable to those mapped along the Argentine margin, are not imaged under the São Paulo Plateau. At the same time, Gladczenko *et al.* (1997) interpreted an extrusive volcanic complex in the southern Santos Basin, and Mohriak *et al.* (2008) mapped a 'volcanic crust limit' extending under the salt layer. All of this would suggest that this area is a volcanic passive margin (VPM: Geoffroy 2005).
- Although, the model of non-volcanic or sedimentary passive margin (SPM) has been primarily derived from the Newfoundland and Iberian margin, the 'exhumed mantle' model (Lavier & Manatschal 2006; Minshull 2009; Péron-Pinvidic & Manatschal 2010) has been suggested by several authors for the Brazilian margin (Gomes *et al.* 2009; Zalán *et al.* 2009; Unternehr *et al.* 2010). Recently, Zalán *et al.* (2011) have further elaborated on the application of this model to the SE Brazilian margin. They propose that a mantle ridge can be mapped along the eastern margin of the São Paulo Plateau, with normal oceanic crust on its seaward side and the continent–ocean boundary (COB) on its landward side. Blaich *et al.* (2011) appear to have taken a 'middle road' in their synthesis, suggesting that although a 'hyperextended continent–ocean transitional domain that shows evidence of rotated fault blocks and detachment surface active during rifting, this segment of the margin is not a "magma-poor" end member' ~~(Zalán *et al.* 2011, p. ??).~~ Q5

Recently, Huismans & Beaumont (2011) have suggested that while *both* the Iberia–Newfoundland and central South Atlantic margins are non-volcanic (magma poor), the resulting geometry of the margins is different because the underlying continental-crustal structure in each case is different. In the case of the former, the entire upper lithosphere undergoes brittle deformation against a ductile lower lithosphere; whereas, in the case of the latter, a weak, viscous lower crust, underlying a brittle upper crust is invoked. This model allows for 'depth-dependent extension involving removal of lower crust'. The weak lower crust acts as the horizontal decoupling layer (Huismans & Beaumont 2011). In the context of our interpretations, this model appears to match the observations quite well, as will be discussed later.

Through interpretation of selected PSDM lines, the geometry of the continent–ocean transition is described for selected lines in this paper. Our motivation in defining the COB is not so much in getting a 'perfect' fit between Brazil and Africa but to reconstruct the crustal geometry for basin modelling, a key technology used in assessing the hydrocarbon potential of various basins. However, because of the thick salt layer, and depths ranging from 10–40 km, the imaging of the crystalline basement and the Moho is not always very clear. Hence, it is to be expected that other interpreters would use the same data to map crustal geometry differently from what we have shown here. The key issues that are addressed through the~~se~~ examples are as follows.

- Should the continental margin under the Santos basins be considered a VPM or a non-volcanic (magma-poor) margin?
- What is the extent of continental crustal extension in this area and what is geometry of this transition?
- What criteria should be used to define the COB?

New seismic data

All the data have been acquired with a shot interval of 50 m, a receiver interval of 25 m and a sample rate of 2 ms. As mentioned earlier, the cable length for these data, which were acquired in 2008, was 10 km and the recording time was 18 s. All the final profiles are 90-fold and have undergone Kirchoff PSDM (pre-stack depth migration). Two of the lines have also been migrated with reverse time migration (RTM). Close collaboration between the interpreters and the seismic-imaging groups was maintained during the velocity-model building process. For the oceanic- and continental-crustal layers in the velocity models, both worldwide crustal-velocity databases and local refraction-data information, in addition to gravity modelling, were used. For the initial velocity model, we interpret the top of the crystalline 'basement' horizon, which is the top of the continental basement (igneous or metamorphic) on land or in shallow offshore, or the top of oceanic crust, offshore. Then, three intra-crustal horizons are modelled: the base of the upper crust; the base of the middle crust; and the base of the lower crust (Moho). Once these initial models are matched with gravity profiles along the seismic lines, the thickness and associated velocity (converted from the modelled density) becomes part of the initial velocity model used for PSDM.

After the initial interpretations have been carried out, in many cases another iteration of gravity modelling is performed to refine the interpreted crustal structure. Thus, gravity models are used in a two-step process to support the seismic interpretation: once to build the initial velocity model for depth migration; and the second time to review the feasibility of the interpreted crustal structure. For all of the lines shown in this paper, we have included the gravity models with the seismic interpretation (Figs 5–7). The good match between the observed and calculated gravity shown in these figures was obtained by iteration of the seismic interpretation with gravity models.

Seismic lines 375, 600 and 150

A brief description of the features highlighted in each of the three lines is given here. The full lines are displayed at a vertical exaggeration of approximately 4 or 4.5. Additional images of segments of the lines are shown at vertical exaggerations ranging from 2.5 to 7. Further discussion of the break-up process and of the nature of the COB follows these descriptions.

Line 375

Line 375 is more than 800 km long. The full section to 40 km depth is shown in Figure 5 (location shown in Figs 2 & 3). As the focus in this paper is on crustal

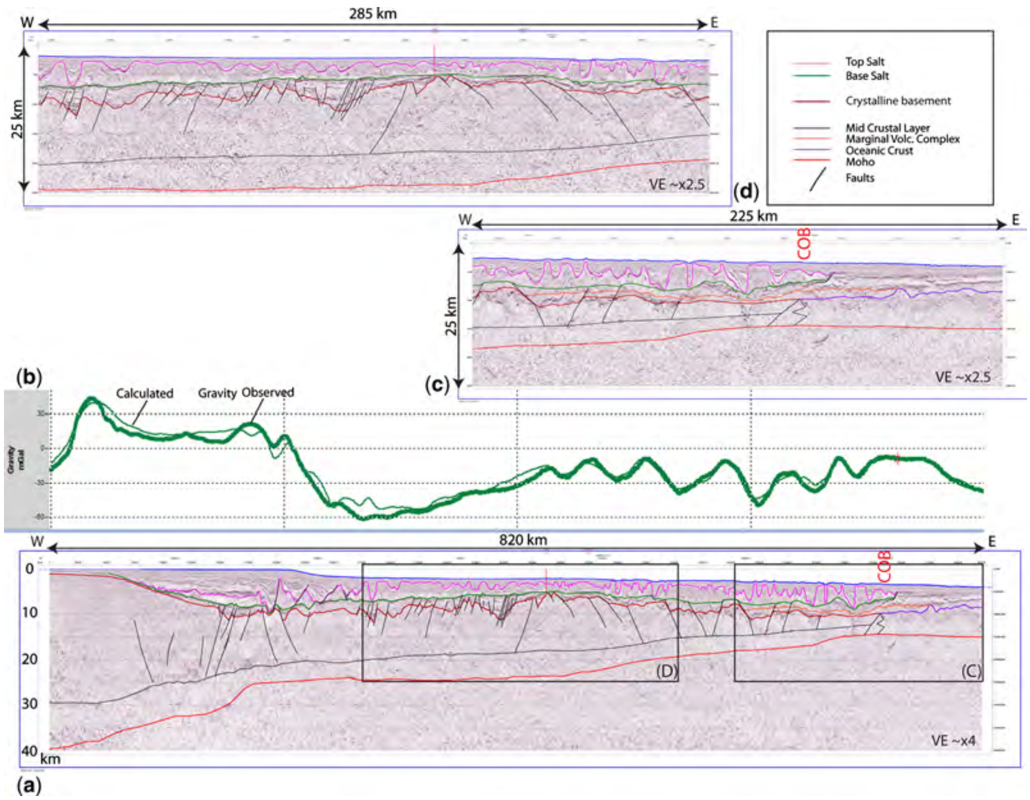

Fig. 5. (**a**) A 40 km PSDM image of Line 375 (located in Figs 2 & 3). The box in the upper right explains the colour scheme for the horizons interpreted on this and other seismic sections. COB marks the location of the continent–ocean boundary. (**b**) Free-air gravity anomalies along Line 375 (thick line, measured; thin line, calculated). (**c**) Expanded image of the top 25 km of the easternmost segment of Line 375 (box marked as C in a). (**d**) Expanded image (top 25 km) of a central segment of Line 375 (box marked as D in a). Further details are given in the text.

