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Notes

Crustal-scale architecture and segmentation of the South Atlantic volcanic margin

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Abstract: Seismic reflection and refraction profiles, and potential field data, complemented by crustal-scale gravity modelling, plate reconstructions and well cross-sections are used to study the evolution of the South Segment of the South Atlantic conjugate margins. Distinct along-margin structural and magmatic changes that are spatially related to a number of conjugate transfer systems are revealed. The northern province, between the Rio Grande Fracture Zone and the Salado Transfer Zone, is characterized by symmetrical seawards-dipping reflections (SDRs) and symmetrical continent–ocean transitional domain. The central province, between the Salado Transfer Zone and the conjugate Colorado–Hope transfer system, is characterized by along-strike tectono-magmatic asymmetry. The Tristan da Cunha plume, located on the central province of the South Segment, may have influenced the volume of magmatism but did not necessarily alter the process of rifted margin formation. Thus implying that, apart from voluminous magmatism, the extensional evolution of the central province of the South Segment may have much in common with 'magma-poor' margins.

The opening of the South Atlantic and subsequent passive margin formation was the culminating result of lithospheric extension during Mesozoic time followed by the break up of the Palaeozoic Gondwana super-continent (e.g. Rabinowitz & LaBrecque 1979; Austin & Uchupi 1982; Nürnberg & Müller 1991; Chang *et al.* 1992). The link between the South and Central segments of the South Atlantic was established by Albian–Turonian times (Koutsoukos & Dias-Brito 1987; Koutsoukos *et al.* 1991). The South Atlantic Ocean can be divided into four segments (Fig. 1), from north to south: the Equatorial Segment, the Central Segment, the South Segment and the Falkland Segment (e.g. Moulin *et al.* 2010). In this study we focus on the conjugate evolution of selected provinces along the volcanic margins of the South Segment.

The South Segment is limited between the Falkland–Agulhas Fracture Zone to the south and the Rio Grande Fracture Zone to the north (Fig. 1). The first oceanic crust in this segment was formed in Hauterivian time, between 134 and 132 Ma in the south and 132–130 Ma towards the north (Austin & Uchupi 1982; Moulin *et al.* 2010). The rift structures in Argentina are oriented obliquely to the coastline, trending in a NW–SE direction from the onshore to the offshore region (Tankard *et al.* 1995). Furthermore, this segment (Fig. 1) is characterized by seawards-dipping reflections (SDRs) and high-velocity–high-density lower crust, which may be associated with voluminous igneous activity during continental break-up (Gladczenko *et al.* 1998; Hinz *et al.* 1999; Talwani & Abreu 2000; Franke *et al.* 2007, 2010; Schnabel *et al.* 2008; Blaich *et al.* 2009, 2011; Hirsch *et al.* 2009). Break-up-related magmatism is also observed north of the Rio Grande Fracture Zone (Santos and Campos basins); however, with dramatically decreased volume (Mohriak *et al.* 2008; Contreras *et al.* 2010). The generated excess and distribution of melting observed on the South Atlantic volcanic margins may be attributed to the influence of a mantle plume (e.g. White & Mckenzie 1989; Torsvik *et al.* 2006) and/or to the involvement of different mechanisms (e.g. Mutter *et al.* 1988; Thompson & Gibson 1991; Franke *et al.* 2007).

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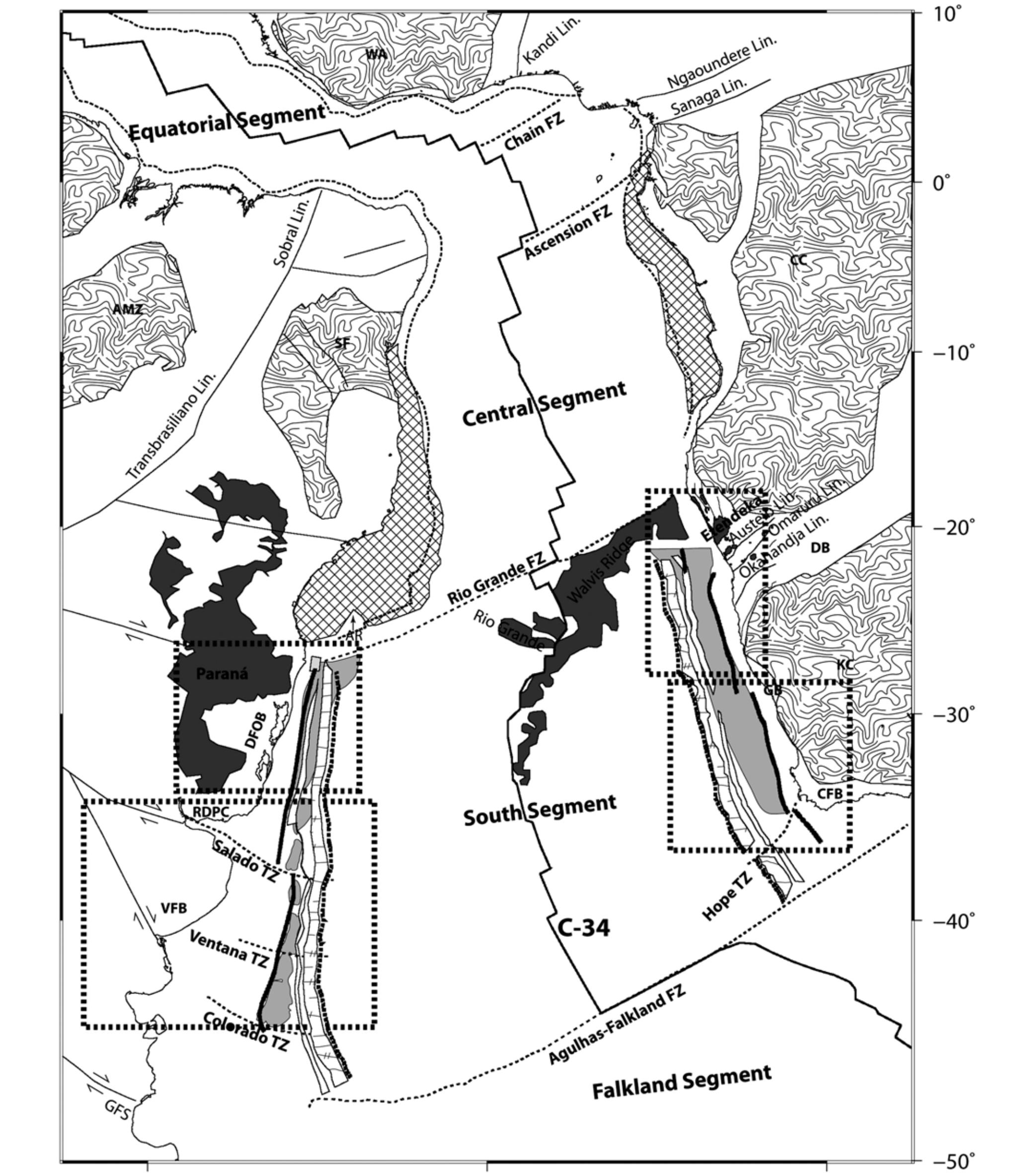

