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–ocean 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 (<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.

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 Espírito 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)
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).


Multidisciplinary studies carried out in the Brazilian margin during the 1970s included seismic reflection
and refraction surveys, shipboard gravity and magnetic measurements, sea-floor sediment sampling, and integration on 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 Espírito 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 surveyed in 1974 and, on the basis of thermal anomalies associated with these structures and 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.

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.
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.

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
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 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 continental–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.

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. The 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 Trinidad, 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. 22).

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 off-
shore, 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 pro-
files 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 mod-
eling is performed to refine the interpreted crustal
structure. Thus, gravity models are used in a
two-step process to support the seismic interpret-
ation: 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 approxi-
mately 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

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**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.
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
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 ..
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 Late Albian age (Figs 2, 3 & 8) (Kumar & Gamboa 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

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’ (Bulhós & 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.
of approximately 7. The display is that of ‘volume of amplitudes’ (Bulhoes & 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–ocean 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 maintained’ (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 Sao 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 Sao 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 & Gambboa 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 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 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 Sao Paulo Plateau was described as a ridge-jump by Kumar & Gambboa (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
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 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.
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 character-
istics 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 crystal-
line 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 contin-
ental 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 contin-
ent (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 frac-
ture zones is quite possible as samples of peridotites
have been dredged from several fracture zones
(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 spread-
ing 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
Platue 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 ambi-
guities in the data, and the same seismic data could
be interpreted using an alternate model. Only addi-
tional 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 architec-
ture 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 defi-
nition 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 tech-
nology 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
subidence history without an extension discre-
pancy. Thus, reconstructing the geometry of the
crust under the basins in continental margins is criti-
cal in understanding their evolution and this might
provide valuable insights for petroleum explora-
tion.

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
defaults in the upper crust and possibly by plastic
deformation below the brittle–ductile boundary.
In our interpretation of the seismic data we have
deduced the presence of a 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 magma-
tism 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 seg-
ments 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


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