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structure, we have shown our interpretation of the continental crust, oceanic crust and the salt layer. The interval from the top salt to the sea floor represents post-Aptian sediments ('drift' sediments of Moreira *et al.* 2007), but, in order to highlight the nature of the data, we have not marked any horizons in that interval. Similarly, the interval between the base of the salt and the top of the crystalline basement represents the pre-salt interval consisting of Late Jurassic (?) through to Barremian-age, syn-rift and sag-basin sediments (referred to as rift and post-rift by Moreira *et al.* 2007). The pre-salt sequences below the salt are present in the syn-rift fault blocks, as well as in the overlying sag basin. This interval has been the focus of recent major discoveries in the area. The two discoveries shown in Figure 5a, d are Tupi (to the west) and Jupiter (to the east) (GeoExpro 2008).

A modelled gravity profile (free air) and comparison with shipboard measured gravity (thick line in Fig. 5b) shows a fairly good match with our seismic interpretation. Figure 5c, d shows enlarged images of parts of the line (shown in black rectangles in Fig. 5a) at a vertical exaggeration of approximately 2.5.

The top of the continental crust has been interpreted to be abruptly faulted in a series of normal faults. The faults dip landwards as well as oceanwards. Most of the faults die out or are not imaged at a horizon ranging in depth from 30 km to less than 15 km. This horizon has been termed in this paper as the 'mid-crustal layer'. In all likelihood, this might mark the brittle–ductile boundary in the crystalline basement analogous to that described by Dinkelman *et al.* (2009) and Zalán *et al.* (2009, 2011). The sudden and steep drop of the crystalline basement from the inner shelf to the mid-shelf and slope is also reflected in the gravity-anomaly map of Figure 3. The Moho rises from a depth of almost 40 km to about 25 km under the outer shelf, and then rises to a depth of almost 15 km at the eastern end of the line.

The thinned or stretched continental crust is in excess of 15 km thick, but it continues to tapers further east until the continental crust terminates slightly landwards of the edge of the salt layer (Fig. 5, termination marked as 'COB'). The pre-salt sediments in the grabens appear to be significantly thinner east of the two discoveries than they are further west (Fig 5a, d).

The oceanic crust is interpreted to be about 8 km thick at the eastern end of the line. A marker, shown in orange under the base of salt, extends from the western end of Figure 5c and partly overlies the oceanic crust. This horizon has been termed here the Marginal Volcanic Complex (MVC), representing the volcanic activity to mark the final breaking of the continent and the beginning of the sea-floor spreading. The COB is marked where the thickness of continental crust reaches zero. We have shown the COB as a zigzag line, implying a transitional but fairly sharp boundary.

Line 600

Line 600 is more than 600 km long, extending from a water depth of more than 20 m in the NW to the edge of the São Paulo Plateau in the SE. One of the seamounts in the Charcot Group is located at its SE end (Fig. 6, location shown in Figs 2 & 3). Similar to the interpretation shown in Figure 5, we have shown the entire line (Fig. 6a), gravity model (Fig. 6b) and expanded scale segments of the line (Fig. 6c, d). We have also attempted to keep the vertical scales the same as in Figure 5. As in Figure 5, we have only interpreted the top and the base of the salt. The base of salt layer forms a wide arch. The large recent pre-salt discoveries are located under the salt towards the crest of this arch (Figs 2 & 3). The sequence between the base of the salt and the top of the crystalline basement consists of syn-rift and sag-basin sediments. The centre of Figure 6d shows a graben, almost 50 km wide, where these sediments reach almost 8 km in thickness. Generally, this sequence ranges from 2 to 3 km in thickness.

The top of the continental crust is down-faulted by more than 10 km in a series of normal faults; this gradient is also reflected in the gravity-anomaly map (Fig. 3). The Moho rises from a depth of almost 32 km, to depths ranging between 25 and less than 20 km. The thinned or stretched continental crust starts at about 20 km thickness under the mid-shelf and remains in the 10–15 km range until just before it reaches zero thickness at the COB (Fig. 6). As in Figure 5, we have marked a mid-crustal layer in this seismic line as well. Almost all of the normal faults die out against this horizon along the length of the line.

The oceanic crust is interpreted to be almost 10 km thick, including the seamount that rises above the sea floor. The Moho gets deeper under the seamount, as required by isostasy. As in Figure 5, we have also shown a MVC layer (orange horizon) extending under the salt and above the crystalline basement for approximately 75 km. As depicted on the seismic interpretation (Fig. 6c), the MVC layer forms the topography over the oceanic crust, which is shown to be about 8 km thick. As in Figure 5, the COB is marked with a zigzag line where the thickness of continental crust is zero (Fig. 6).

Line 150

Line 150 is more than 900 km long and extends WNW–ESE from the inner shelf to the edge of

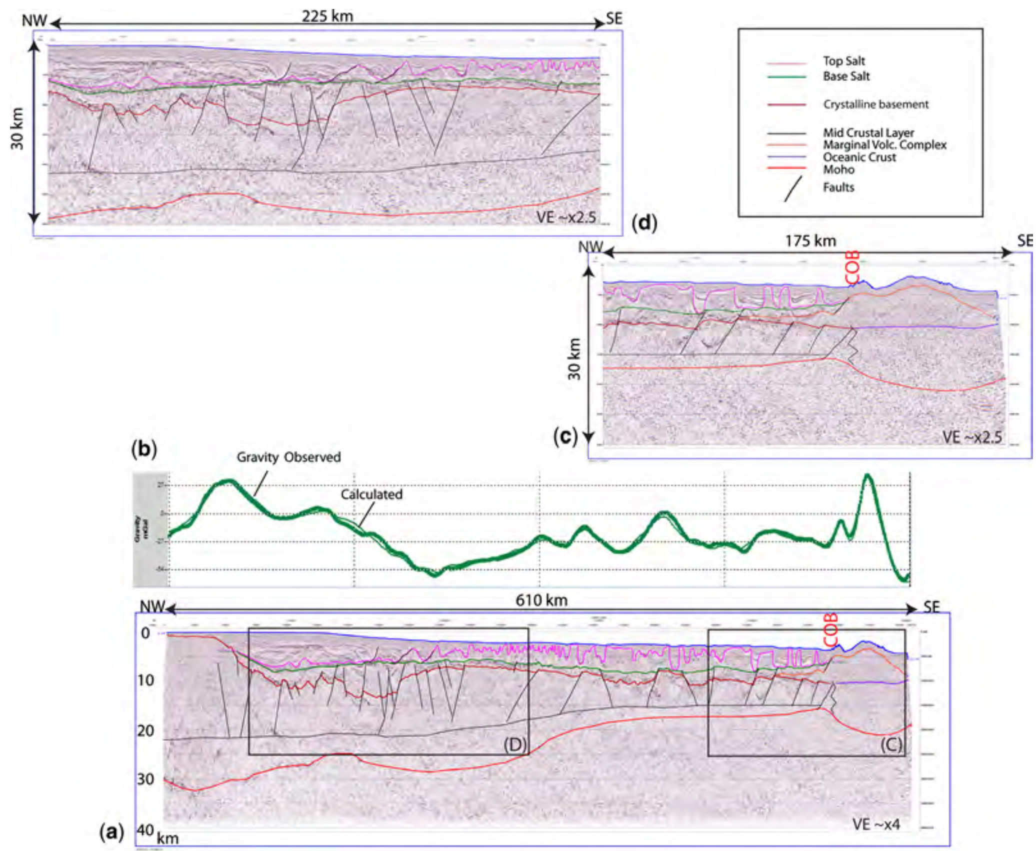

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Fig. 6. (**a**) A 40 km PSDM image of Line 600 (located in Figs 2 & 3). The box in the upper right explains the colour scheme for the horizons interpreted on this and other seismic sections. COB marks the location of the continent–ocean boundary. (**b**) Free-air gravity anomalies along Line 600 (thick line, measured; thin line, calculated). (**c**) Expanded image of the top 30 km of the easternmost segment of Line 600 (box marked C in a). (**d**) Expanded image (top 30 km) of a central segment of Line 600 (box marked D in a). Further details are given in the text.

the São Paulo Plateau. Because its strike is nearly parallel to a fracture zone, the crustal architecture seen in this line is very different from the other two described above (Fig. 7, location shown in Figs 2, 3 & 8). Similar to the interpretations shown in Figures 5 & 6, we have only marked the Moho, the continental crust, the oceanic crust, the MVC layer and the salt layer. In addition, we have shown another reflector, in light blue, marking it as the top of the 'syn-rift and SDRs' sequence. This reflector pinches out just before the narrow zone of the salt layer appears on the seismic line. The salt layer occurs only for about 100 km along the central part of the line. As shown here, the pre-salt section under the salt is very thin or absent.