Fig. 1. General tectonostructural plate reconstruction map of the South Atlantic at Chron 34 (*c.* 83 Ma) (modified from Blaich *et al.* 2011). For this well-constrained reconstruction, we use the rotation poles of Nürnberg & Müller (1991) and PLATES software (Institute for Geophysics, University of Texas at Austin). The dashed rectangles indicate the studied provinces along the South Atlantic conjugate margins. Cratons, Aptian salt extension, M sequence magnetic anomalies, C-34 magnetic anomaly and main structural constraints are after Moulin *et al.* (2010) and references therein. Cretaceous volcanism is after Gladczenko *et al.* (1998) and Moulin *et al.* (2010). The location of the Abimael Ridge (AR) is based on the interpretation of Mohriak (2001). The continent–ocean boundary (COB) location along the equatorial segment (Moulin *et al.* 2010) and along the central segment (Blaich *et al.* 2011) is indicated. Structures

Despite the wide global distribution of rifted volcanic margins (Eldholm *et al.* 2000; Menzies *et al.* 2002), the nature of the processes that rupture the continental crust and lead to progressive oceanic crust formation remains controversial (e.g. Rosendahl *et al.* 2005; Rosenbaum *et al.* 2008). Aggravating the issue, the deep crustal structures along the continent–ocean transition (COT) are partially or totally masked by magmatic materials, blurring the clear distinction between highly intruded and probably underplated continental crust and oceanic crust (e.g. Ebinger & Casey 2001).

In this study of the South Atlantic volcanic margins we investigate representative conjugate provinces located within the South Segment: the SE Brazil–Namibia margins and the Argentine–South Africa margin. We analyse an available grid of regional multichannel seismic (MCS) reflection profiles, together with published seismic reflection/refraction profiles across these provinces. In the conjugate margin context, the integration of seismic and potential field data, and conducted two-dimensional (2D) gravity modelling, together with potential field plate reconstructions provide adequate means to study and understand the evolution of the South Atlantic volcanic margins, to elucidate structural elements and features that reflect the processes that lead to the rupture of the continental crust, as well as to refine and constrain the structural architecture and nature of the continent–ocean transitional domain. Note that the term 'continent–ocean transitional domain' is adopted and defined as the part of the lithosphere that is located between the clearly identifiable stretched continental crystalline crust domain and the first appearance of fully oceanic (i.e. fully igneous) crust formed by seafloor spreading (e.g. Blaich *et al.* 2011).

Potential field plate reconstructions were performed using the PLATES software (Institute for Geophysics, University of Texas at Austin: e.g. Lawver *et al.* 1999) and published rotation poles (Nürnberg & Müller 1991; Torsvik *et al.* 2009; Moulin *et al.* 2010). Intraplate deformation in both South America and Africa has been proposed and constitutes an essential requirement in order to solve the kinematic problems during continental break-up and the subsequent formation of the South Atlantic Ocean (e.g. Torsvik *et al.* 2009; Moulin *et al.* 2010). As the studied conjugate provinces are located between major zones of intraplate deformation, plate reconstructions were performed assuming rigid plates.

The MCS profiles within the study area were compiled and extended to the ultra-deep-water oceanic province in order to construct representative regional conjugate transects used in crustal-scale gravity modelling. The regional transects are based on the interpreted seismic reflection profiles, extracted bathymetry and gravity anomaly data, and on initial estimates of the Moho relief using both isostatic balancing and inverse gravity modelling; the latter method is described in detail by Blaich *et al.* (2008, 2009).

Margin setting

The gridded aeromagnetic anomaly field map (Fig. 2) reflects an overall NW–SE-trending magnetic pattern, and is characterized by well-defined magnetic anomalies that can be separated into zones of distinct internal magnetic character. Close to the Rio Grande Fracture Zone, however, where the Rio Grande Plateau and Walvis Ridge are located and interpreted as the trails of the Tristan da Cunha plume, a complex magnetic pattern is observed. There, the anomalies are more chaotic and do not show the same linear character as further south, implying that magnetic anomalies in this area are not unambiguously recognized and thus disputed (Fig. 2). The prominent positive, linear 'G magnetic anomaly' (Rabinowitz & LaBrecque 1979) was interpreted as a magnetic 'edge effect' caused by the different magnetic properties of continental and oceanic crust. The 'G magnetic anomaly', in this way, was defined as the continent–ocean boundary (COB) and its location was set at the landwards end of the broad positive anomaly (Fig. 2) (Rabinowitz & LaBrecque 1979). Alternative explanations for the 'G magnetic anomaly' have been offered since the cause of this anomaly is controversial. For example, magnetic modelling across the Argentine (Hinz *et al.* 1999), Namibia (Bauer *et al.* 2000) and South Africa margins (Blaich *et al.* 2009, 2011) has indicated thick layers of extrusive basalts, identified as SDRs, as the causal source of the 'G magnetic anomaly.' Thus, the 'G magnetic anomaly' coincides roughly with the landwards edge of the SDRs (Hinz *et al.* 1999; Blaich *et al.* 2009). As the major part of volcanic extrusives terminate

Fig. 1. (*Continued*) located in onshore Namibia are after Gladczenko *et al.* (1998). Seawards-dipping reflections (SDRs) and related volcanics are from Moulin *et al.* (2005) and Franke *et al.* (2007, 2010) for South America, and from Bauer *et al.* (2000) for Africa. 'G magnetic anomaly' after Rabinowitz & LaBrecque (1979); Lin, lineament; WA, West Africa Craton; CC, Congo Craton; DB, Damara Belt; GB, Gariep Belt; KC, Kalahari Craton; CFB, Cape Fold Belt; AMZ, Amazonia Craton; SF, São Francisco Craton; DFOB, Dom Feliciano Orogenic Belt; RDPC, Río de La Plata Craton; VFB, Ventana Fold Belt; GFS, Gastre Fault System; TZ, transfer zone; FZ, fracture zone.