At the western end of the line, the top of the continental crust is down-faulted by almost 20 km in a series of normal faults; this gradient is reflected in the gravity anomaly (Fig. 3). The Moho rises very abruptly from a depth of almost 40 km to almost 10 km. We have shown the continental crust terminating at about 200 km from the western end of the line. The COB is marked at this location (Fig. 7).

As shown in Figure 7, the continental crust is ruptured across a more than 100 km-wide zone where the Moho is very shallow. To the east of this zone, a block of continental crust is also interpreted for another 500 km; and a second, eastern COB is marked on the line. Because the two continental blocks shown in this line appear isolated, it is possible that such a geometry might have been interpreted as detached micro-continents at the southern end of the São Paulo Plateau (Henry *et al.* 2010; Alvey *et al.* 2011), probably along with a limited amount of sea-floor spreading when considering the proximity to the Tristan da Cunha

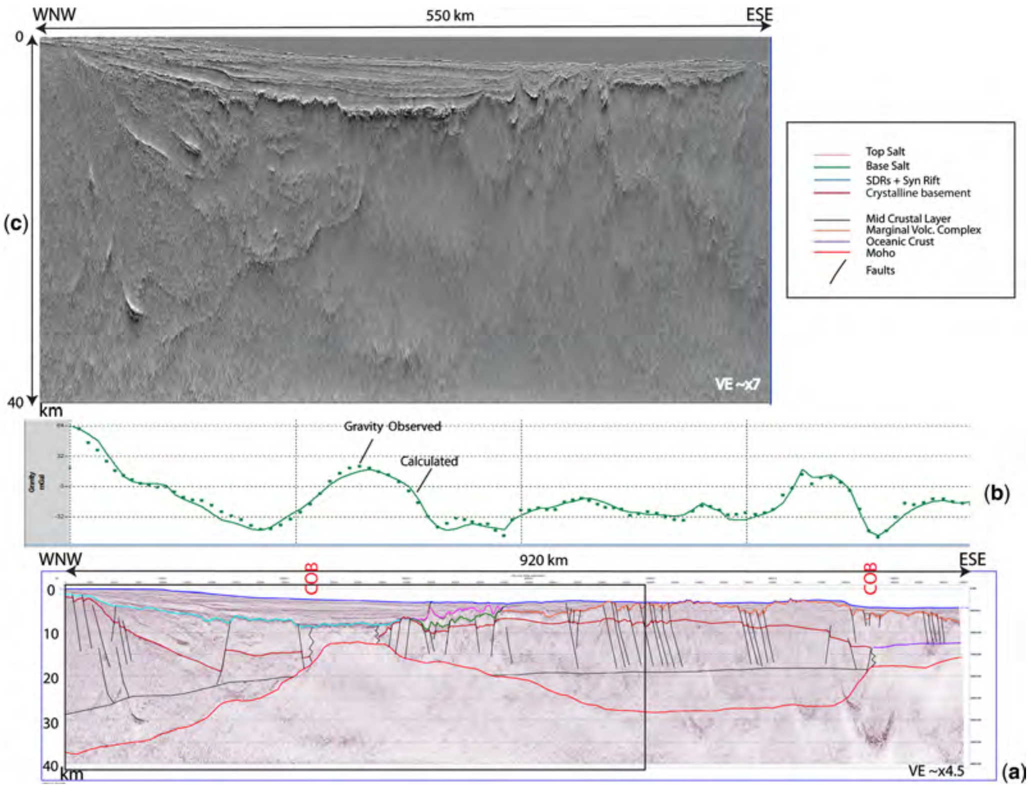

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Fig. 7. (**a**) A 40 km PSDM image of Line 150 (located in Figs 2 & 3). The box in the upper right explains the colour scheme for the horizons interpreted on this section. Note that the blue horizon (syn-rift + SDRs) is not interpreted in Figures 5 & 6. (**b**) Free-air gravity anomalies along Line 600 (dotted line, measured; thin line, calculated).
(**c**) Uninterpreted expanded scale view of the western part of the line (black box in a). This image is a display of the ‘volume of amplitudes’ (Bulhõs & de Amorim 2005). The steep rise of the Moho to almost below the sediments is very clear on the image. Further details are given in the text.

mantle plume (T in Fig. 1) and the substantial amounts of magma it was producing at that time.

The striking feature of this line is the extensive MVC layer shown in our interpretation. Volcanic features, rising above the sea floor are located along the line. DSDP Site 356 was drilled along the flank of the linear ridge seen in this line; the deepest sediments drilled being of **Q6** ~~Late~~ Albian age (Figs 2, 3 & 8) (Kumar & Gambôa 1979). In addition, a linear magnetic anomaly is located just to the north of where the topographical ridge appears on the line (shipboard magnetic measurements collected during the seismic acquisition).

Along the western end of the line, a zone of thick sediment/volcanics is interpreted overlying the thinned continental crust. Between the blue horizon and the crystalline basement, we interpret this sequence as consisting of SDRs with interlayered syn-rift sediments. The SDRs seen on this line become very prominent and thick just to the south (Kumar *et al.* 2010). Franke *et al.* (2007) mapped an extensive zone of SDRs along the Argentine margin (see also Fig. 1). The mapping carried out by Meisling *et al.* (2001) supports our interpretation of these SDRs. The western part of this line overlies their ‘Tristan da Cunha hot spot volcanic ridge’. Their map shows much reduced volcanics to the north of the location of this line. Meisling *et al.*’s (2001) ocean–continent boundary (COB) coincides with the eastern edge of the termination of our salt layer in Figure 7. We have placed the second COB almost 400 km to the east. In reality, because the line is oriented along the strike of the COB (east–west, Fig. 8), moving the COB north by less than 50 km puts most of the line on oceanic crust. Figure 7b is the gravity model along this line (dots, measured gravity; line, calculated gravity).

As Figure 7c, we have shown an uninterpreted segment (western 550 km) at a vertical exaggeration of approximately 7. The display is that of 'volume of amplitudes' (Bulhões & de Amorim 2005) and is very effective in showing large impedance contrasts. On this section, the rise of Moho to a level below the sediments and the break-up of continental blocks into two is quite clear. In Figure 7a, we have shown the eastern COB, with a zigzag line in the same manner as for the other two lines (Figs 5a, c & 6a, c).

Discussion

Through these examples, we illustrate the seismic imaging of continent–oceanic transition in the central part of the South Atlantic. Figures 5 & 6 show a very wide zone (*c*. 500 km) of thinned continental crust. As shown here, part of the thinning is accomplished through normal faulting, with the master detachment surface at a depth of approximately 20 km (marked as the 'mid-crustal layer'). From a volumetric and kinematic calculation, Aslanian *et al.* (2009) and Aslanian & Moulin (2012) have also suggested that in order to account for the total displacement needed from the original fit of the continents to the present-day configuration, ~~'the integrity of the lower crust cannot be main-~~
Q7 ~~tained' (p. ??)~~. This implies ductile flow out of the lower crust to accomplish the observed total thinning. Our mid-crustal layer (Figs 5 & 6) marks the horizon below which we would expect ductile deformation in the continental crust.

A layer of volcanic material extending landwards and overlying the thinned continental crust is also shown in each of the three examples. As Geoffroy (2005) has suggested, this is the zone where SDRs would be expected. Although we see them in Figure 7 at the landward edge of the line, in Figures 5 & 6 no suggestion of SDRs is visible. In fact, clear-cut SDRs are not seen anywhere in the Santos and Campos basins offshore. Conversely, Mohriak *et al.* (2008) have mapped a zone of volcanic crust on the São Paulo Plateau (black line, Fig. 8). These are suggested to be subaerial to shallow-water volcanics deposited over the thinned continental crust just before the sea-floor spreading initiates. Although the layer of volcanic material above the thinned continental crust is shown here as a continuous layer, the entire layer is unlikely to be uniform throughout, and local and regional variations in rock types are bound to be present. These cannot be resolved from the data available at this time.

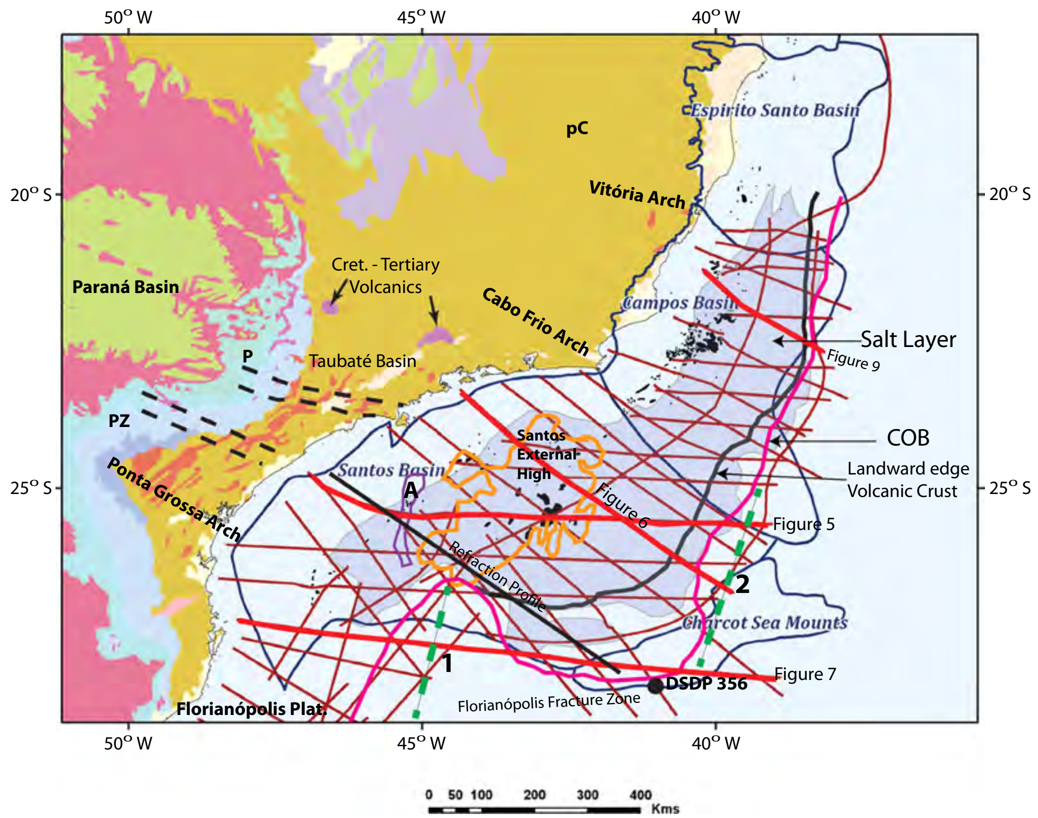
The setting for Line 150 (Fig. 7) is distinct from those for lines 375 and 600 (Figs 5 & 6). The southern margin of the São Paulo Plateau has been described as a shear margin that follows the trajectory of the FFZ (also described in the literature as the Rio Grande Fracture Zone) (Kumar & Gambôa 1979; Fontana 1996) (Figs 2, 3 & 8). The Moho appears to shoal to a depth of 10 km, and the mantle appears to be exhumed below the sediment layer. On the map shown in Figure 8, this zone of very shallow mantle coincides with the re-entrant shown in the COB.

This re-entrant has been interpreted by Mohriak *et al.* (2008), Gomes *et al.* (2009) and others as representing an area where the rifting in the Santos Basin was initiated in Valanginian time (Henry *et al.* 2010) (green dashed line 1 in Fig. 8). The extension of this re-entrant into the Abimael Ridge (Fig. 8) further supports this idea. However, this attempted break-up was short lived and the attempted rift failed (Scotchman *et al.* 2010) (Figs 7 & 8). The Santos External High (Fig. 8) (Gomes *et al.* 2009) is located at the northern end of this Q8
aborted rift (see also Figs 5 & 6). It is possible that mantle uplift, associated with the attempted break-up of the crust under the Santos Basin, created this high and might have also enhanced the thermal maturation of pre-salt source rocks overlying the high. It is also possible that this high is a younger feature, associated with ~~late~~ Cretaceous 'readjustments' of the South Atlantic spreading direction, which also caused magmatism in the Santos and Campos basins (Meisling *et al.* 2001). The hydrocarbon fields located inside the boundaries of this high primarily represent recently discovered large pre-salt accumulations.

The successful break-up of the South American and African continent took place in ~~Late~~ Aptian–~~Early~~ Albian time when the continents separated Q9
approximately along the seaward edge of the salt layer and at the COB, as shown in Figure 8 (green dashed line 2). This multistage history of the formation of the São Paulo Plateau was described as a ridge-jump by Kumar & Gambôa (1979) and Meisling *et al.* (2001).

Models for crustal extension and continent–ocean boundary geometry

One of the objectives of this paper is to evaluate various models proposed for the early evolution of the South Atlantic opening. In the recent literature, two competing models for the area have been described: (1) a depth-dependent extension, two-stage model (also referred to as the 'modified McKenzie model' in this paper) (Huismans & Beaumont 2011); and (2) a hyperextended crust model (Unternehr *et al.* 2010) (also referred to as the 'exhumed Moho' model in this paper). We believe that the data shown here are especially suitable to evaluate these models since crustal-scale PSDM seismic data have rarely been shown in published literature to evaluate models for continental-margin