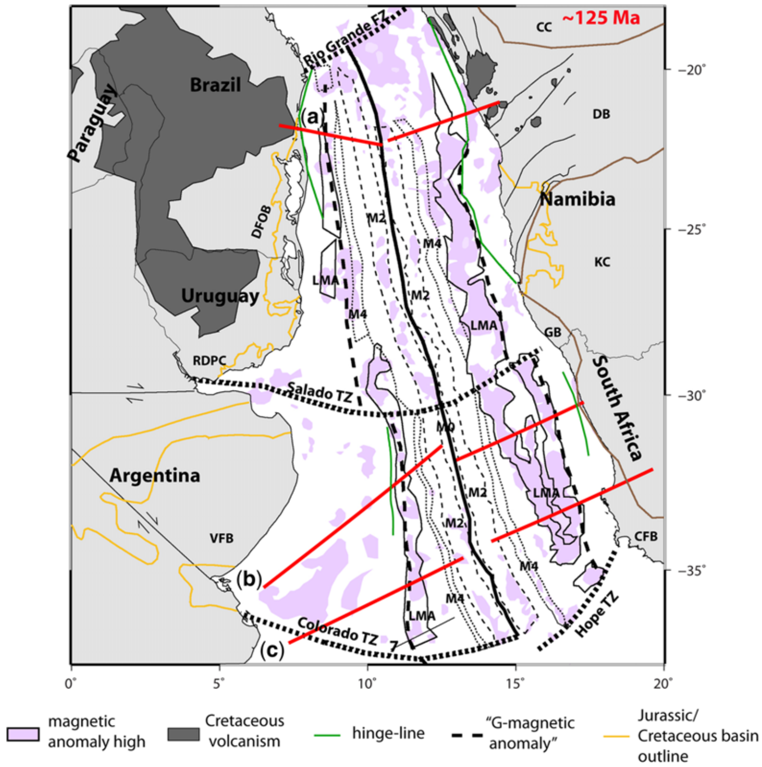

Fig. 2. Plate reconstructions at Chron M0 (*c.* 125 Ma) utilizing the rotation poles of Moulin *et al.* (2010). The $3' \times 3'$ gridded aeromagnetic anomaly field (IAGA 2007) is indicated. The locations of conjugate transects are indicated. Cretaceous volcanism and main structural constraints are after Gladczenko *et al.* (1998) and Moulin *et al.* (2010). Jurassic–Cretaceous basins are derived from Abreu (1998) and Moulin *et al.* (2010). Hinge lines are derived from Moulin *et al.* (2010) and references therein, and from observations made in the current study. M sequence magnetic anomalies after Moulin *et al.* (2010); LMA, Large Marginal Anomaly (Moulin *et al.* 2010). ThD, thinned crystalline crust domain; TrD, transitional domain; 'G magnetic anomaly' after Rabinowitz and LaBrecque (1979); CC, Congo Craton; DB, Damara Belt; GB, Gariep Belt; KC, Kalahari Craton; CFB, Cape Fold Belt; DFOB, Dom Feliciano Orogenic Belt; RDPC, Río de La Plata Craton; VFB, Ventana Fold Belt; TZ, transfer zone; FZ, fracture zone.

largely southwards of the Colorado transfer system (Franke *et al.* 2007; Becker *et al.* 2012), the 'G magnetic anomaly' is weak or absent southwards of the Colorado–Hope transfer system. These observations suggest that the 'G magnetic anomaly' is associated with the wedge of SDRs and extrusive basaltic complexes, which may extend over continental crust in the proximal feather edge, and does not necessarily correspond to the true COB location, beyond which only post-break-up magmatic crust might be present.

The Large Marginal Anomaly (LMA: Moulin *et al.* 2010) along the South America margin is narrow, and not as prominent and wide as in the conjugate African margin, where it is characterized by a double branch along the Orange Basin (Moulin *et al.* 2010). In this setting, the reconstructed conjugate magnetic anomaly map indicates overall symmetry at the Pelotas–Walvis conjugate basins, whereas asymmetry is observed and is characterized by a narrow/wide margin configuration further south. Along the NE Atlantic margin, a similar magnetic asymmetry has been explained by an asymmetric sea-floor spreading (e.g. Larsen & Saunders 1998) or by stretched and intruded continental crust, where the asymmetry is caused by the initial continental stretching rather than the subsequent sea-floor spreading (e.g. White & Smith 2009).

Crustal architecture

The representative crustal transects obtained through 2D gravity modelling in the current study (Fig. 3) outlines the crustal structure of the South Segment. Although evidence for syn-rift halfgrabens is not overwhelming in the Pelotas Basin (Abreu 1998; Talwani & Abreu 2000; Contreras *et al.* 2010), antithetic normal faults forming half-graben systems are observed and could be filled by pre-rift and/or syn-rift sedimentary rocks (Figs 3a & 4). These structures, however, are believed to be predominantly infilled by basalt flows (Talwani & Abreu 2000). Oceanwards, a characteristic wedge of SDRs is observed (Fig. 4) and is believed to have been emplaced during Early Cretaceous,