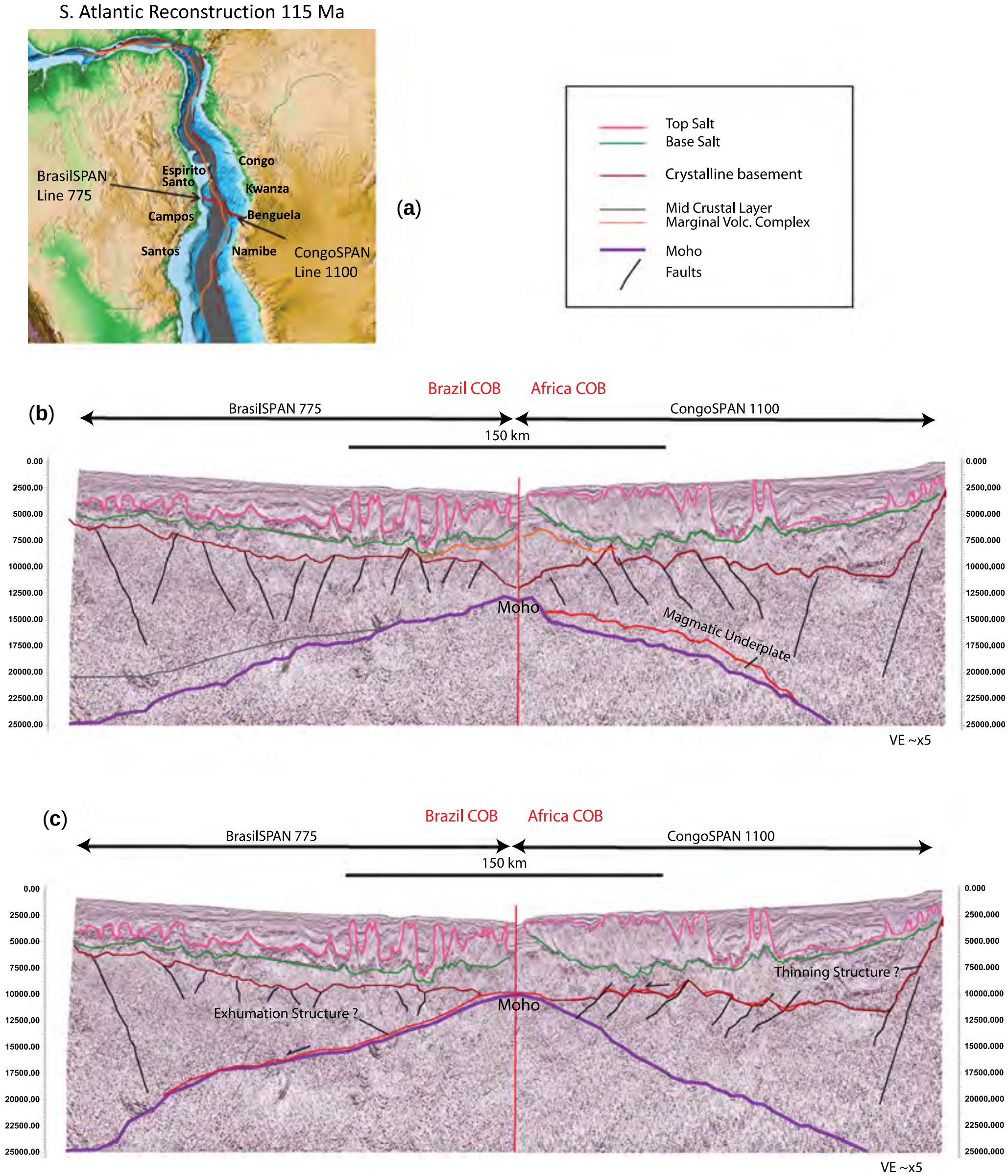
Colour online/ colour hardcopy

Fig. 8. Regional map of the study area. The map shows the extent of the salt layer (given in a pale lavender colour) based on our work as well as that of Davison (2007). The orange line marks the extent of the Santos External High of Gomes *et al.* (2009). The thick black line marks the landward edge of the volcanic crust and the linear feature (in purple) to the west of the Santos High (marked with an A) is the Abimael Ridge (Mohriak *et al.* 2008). The COB (pink line) is shown from our interpretation (see also Henry *et al.* 2010). Note the re-entrant in the COB, at the southern end of the Santos Basin. This re-entrant is on the trend with the Abimael Ridge. The green dashed line (labelled 1) represents the unsuccessful Valanginian-age rift, whereas the other green line to the east (labelled 2) represents the ~~Late~~ Aptian–~~Early~~ Albian age successful rift that separated South America from Africa. Further details are given in the text. **Q22**
All other features are the same as in Figures 2 & 3.

evolution. Our data demonstrate that even with the latest technology, in areas of complex structures, especially in ~~underlying~~ thick salt layers, seismic data leave ambiguities in interpretation. Therefore, we have validated our interpretations with gravity modelling. Nevertheless, in the face of ambiguities, to some extent, the interpretations at the crustal level remain ‘model driven’.

Figure 9a shows two conjugate lines (BrasilSPAN line 775 and CongoSPAN line 1100) located on a South Atlantic reconstruction at 115 Ma, utilizing the GPlates software (http://www.gplates.org/). In **Q10** Figure 9b, c, both of these lines are shown to a depth of 25 km with the oceanic crust, created since 115 Ma, removed. Figure 9b shows the interpretation following the Huismans & Beaumont (2011) model, whereas Figure 9c shows the Unternehr *et al.* (2010) model applied to the same two lines.

The characteristics of the Type II margins of Huismans & Beaumont (2011) include: ultrawide regions of thin continental crust; faulted early syn-rift sedimentary basins; undeformed syn-rift sediments; capping of these late syn-rift sediments by evaporites in ‘sag basins’; limited syn-rift subsidence; no syn-rift flank uplifts; no clear evidence of exposed mantle lithosphere; some syn-rift magmatism; lower-crustal regions with seismic velocities consistent with magmatic underplating; and a normal magmatic mid-oceanic ridge–crust system established soon after crustal break-up. This model suggests that the continental mantle lithosphere breaks up before the continental crust breaks up



Colour online/ colour hardcopy

Fig. 9. (**a**) Reconstructed view of the South Atlantic at 115 Ma (using the G-Plates software; http://www.gplates.org/). Line 775 from Brazil (located in Fig. 8) and Line 1100 from Africa are shown in their conjugate positions. The COBs for South America (orange line) and Africa (red line) as mapped by Davison (2007) are also shown. (**b**) The image combines the two lines at the COBs for Brazil and Africa to illustrate the anticipated geometry of the Moho and the ocean–continent transition zone on both sides of the developing mid-ocean ridge, just prior to the final break-up. The colour scheme for the horizons is mostly the same as given in Figures 5–7 and is displayed in the box. The interpretation shown here follows that of Figures 5 & 6 and follows the model of Huismans & Beaumont (2011, their Type II margin). (**c**) An attempted interpretation of the same two lines using the model of Unternehr *et al.* (2010). This represents a modified simple-shear model with the red line following the top of the crystalline basement in Africa and the base of the crystalline basement in Brazil as the major detachment that breaks the continents apart. Although our observations support the model shown in (b), we show the interpretation in (c) to highlight that the ambiguities in the interpretation of continental margin geometries remain, and much work needs to be done to sort out which model applies to which margin in different parts of the world.

and, therefore, no evidence of exhumed mantle is seen at the COB. Instead, volcanics associated with the initiation of sea-floor spreading are expected. In our observations, all of these characteristics are observed at the SE Brazilian margin.

In Figure 9c, we have attempted to make an interpretation of the same sections following the model of Unternehr *et al.* (2010). If this model applies here, the red line marking the *top* of crystalline basement on the Congo line and the *base* of the crystalline basement on the Brazilian line would form the master detachment that would separate the two continental blocks. Thus, the African side would become the footwall margin and the Brazilian side would become the hanging-wall margin. Later, normal faulting in the continental crust would take place, especially on the Brazilian side, after the detachment has occurred. In this model, the continental crust breaks up before the continental mantle lithosphere breaks up and, therefore, a zone of exhumed mantle directly underlying the sediments would be expected at the edge of continent (Unternehr *et al.* 2010). As we have shown in Figures 5 & 6, a zone of exhumed mantle is not present and this interpretation is further validated by our gravity models.

Although Zalán *et al.* (2009, 2011) have recently proposed a 'mantle ridge' along the eastern edge of the São Paulo Plateau, the only seismic example shown by them is a line that intersects with the very eastern edge of our line 150 (Fig. 7a). In our interpretation, the easternmost 50 km or so of Figure 7a are located in the FFZ. Presence of very shallow (exhumed) Moho along the strike in fracture zones is quite possible as samples of peridotites have been dredged from several fracture zones **Q11** (Bonatti *et al.* 1994). In addition, we interpret a zone of very shallow Moho on this line further west. As mentioned above, this is related to an earlier rifting event that resulted in a failed spreading centre; which is, when considering its proximity to the Tristan da Cunha mantle plume (T in Fig. 1) at the time, similar in geometry to the volcanic margin model proposed by White *et al.* (1987). Beside these occurrences of very shallow Moho, at least in our interpretation, the presence of a mantle ridge along the COB of the eastern margin of the São Paulo Plateau is not justified.

Although our preference is for the two-stage model of Huismans & Beaumont (2011) model – where crustal thinning is achieved partly by faulting and mostly by viscous removal of lower crust, with no exhumed mantle at the COB – there are ambiguities in the data, and the same seismic data could be interpreted using an alternate model. Only additional regional studies, coupled with refraction data and gravity and basin models, would provide further answers in this matter.

Exploration implications

Understanding the crustal-level structural architecture of basins has become critical for two reasons. (1) As the quest for oil and gas has extended into increasingly deep waters, the 'basement' structures and their effect on subsequent basin filling needs to be understood. Specifically in the context of sub-salt exploration in Brazil, the origin and definition of the 'Santos External (or Outer) High' (Modica & Brush 2004; Mohriak & Paula 2005; Gomes *et al.* 2009) needs to be understood in order to expand and define the limits of this play. (2) As basin modelling has become a critical technology in basin evaluation, the nature and thickness of the underlying crust provides basic parameters for reconstructing the subsidence and thermal history of potential source rocks.

Although depth-dependent extension is proposed here for explaining the evolution of the SE Brazilian margin, its limitations in accounting for the observed subsidence in basins has been discussed (Reston 2009). At the same time, Ranero & Pérez-Gussinyé (2010) have proposed that sequential faulting in the upper crust can explain the observed subsidence history without an extension discrepancy. Thus, reconstructing the geometry of the crust under the basins in continental margins is critical in understanding their evolution and this might provide valuable insights for petroleum exploration.

Summary and conclusions

- Our data show that the São Paulo Plateau is underlain by a stretched and thinned continental crust. The stretching has taken place by normal faults in the upper crust and possibly by plastic deformation below the brittle–ductile boundary. In our interpretation of the seismic data we have not placed an underplated high-velocity layer on the Brazilian side but it might be present on the African side (Fig. 9b) (Huismans & Beaumont 2011).
- We have not seen strong evidence of exhumed mantle at the COB, as has been suggested by some recent papers. We believe that the magmatism in this segment of the margin was somewhat reduced compared to the areas to the south, where up to 10–15 km of SDRs can be observed in the seismic data in the offshore Pelotas Basin.
- As the southern boundary of the plateau is marked by the FFZ (manifested as the São Paulo Ridge), it is possible that there are segments of exhumed mantle along this boundary.
- The syn-rift and sag basins above the continental crust, but below the salt layer, have a significant volcanic component. At the COB, we believe

that extension might have been partly accomplished by volcanic intrusions and extrusions.

- We suggest that the COB should be defined as the seaward zero edge of the stretched or thinned continental crust. Beyond this boundary, we should only expect crust of oceanic affinity (or exhumed mantle).
- Although we have not discussed the geometry and depth of deposition for the salt in this paper, our data clearly support a failed rift in the Valanginian, which extended part of the way into the São Paulo Plateau. Mohriak (2001) suggested that this might correspond to an oceanic propagator that was aborted by ~~Late~~ Aptian times, thus advancing from the Pelotas Basin towards the Santos Basin, and effectively separating parts of the Brazilian and African salt by igneous intrusions. This failed rift, where the continents almost separated, also shows an example of possible exhumed Moho (Fig. 7). The aborted rift then shifted to the east near the present-day seaward boundary of the São Paulo Plateau, creating the final separation between Africa and Brazil at least in this segment of the South Atlantic. This shift probably occurred in ~~Late~~ Aptian–~~Early~~ Albian time.

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References

Alvey, A., Kusznir, N. J. & Roberts, A. M. 2011. Detached micro-continents offshore southern Brazil: Crustal thickness from gravity inversion and plate reconstructions. *In*: *AAPG Annual Conference and Exhibition, 10–13 April 2011, Houston, Texas*. AAPG, Search and Discovery Article, 90124. World Wide Web Address: http://www.searchanddiscovery.com/abstracts/html/2011/annual/abstracts/Alvey.html.

Aslanian, D. & Moulin, M. 2012. Palaeographical consequences of conservational models in the South Atlantic Ocean. *In*: Mohriak, W. U., Danforth, A., Post, P. J., Brown, D. E., Tari, G. C., Nemčok, M. & Sinha, S. T. (eds) *Conjugate Divergent Margins*. Geological Society, London, Special Publications, **369**, first published online February 2012, http://dx.doi.org/10.1144/SP369.5.

Aslanian, D., Moulin, M. *et al.* 2009. Brazilian and African passive margins of the central segment of the South Atlantic Ocean: kinematic constraints. *Tectonophysics*, **468**, 98–112.

Asmus, H. E. 1984. Geologia da margem continental brasileira. *In*: Schobbenhaus, C., Campos, D. A., Derze, G. R. & Asmus, H. E. (eds) *Geologia do Brasil*. Departamento Nacional da Produção Mineral (DNPM), Brasília, 443–472.

Bailey, E. B. 1936. Sedimentation in relation to tectonics. *Geological Society of America Bulletin*, **47**, 1713–1726.

Bauer, K., Neben, S. *et al.* 2000. Deep structure of the Namibia continental margin as derived from integrated geophysical studies. *Journal of Geophysical Research*, **105**, 25,829–25,853.

Bernoulli, D. & Jenkyns, H. C. 2009. Ophiolites in ocean–continent transitions: from the Steinmann Trinity to sea-floor spreading. *Comptes Rendus Geoscience*, **341**, 363–381.

Blaich, O. A., Faleide, J. I. & Tsikalas, F. 2011. Crustal breakup and continent–ocean transition at South Atlantic conjugate margins. *Journal of Geophysical Research*, **116**, B01402.

Bonatti, E., Ligi, M., Gasperini, L., Peyve, A., Raznitshin, Y. & Chen, Y. J. 1994. Transform migration and vertical tectonics at the Romanche fracture zone, equatorial Atlantic. *Journal of Geophysical Research*, **99**, 21,779–21,802.

Bulhões, E. M. & de Amorim, W. N. 2005. Princípio da SismoCamada Elementar e sua aplicação á Técnica Volume de Amplitudes (tecVA). *In*: *9th International Congress of the Brazilian Geophysical Society*, Salvador-Bahia, Brazil, 11–14 September. Brazilian Geophysical Society (SBGf), Rio de Janeiro, *Expanded Abstracts*. Q12

~~Bullard, E. C., Everett, J. E. & Smith, A. G. 1965. The fit of the continents around the Atlantic. *In*: Blackett, P. M. S., Bullard, E. C. & Runcorn, S. K. (eds) *A Symposium on Continental Drift. Royal Society of London Philosophical Transactions*, **258**, 41–51.~~ Q13

Cande, S. & Rabinowitz, P. D. 1979. *Magnetic Anomalies: Continental Margin of Brazil*. AAPG, Tulsa, OK.

CPRM-SERVIÇO GEOLÓGICO DO BRASIL. 2004. *Carta Geológica do Brasil ao Milionésimo: sistema de informações geográficas – SIG [Geological Map of Brazil, 1:1 000 000 scale: Geographic Information System – GIS]*. Companhia de Pesquisa de Recursos Minerais (CPRM), Brasília (41 CD Roms: ISBN 85-7499-009-4).

Davison, I. 2007. Geology and tectonics of the South Atlantic Brazilian salt basins. *In*: Ries, A. C., Butler, R. W. H. & Graham, R. H. (eds) *Deformation of the Continental Crust: The Legacy of Mike Coward*. Geological Society, London, Special Publications, **272**, 345–359.

De Wit, M. J., Stankiewicz, J. & Reeves, C. 2008. Restoring Pan-African–Brasiliano connections: more Gondwana control, less Trans-Atlantic corruption. *In*: Pankhurst, R. J., Trouw, R. A. J., Brito Neves, B. B. & De Wit, M. J. (eds) *West Gondwana: Pre-Cenozoic Correlations Across the South Atlantic Region*. Geological Society, London, Special Publications, **294**, 399–412.