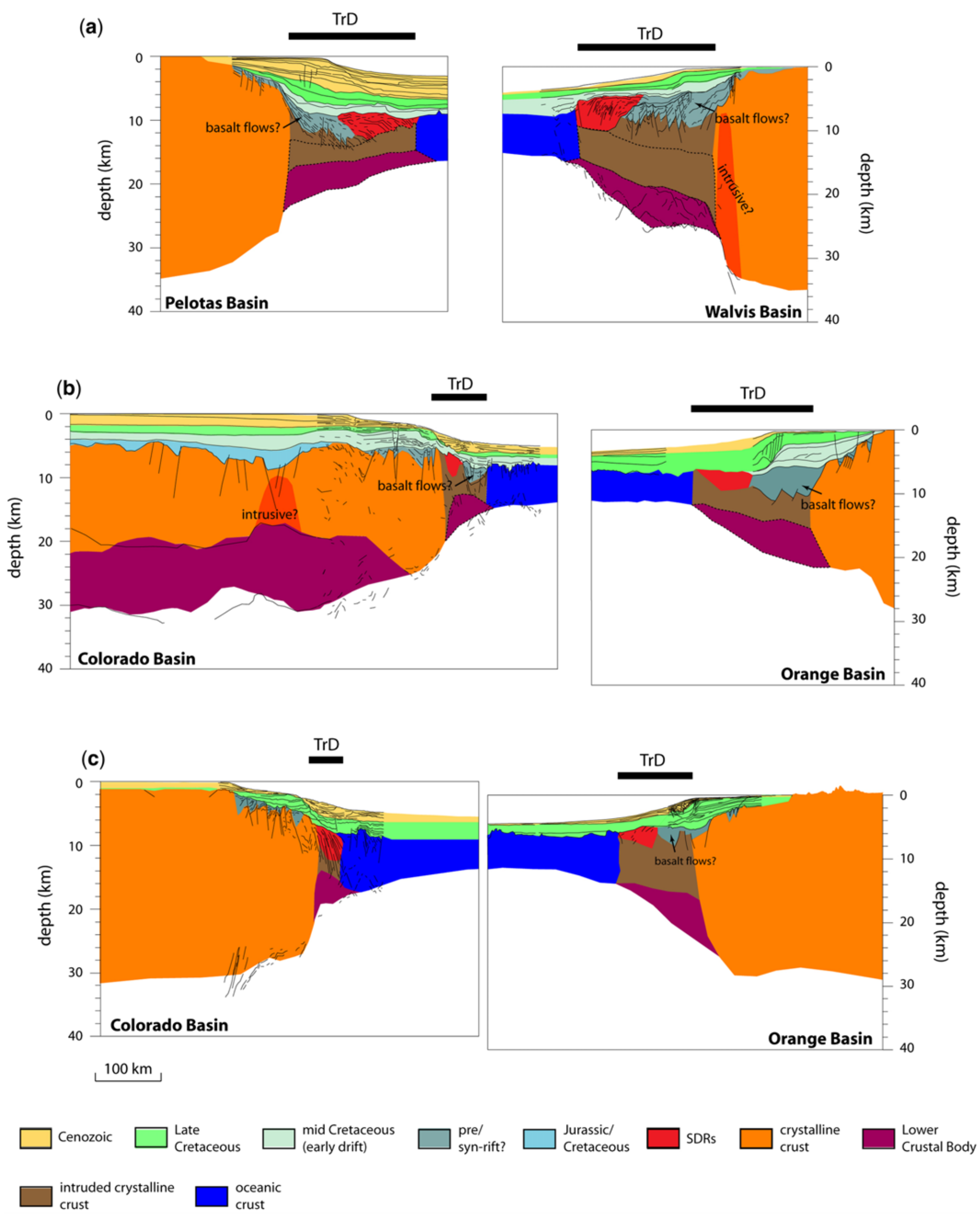

Fig. 3. Conjugate transects along segments of the southern South Atlantic margins, with a transitional domain (TrD) between the continental and oceanic crusts. The location of the profiles are shown in Figure 2. (**a**) Pelotas Basin (Brazil) – Walvis basin (Namibia); (**b**) and (**c**) Colorado Basin (Argentina) – Orange Basin (South Africa).

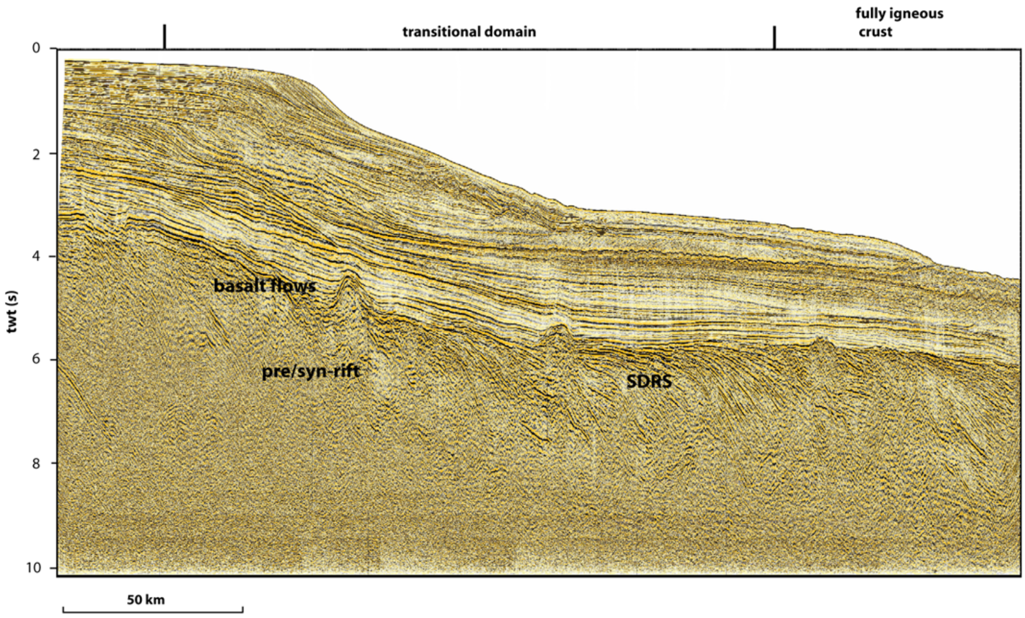

Fig. 4. Seismic example of the transitional domain along the Pelotas Basin (modified from Cainelli & Mohriak 1998). SDRs, seawards-dipping reflections; twt, two-way travel time.

during break-up (Abreu 1998), and has been often interpreted as proto-oceanic crust (Talwani & Abreu 2000). A very thick package of sedimentary strata overlies the basalt flows and SDRs (Figs 3a & 4). Although the Moho discontinuity has been poorly constrained by old vintage seismic reflection/refraction profiles along the Pelotas Basin (Fontana 1996; Mohriak 2003), Blaich *et al.* (2011) indicated a gentle shallowing of the Moho discontinuity from the platform to the shelf break, and a rapid climbing towards oceanic crust. Moreover, an acceptable 2D gravity model fit is only accomplished by a high-density crystalline crust (3000 kg m^{-3}), and a high-density lower crustal body (3100 kg m^{-3}) located below the basalt flows and SDRs (Fig. 3a). The high-density crust located directly below the SDRs may indicate heavily intruded continental crust (e.g. Cornwell *et al.* 2006; Schnabel *et al.* 2008) and it can be interpreted as a region of feeder dykes related to the emplacement of the SDRs (Blaich *et al.* 2011). Furthermore, the high-density lower crust is believed to be associated, analogously, with other continental margins worldwide, with underplating and/or voluminous igneous rocks intruded into the lower crust (e.g. White *et al.* 2008; White & Smith 2009). Gravity modelling further indicates continental crust densities (2800 kg m^{-3}) below the inner basalt flows, where the crust is characterized by synthetic and antithetic normal faults (Fig. 3a) (Blaich *et al.* 2011).

A schematic interpretation of a depth-converted deep seismic profile in the Pelotas Basin (Fig. 5) indicates a very thick continental crust (possibly exceeding 40 km in thickness) in the proximal margin, with igneous accretion from about 20 km depth to the Moho discontinuity. Seward-dipping reflector wedges are characterized basinwards of the shelf-break, forming a transition to oceanic crust where the Moho reflectors is clearly visible at depths of between 15 and 20 km. A gravity model (Fig. 6) was constructed in order to constrain the seismic interpretation with crustal densities derived from refraction velocities obtained in the southern South Atlantic margin (Leyden *et al.* 1971), average velocities for volcanic and igneous rocks related to the Serra Geral and Entendeka large igneous provinces, refraction from SDR edges offshore India (e.g. Ajay *et al.* 2010), and lower crust mantle refraction velocities obtained from different sources in the oceanic realm. The gravity and magnetic anomalies cross-plotted along the profile (Fig. 6) indicate that at a distance of between 200 and 250 km there is a marked change in the anomalies, which is interpreted as being associated with the boundary between the transitional domain and the fully igneous domain (e.g. Blaich *et al.* 2011).

Along the conjugate margin off Namibia (Fig. 3a), the representative crustal transect obtained from 2D gravity modelling (Blaich *et al.* 2011) outlines the crustal structure of the Walvis Basin.

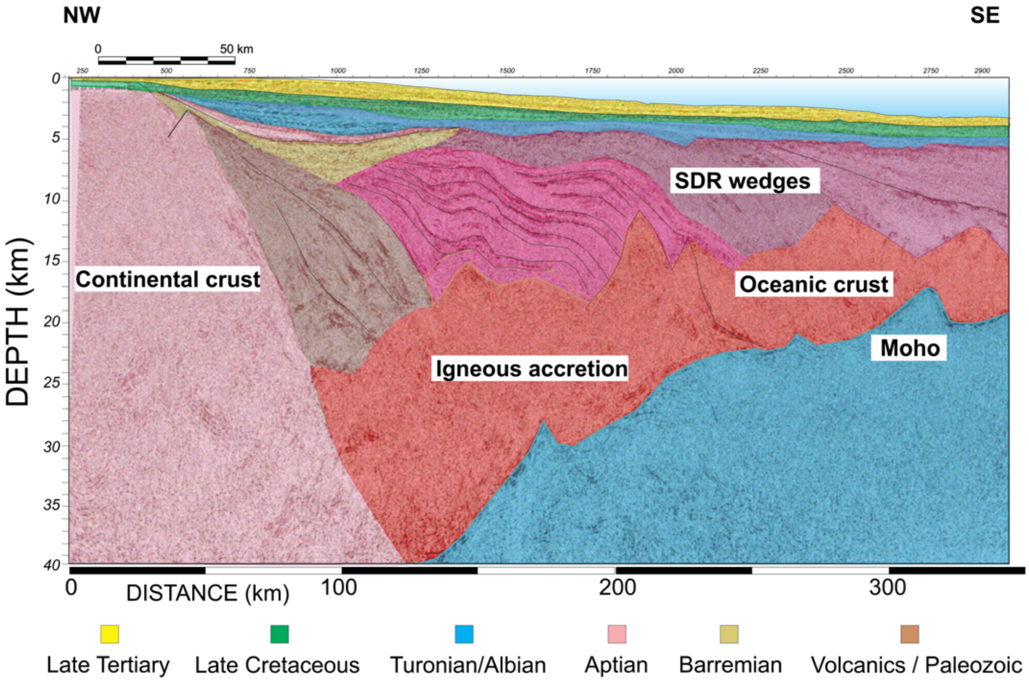

Fig. 5. Deep seismic profile in the Pelotas Basin, near the Florianópolis platform (north of transect a in Figs 2 & 3a), with a schematic interpretation showing the rifted crust in the proximal margin. The transition to oceanic crust is characterized by thick wedges of SDRs and the igneous accretion in the lower crust, above a well-defined seismic Moho clearly identified on oceanic crust.

Geophysical constraints are robust along the transect, and are composed of MCS reflection profiles (Gladczenko *et al.* 1998; Bauer *et al.* 2000) and wide-angle seismic refraction studies (Bauer *et al.* 2000). Furthermore, gravity modelling provides additional constraints to the seismic interpretation, increasing the understanding of the crustal architecture (Fig. 3a). Synthetic and antithetic normal faults forming half-graben systems are observed seawards and landwards of the shelf edge (Fig. 3a). Gladczenko *et al.* (1998) proposed that the grabens are infilled mostly with Palaeozoic pre-rift sediments, forming a very deep and wide pre-rift sedimentary basin. Gravity modelling, constrained by wide-angle refraction data (Bauer *et al.* 2000), however, suggests that the size of the pre-rift basin was overestimated (Fig. 3a). Furthermore, similar to the conjugate Pelotas Basin, the half-graben systems along the Walvis Basin could also be filled with syn-rift sedimentary sequences and basalt flows (Fig. 3a). This assumption is further supported by the fact that Bauer *et al.* (2000) have identified inner basalt flows (inner SDRs) that filled similar basins in the vicinity of the modelled transect (Fig. 7). Gravity modelling further indicates continental crust densities (2800 kg m^{-3}) directly below the inner basalt flows, where the crust is characterized by synthetic and antithetic normal faults (Fig. 3) (Blaich *et al.* 2011). Oceanwards, a characteristic wedge of SDRs is observed (Fig. 7). Below the SDRs, high seismic velocities (>7 km s^{-1}) (Bauer *et al.* 2000) and high densities (3000 kg m^{-3}) (Blaich *et al.* 2011) are indicated and interpreted as a region of feeder dykes related to the emplacement of the SDRs (Figs 3 & 5). An intracrustal band of high-amplitude seismic reflections that are subparallel to the gently shallowing Moho reflections seems to separate crustal levels with different reflectivity character (Gladczenko *et al.* 1998). Furthermore, the presence of high velocities (*c*. 7.6 km s^{-1}) below the intracrustal band of seismic reflections was proposed to indicate underplating (Bauer *et al.* 2000); however, this feature may also indicate voluminous igneous rocks intruded into the lower crust (e.g. White & Smith 2009). These observations are supported by our gravity modelling, where a high-density lower crustal body (3100 kg m^{-3}) is required (Blaich *et al.* 2011). Landwards of the shelf edge, a single Moho reflector dips steeply landwards (Fig. 3a). In order to accomplish an acceptable 2D gravity model fit, a high-density (3000 kg m^{-3}) body within the crust is required landwards of the