Dinkelman, M. G., Granath, J., Bird, D., Helwig, J., Kumar, N. & Emmet, P. 2009. Deducing the brittle–ductile transition in continental crust through deep, long offset 2D PSDM, seismic data. *In*: *AAPG International Conference and Exhibition*, 15–18 November

2009, Rio de Janeiro, Brazil. AAPG, Search and Discovery Article, 40511. World Wide Web Address: http://www.searchanddiscovery.com/documents/2010/40511dinkelman/ndx_dinkelman.pdf.

Fontana, R. L. 1996. *Geotectônica e sismoestratigrafia da bacia de Pelotas e Plataforma de Florianópolis*. PhD thesis, Universidade Federal do Rio Grande do Sul.

Franke, D., Neben, S., Ladage, S., Schreckenberger, B. & Hinz, K. , 2007. Margin segmentation and volcano-tectonic architecture along the volcanic margin off Argentina/Uruguay, South Atlantic. *Marine Geology*, **244**, 46–67, http://dx.doi.org/10.1016/j.margeo.2007.06.009.

GEOEXPRO. 2008. *Monsters of the Deep*. World Wide Web Address: http://www.geoexpro.com/article/Monsters_of_the_Deep/ffe3cf63.aspx.

Geoffroy, L. 2005. Volcanic passive margins. *Comptes Rendus Geoscience*, **337**, 1395–1408.

Gernigon, L., Ringenbach,, Planke, S. & Le Gall, B. 2004. Deep structures and breakup along volcanic rifted margins: insights from integrated studies along the outer Vøring Basin (Norway). *Marine and Petroleum Geology*, **21**, 363–372. Q14

Gladczenko, T. P., Hinz, K., Eldholm, O., Meyer, H., Neben, S. & Skogseid, J. 1997. South Atlantic volcanic margins. *Journal of the Geological Society, London*, **154**, 465–470.

Gomes, B. S. 1992. Integração preliminar dos dados gravimetricos marítimos da Petrobras e do Projeto Leplac: Bacias de Campos, Santos e Pelotas. *Anais do XXXVII Congresso Brasileiro de Geologia, São Paulo, SP*, **1**, 559–560.

Gomes, P. O., Gomes, B. S., Palma, J. J. C., Jinno, K. & Souza, J. M. 2000. Ocean–continent transition and tectonic framework of the oceanic crust at the continental margin off NE Brazil: results of LEPLAC Project. *In*: Mohriak, W. U. & Talwani, M. (eds) *Atlantic Rifts and Continental Margins*. American Geophysical Union, Geophysical Monograph, **115**, 261–291.

Gomes, P. O., Kilsdonk, B., Minken, J., Grow, T. & Barragan, R. 2009. The outer high of the Santos Basin, Southern São Paulo Plateau, Brazil: pre-salt exploration outbreak, Paleogeographic setting, and evolution of the syn-rift structures. *In*: *AAPG International Conference and Exhibition*, 15–18 November 2009, Rio de Janeiro, Brazil. AAPG, Search and Discovery Article, 10193. World Wide Web Address: http://www.searchanddiscovery.net/documents/2009/10193gomes/index.htm.

Henry, S. G., Kumar, N., Danforth, A., Nuttall, P. & Venkatraman, S. 2010. Mapping the South Atlantic continental-oceanic boundary: rift to early drift along extensional and transform margins. *In*: *AAPG International Conference and Exhibition*, Calgary, Canada, 12–15 September 2010. AAPG, Search and Discovery Article, 90108. World Wide Web Address: http://www.searchanddiscovery.com/abstracts/pdf/2010/intl/abstracts/ndx_henry.pdf.

Hinz, K., Neben, S., Schreckenberger, B., Roeser, H. A., Block, M., Souza, K. G. & Meyer, H. 1999. The Argentine continental margin north of 48° S: sedimentary successions, volcanic activity during breakup. *Marine and Petroleum Geology*, **16**, 1–25.

Huismans, R. & Beaumont, C. 2011. Depth-dependent extension, two-stage breakup and cratonic underplating at rifted margins. *Nature*, **473**, 74–78, http://dx.doi.org/10.1038/nature09988.

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION. 1974. *The International Decade of Ocean Exploration (IDOE) 1971–1980*. World Wide Web Address: http://www.jodc.go.jp/info/ioc_doc/Technical/013802eo.pdf.

Jackson, M. P. A., Cramez, C. & Fonck, J-M. 2000. Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins: implications for salt tectonics and source rocks. *Marine and Petroleum Geology*, **17**, 427–498.

Karner, G. D. 2000. Rifts of the Campos and Santos basins, southeastern Brazil: distribution and timing. *In*: Mello, M. & Katz, B. (eds) *Petroleum Systems of South Atlantic Margins*. AAPG, Memoir, **73**, 301–316.

Karner, G. D. & Driscoll, N. W. 1999. Tectonic and stratigraphic development of the West African and eastern Brazilian margins: insights from quantitative basin modelling. *In*: Cameron, N. R., Bate, R. H. & Clure, V. S. (eds) *The Oil and Gas Habitats of the South Atlantic*. Geological Society, London, Special Publications, **153**, 11–40.

Karner, G. D. & Gambôa, L. A. P. 2007. Timing and origin of the South Atlantic pre-salt sag basins and their capping evaporites. *In*: Schreiber, B. C., Lugli, S. & Babel, M. (eds) *Evaporites Through Space and Time*. Geological Society, London, Special Publications, **285**, 15–35. Q15

Kumar, N. & Gambôa, L. A. P. 1979. Evolution of the São Paulo Plateau (southeastern Brazilian margin) and implications for the early history of the South Atlantic. *Geological Society of America Bulletin*, **90**, 281–293.

Kumar, N., Gambôa, L. A. P., Schreiber, B. C. & Mascle, J. 1977. Geologic history and origin of São Paulo Plateau (southeastern Brazilian margin), comparison with southern Angolan margin, and the early evolution of northern South Atlantic. *In*: Perch-Nielsen, K., Supko, P. R. *et al.* (eds) *Initial Reports of the Deep Sea Drilling Project*, **Volume 39**. US Government Printing Office, Washington, DC, 927–945.

Kumar, N., Leyden, R., Carvalho, J. & Francisconi, O. 1979. *Sediment Isopach Map: Continental Margin of Brazil*. AAPG, Tulsa, OK.

Kumar, N., Henry, S., Danforth, A., Nuttall, P. & Venkatraman, S. 2010. Tectonic and stratigraphic evolution of Pelotas Margin (southeastern Brazil): deep seismic-reflection images from long-offset, Prestack Depth Migrated (PSDM), regional 2-D data. *In*: *AAPG International Conference and Exhibition*, Calgary, Canada, 12–15 September 2010. AAPG, Search and Discovery Article, 90108. World Wide Web Address: http://www.searchanddiscovery.com/abstracts/pdf/2010/intl/abstracts/ndx_kumar.pdf.

Lavier, L. L. & Manatschal, G. 2006. A mechanism to thin the continental lithosphere at magma-poor margins. *Nature*, **440**, 324–328.

Lentini, M. R., Fraser, S. I., Sumner, H. S. & Davies, R. J. 2010. Geodynamics of the central South Atlantic conjugate margins: implications for hydrocarbon potential. *Petroleum Geoscience*, **16**, 217–229. Q16

Leyden, R., Ludwig, W. J. & Ewing, M. 1971. Structure of continental margin off Punta del Este, Uruguay, and Rio de Janeiro, Brazil. *AAPG Bulletin*, **55**, 2161–2173.

Leyden, R., Asmus, H., Zembruscki, S. & Bryan, G. 1976. South Atlantic diapiric structures. *AAPG Bulletin,* **60**, 196–212.

Leyden, R., Damuth, J. E., Ongley, L. K., Kostecki, J. & Van Stevenick, W. 1978. Salt diapirs on São Paulo Plateau, Southeastern Brazilian continental margin. *AAPG Bulletin*, **62**, 657–666.

McKenzie, D. 1978. Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters*, **40**, 25–32.

Meisling, K. E., Cobbold, P. R. & Mount, V. S. 2001. Segmentation of an obliquely rifted margin, Campos and Santos basins, southeastern Brazil. *AAPG Bulletin*, **85**, 1903–1924.