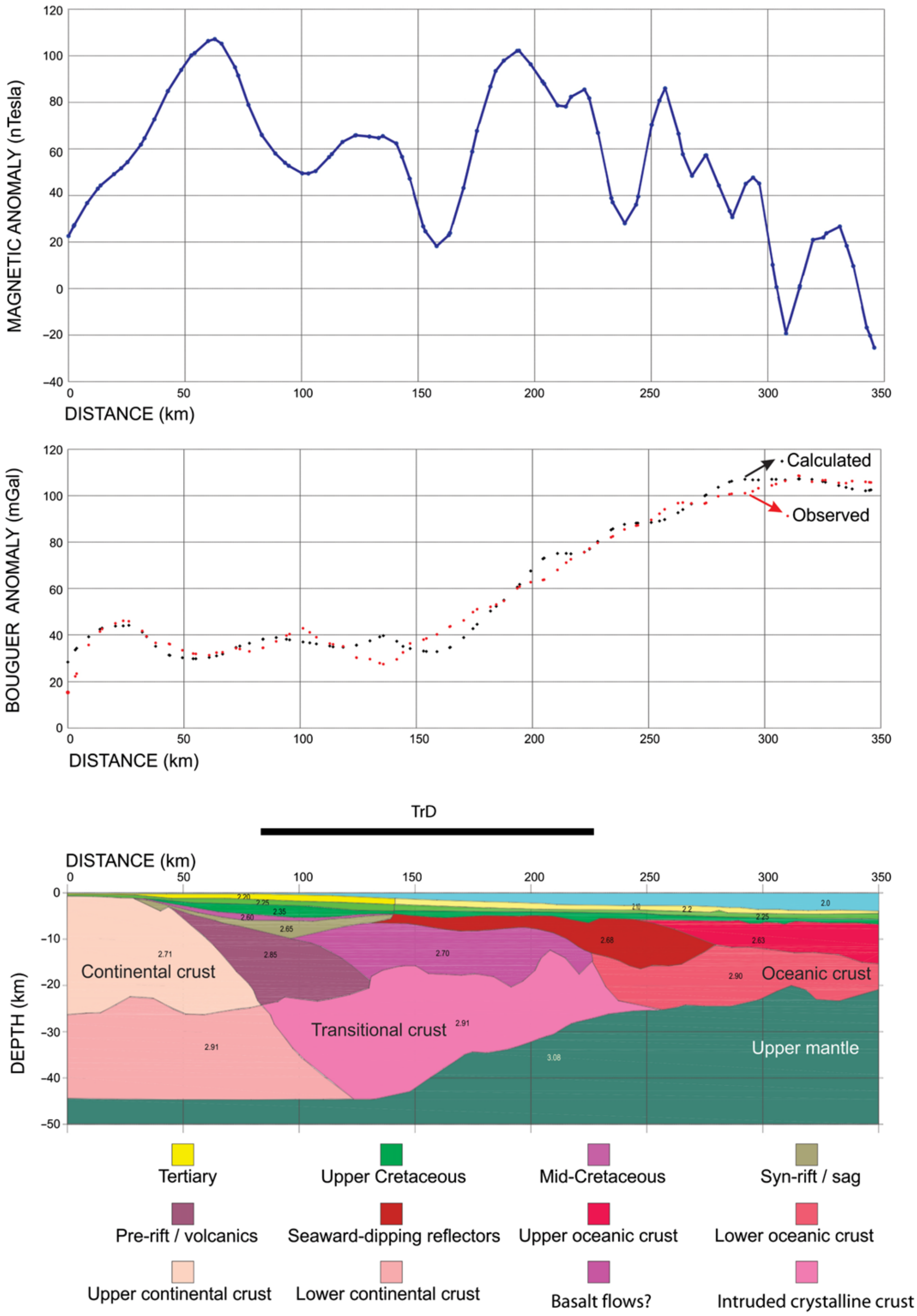

Fig. 6. Gravity model of the regional seismic profile along the Pelotas Basin, with sedimentary, crustal and densities. The continental domain is characterized by a narrow rift in the platform. The transitional domain is characterized by a

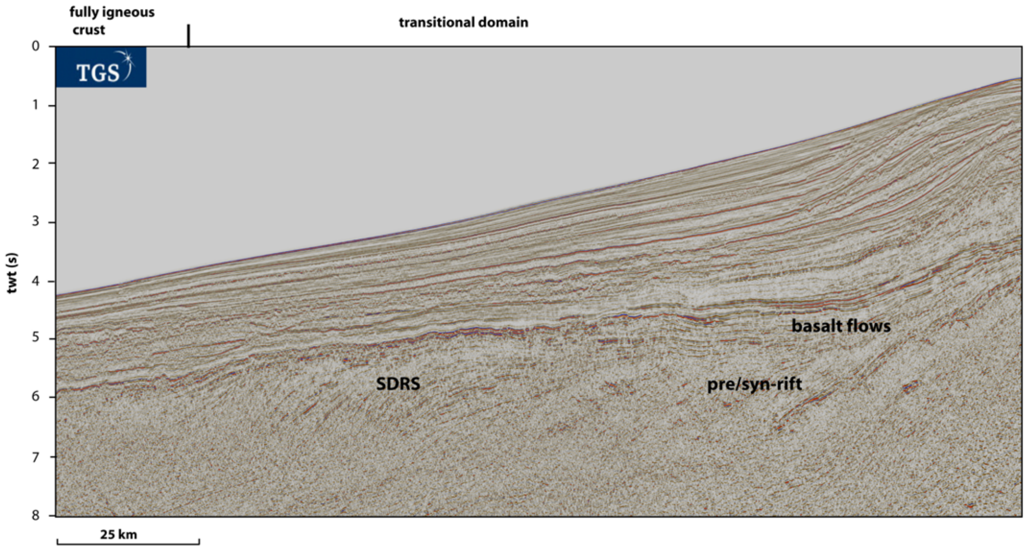

Fig. 7. Seismic example of the transitional domain along the Walvis (Blaich *et al.* 2011). SDRs, seawards-dipping reflections; twt, two-way travel time.