Menzies, M. A., Klemperer, S. L., Ebinger, C. J. & Baker, J. 2002. Characteristics of volcanic rifted margins. *In*: Menzies, M. A., Klemperer, S. L., Ebinger, C. J. & Baker, J. (eds) *Volcanic Rifted Margins: Boulder*. Geological Society of America, Special Paper, **362**, 1–14. Q17

Minshull, T. A. 2009. Geophysical characterisation of the ocean–continent transition at magma-poor rifted margins. *Comptes Rendus Geosciences*, **341**, 382–393.

Modica, C. J. & Brush, E. R. 2004. Postrift sequence stratigraphy, paleogeography, and fill history of the deep-water Santos Basin, offshore southeast Brazil. *AAPG Bulletin*, **88**, 923–946.

Mohriak, W. U. 2001. Salt tectonics, volcanic centers, fracture zones and their relationship with the origin and evolution of the South Atlantic Ocean: geophysical evidence in the Brazilian and West African margins. *In*: *7th International Congress of the Brazilian Geophysical Society, Salvador-Bahia, Brazil, October 28–31, Expanded Abstracts*. Brazilian Geophysical Society (SBGf), Rio de Janeiro, 1594–1597.

Mohriak, W. U. 2004. Recursos energéticos associados à ativação tectônica Mesozóico-Cenozóica da América do Sul. *In*: Mantesso-Neto, V., Bartorelli, A., Carneiro, C. D. R. & Brito-Neves, B. B. (eds) *Geologia do continente sul-americano: evolução da obra de Fernando Flávio Marques de Almeida*. Beca Produções Culturais, São Paulo, 293–318.

Mohriak, W. U. & Paula, O. B. 2005. Major tectonic features in the southeastern Brazilian margin. *In*: *9th International Congress of the Brazilian Geophysical Society*, Salvador-Bahia, Brazil, 11–14 September, Expanded Abstracts. Brazilian Geophysical Society (SBGf), Rio de Janeiro. Q18

Mohriak, W. U., Rosendahl, B. R., Turner, J. P. & Valente, S. C. 2002. Crustal architecture of South Atlantic volcanic margins. *In*: Menzies, M. A., Klemperer, S. L., Ebinger, C. J. & Baker, J. (eds) *Volcanic Rifted Margins*. Geological Society of America, Special Paper, **362**, 159–202.

Mohriak, W. U., Nemčok, M. & Enciso, G. 2008. South Atlantic divergent margin evolution: rift-border uplift and salt tectonics in the basins of SE Brazil. *In*: Pankhurst, R. J., Trouw, R. A. J., Brito Neves, B. B. & De Wit, M. J. (eds) *West Gondwana: Pre-Cenozoic Correlations Across the South Atlantic Region*. Geological Society, London, Special Publications, **294**, 365–398.

Moreira, J. L. P., Madeira, C. V., Gil, J. A. & Machado, M. A. P. 2007. Bacia de Santos. *In*: Milani, E. J. (ed.) *Bacias Sedimentares Brasileiras – Cartas Estratigráficas. Boletim de Geociências da Petrobras*, **15**, 531–549.

Moody, R., Hayes, D. E. & Connary, S. 1978. *Bathymetry of the Continental Margin of Brazil*. Special Map Series, **832**. AAPG, Tulsa, OK.

Moulin, M., Aslanian, D. *et al.* 2005. Geological constraints on the evolution of the Angolan margin based on reflection and refraction seismic data (ZaïAngo project). *Geophysical Journal International*, **162**, 793–810.

Moulin, M., Aslanian, D. & Unternehr, P. 2009. A new starting point for the South and Equatorial Atlantic Ocean. *Earth-Science Reviews*, **97**, 59–95.

Perch-Nielsen, K., Supko, P. R. *et al.* 1977. *Initial Reports of the Deep Sea Drilling Project*, Volume 39. US Government Printing Office, Washington, DC,.

Péron-Pinvidic, G. & Manatschal, G. 2010. From microcontinents to extensional allochthons: witnesses of how continents rift and break apart? *Petroleum Geoscience*, **16**, 189–197.

PETROBRAS. 1979. *Projeto Remac: Coletânea de trabalhos*. CENPES, Petrobras Research Centre, Rio de Janeiro, 1–11.

Rabinowitz, P. D. & Cochran, J. R. 1979. *Free-Air Gravity Anomalies of the Continental Margin of Brazil*. AAPG, Tulsa, OK.

Ranero, C. R. & Pérez-Gussinyé, M. 2010. Sequential faulting explains the asymmetry and extension discrepancy of conjugate margins. *Nature*, **468**, 294–299.

Reston, T. J. 2009. The extension discrepancy and syn-rift subsidence deficit at rifted margin. *Petroleum Geoscience*, **15**, 217–237.

Sandwell, D. T. & Smith, W. H. F. 1997. Marine gravity from geosat and ERS-1 altimetry. *Journal Geophysical Research*, **102**, 10039–10054. For latest updates, World Wide Web Address: http://gcmd.nasa.gov/records/GCMD_SIO_NOAA_GEOSAT_ERS1_MARINEGRAV.html.

~~Schnabel, M., Franke, D. *et al.* 2008. The structure of the lower crust at the Argentine continental margin, south Atlantic at 44°S. *Tectonophysics*, **454**, 14–22~~. Q19

Scotchman, I. C., Gilchrist, G., Kusznir, N. J., Roberts, A. M. & Fletcher, R. 2010. The breakup of the South Atlantic Ocean: formation of failed spreading axes and blocks of thinned continental crust in the Santos Basin, Brazil and its consequences for petroleum system development. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, Petroleum Geology Conference Series, **7**, 855–866.

Thybo, H. & Nielsen, C. A. 2009. Magma-compensated crustal thinning in continental rift zones. *Nature*, **457**, 873–876. Q20

Torsvik, T. H., Rousse, S., Labails, C. & Smethurst, M. A. 2009. A new scheme for the opening of the South

Atlantic Ocean and the dissection of an Aptian salt basin. *Geophysical Journal International*, **177**, 1315–1333.

Unternehr, P., Péron-Pinvidic, G., Manatschal, G. & Sutra, E. 2010. Hyper-extended crust in the South Atlantic: in search of a model. *Petroleum Geoscience*, **16**, 217–229.

Wernicke, B. 1985. Uniform-sense normal simple shear of the continental lithosphere. *Canadian Journal of Earth Science*, **22**, 108–125.

White, R. S., Spence, G. D., Fowler, S. R., McKenzie, D. P., Westbrook, G. K. & Bowen, A. N. 1987. Magmatism at rifted continental margins. *Nature*, **330**, 439–444.

Wolfenden, E., Ebinger, C., Yirgu, G., Renne, P. R. & Kelley, S. P. 2005. Evolution of a volcanic rifted margin: Southern Red Sea, Ethiopia. *Geological Society of America Bulletin*, **117**, 846–864.

Zalán, P. V., Severino, M. C. G. *et al.* 2009. Stretching and thinning of the upper lithosphere and continental–oceanic crustal transition in southeastern Brazil. *In*: *AAPG International Conference and Exhibition*, 15–18 November 2009, Rio de Janeiro, Brazil. AAPG, Search and Discovery Article, 90100. World Wide Web Address: http://www.searchanddiscovery.net/abstracts/html/2009/intl/abstracts/zalan.htm.

Zalán, P. V., Severino, M. C. G., Rigoti, C. A., Magnavita, L. P., de Oliveira, J. A. B. & Vianna, A. R. 2011. An entirely new 3D-view of the crustal and mantle structure of a South Atlantic passive margin – Santos, Campos and Espírito Santo basins, Brazil. Extended abstract. *In*: *AAPG Annual Conference and Exhibition*, 10–13 April 2011, Houston, Texas. AAPG, Search and Discovery Article,orp 90124. World Wide Web Address: http://www.searchanddiscovery.com/abstracts/html/2011/annual/abstracts/Zalan.html.