shelf edge (Blaich *et al.* 2011). This body may be associated with the Cape Cross intrusive complex described by Bauer *et al.* (2000). The conjugate transects along the Pelotas–Walvis basins (Figs 2 & 3a) indicate approximately symmetric conjugate margin configuration that is characterized by a gentle crustal taper and by symmetric SDR provinces (e.g. Talwani & Abreu 2000). This may be illustrated by the regional seismic profile extending from the platform towards the transition to oceanic crust offshore Namibia, in the Walvis Basin region (Fig. 8). This profile, located between the Rio Grande–Walvis Ridge Fracture Zone in the north and the modelled geological transect offshore Namibia (Figs 2 & 3a), indicates a thick Late Cretaceous sequence related to sedimentary depocentres that can be recognized in West Africa south of the Congo River (Anka *et al.* 2010; Macgregor 2012). The regional seismic profile indicates that the continental crust (C in Fig. 8) may be locally rifted forming depocentres with Aptian–Barremian sediments (A in Fig. 8). Further oceanwards, beyond the outer high, thick wedges of SDRs are developed sequentially (B in Fig. 8).

At the southern part of South Segment, the representative conjugate crustal transects obtained through 2D gravity modelling (Fig. 3b, c) outline the crustal structure of the Argentine–South Africa conjugate margins. Explicit modelling details of the transects in Figure 3b, c are presented by Blaich *et al.* (2009), while in this study we discuss particular issues on the conjugate transects that elucidate the margin evolution of the southern part of the South Segment. Along the Argentine margin, wide-angle seismic refraction data (Franke *et al.* 2006) combined with gravity modelling (Franke *et al.* 2006; Blaich *et al.* 2009) indicate a high-velocity–high-density lower crust on the western part of the transect (Fig. 3b, c). Such a high-velocity–high-density lower crustal body may be inherited from Palaeozoic accretion of terranes against SW Gondwana (e.g. Ramos 1996, 2004). A similar lower crustal body is not observed along the conjugate South Africa margin (Fig. 3b).

Seismic interpretation and gravity modelling indicate well-developed marginal rift basins characterized by half-graben structures along both the Argentine and the South Africa conjugate margins. These structures are locally compensated by shallowing of the Moho discontinuity along the South Africa margin (Fig. 3b, c). Further oceanwards, deeper and extensive central rift basins are interpreted along both conjugate margins, and are characterized by thinning of the crust. The sedimentary infill of the central rift basin is believed to comprise syn-rift sediments and basalt flows

Fig. 6. (*Continued*) rather thick crust possibly intruded by igneous rocks previous to the break-up. Seawards-dipping reflectors correspond to volcanic layers that onlap the continental crust in the western feather edge. Basinwards of the shelf-break, these layers mark a transition to the fully igneous crust. Gravity anomaly and magnetic anomaly (based on EMAG-2) along the regional profile are also indicated. TrD, transitional domain.

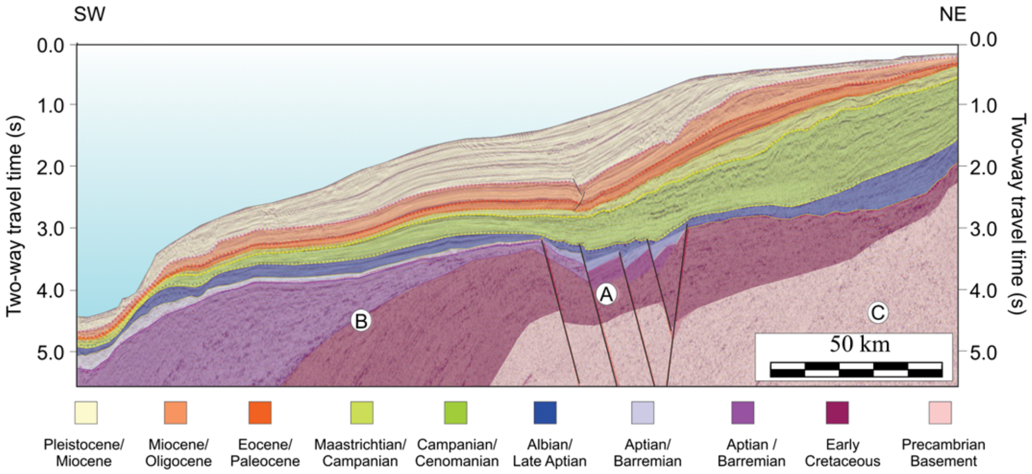

Fig. 8. Regional seismic profile in the Walvis Basin offshore Namibia, showing the transition from continental to oceanic crust by thick wedges of SDRs. C is continental crust; A is intruded continental basement affected by Barremian–Aptian rifting; and B is a SDR wedge.

(Séranne & Anka 2005; Franke *et al.* 2007; Blaich *et al.* 2009; Hirsch *et al.* 2009). Even though SDRs are not easily recognized on the seismic profile along the South Africa margin, such reflections have been proposed previously (Séranne & Anka 2005). Furthermore, results from the gravity modelling and the prominent and positive magnetic anomalies across these basins tend to support the existence of extrusives (Fig. 3b, c). Along the Argentine margin, SDRs are easily recognized on seismic profiles (Fig. 9). Underlying the extrusive lavas, these conjugate margins exhibit high-velocity–high-density lower crustal bodies that are associated with underplating (Franke *et al.* 2006; Hirsch *et al.* 2009; Blaich *et al.* 2009). However, the lower crustal body may be also interpreted as voluminous igneous rocks intruded into the lower crust (e.g. White & Smith 2009).

Continent–ocean transition domain

A transitional domain is interpreted along the South Segment, and is characterized by basalt flows and SDRs located above a high-density crust and a high-density lower crustal body (Fig. 3). The extrusive basalts on the continent–ocean transitional domain form a series of SDR wedges. Along the Pelotas Basin, SDRs are observed landwards of the shelf edge and are associated with a prominent positive magnetic anomaly, including the LMA and 'G magnetic anomaly' (Blaich *et al.* 2011). The Palaeozoic pre-rift basin interpreted by Gladczenko *et al.* (1998) along the conjugate Walvis Basin is also associated with the LMA and with an unidentified magnetic anomaly high further north (Blaich *et al.* 2011). These observations suggest that the supposedly Palaeozoic pre-rift basin may be filled with basalt flows and can also be interpreted as inner SDRs (Figs 2 & 3a). Along the Argentine margin further south, there is clear evidence of inner SDRs (Fig. 8) (e.g. Franke *et al.* 2010) that are also associated with a prominent positive magnetic anomaly, including the LMA and 'G magnetic anomaly' (Fig. 2). Along the conjugate margin off South Africa, inner SDRs and inner basalt flows have also been proposed (e.g. Bauer *et al.* 2000; Blaich *et al.* 2009; Hirsch *et al.* 2009) and appear to be associated with the landwards part of the very wide LMA (Figs 2 & 3b, c). Therefore, the landwards boundary of the transitional domain is characterized by the landwards termination of the inner SDRs/inner basalt flows, which, in turn, are associated with the prominent positive magnetic anomaly (LMA) (Moulin *et al.* 2010) and with the 'G magnetic anomaly' (Rabinowitz & LaBrecque 1979). The fully oceanic (i.e. fully igneous) crust, characterizing the oceanwards boundary of the transitional domain, is placed near the seawards termination of the arcuate outer SDRs (Fig. 3), which is also associated with prominent positive magnetic anomalies (Fig. 2). This implies that the transitional domain–fully oceanic crust boundary is related to the oceanwards termination of the syn-rift volcanic wedges (e.g. Skogseid & Eldholm 1987; Gladczenko *et al.* 1998; White & Smith 2009). The identification of magnetic anomalies corresponding to symmetrically organized spreading ridges between the conjugate margins, however, suggests that the SDRs are actually associated with the

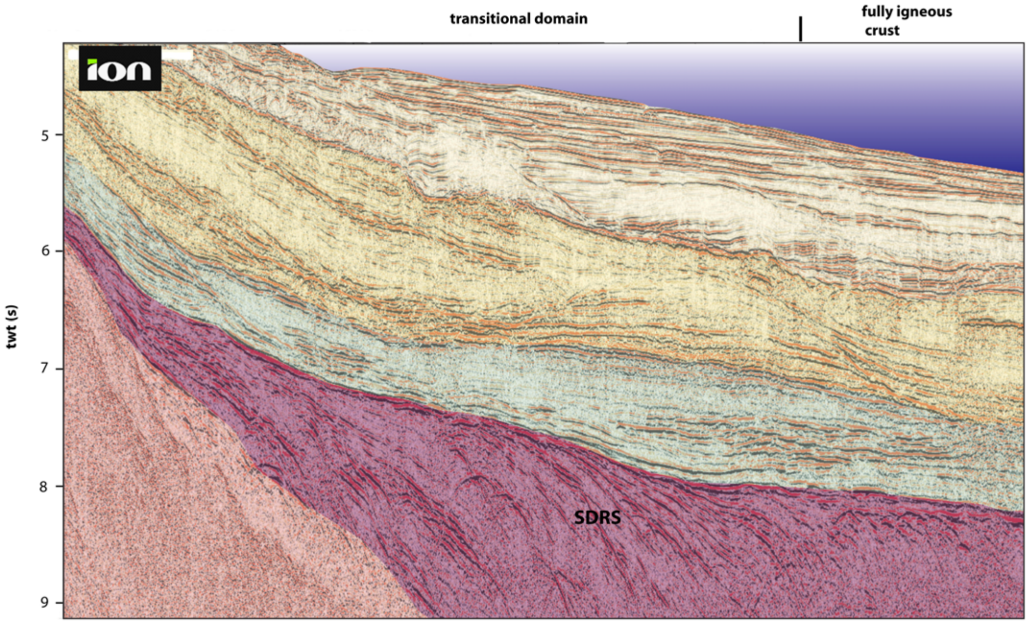

Fig. 9. Seismic example of the transitional domain along the Argentina margin. SDRs, seawards-dipping reflections; twt, two-way travel time.

incipient stages of oceanic crust formation, and thus post-dates the synrift structures observed in the more proximal parts of the margins.

Unlike the SE Brazil–Namibia margin, the transitional domain along the Argentine–South Africa conjugate margin is asymmetric, being considerably wider along the South Africa margin (Fig. 3b, c). Furthermore, a magmatic asymmetry is also evident and is characterized by a broader zone of positive magnetic anomalies along the South African margin (Figs 2 & 3b, c), implying a wider zone influenced by extrusive volcanic material. The fully oceanic (i.e. fully igneous) crust, characterizing the oceanwards boundary of the transitional domain, is placed near the seawards termination of the basalt flows (Fig. 3). Furthermore, this boundary along both Argentine–South Africa conjugate margins is closely associated with magnetic anomaly M4 in the northern area, close to the Salado Transfer Zone. Further south, however, the oceanwards boundary of the transitional domain is associated with the oceanwards termination of the LMA (Fig. 2).

Continental break-up

The continent–ocean transitional domain along 'magma-dominated' margins is characterized by high seismic velocities in the lower crust, which are associated with voluminous igneous rocks intruded into the lower crust (White *et al.* 2008). The voluminous intrusives resulted from enhanced decompressional melting by mantle upwelling and from accretion processes of igneous material during break-up (e.g. White & McKenzie 1989; Bauer *et al.* 2000; Mjelde *et al.* 2002, 2009). These high-seismic-velocity bodies correlate particularly with break-up features such as the large volume of subaerial flood basalts, which flow across the continental hinterlands during continental break-up forming the extrusive counterpart of the intruded crust (Planke & Eldholm 1994; Gladczenko *et al.* 1998; Eldholm *et al.* 2000; Skogseid *et al.* 2000; Talwani & Abreu 2000; White & Smith 2009). In this paper, we discuss and compare the lithospheric extension and break-up of the South Atlantic 'magma-dominated' conjugate margins.

Nature of the transitional domain

The continent–ocean transitional domain along the South Segment, between the Rio Grande Fracture Zone and the conjugate Colorado–Hope transfer system, is characterized by a large volume of flood basalts that form a series of SDRs (e.g. Gladczenko *et al.* 1998; Hinz *et al.* 1999; Franke *et al.* 2007, 2010) and high seismic velocities in the lower crust (Franke *et al.* 2006; Schnabel *et al.* 2008; Hirsch *et al.* 2009) that may be indicative of igneous material accreted to the lower crust during the rifting and break-up stages. Furthermore, the SDRs along both conjugate margins exhibit a characteristic convex-upwards shape (Figs 4, 5 & 7) as a consequence of contemporaneous crustal stretching and subsidence with their emplacement (e.g. Mutter *et al.* 1982). In the northern province of the South Segment, between the Rio Grande Fracture Zone and the Salado Transfer Zone, the melt volume along both conjugate margins decreases southwards, implying that the defined continent–ocean transitional domain along both conjugate margins is very wide close to the Tristan da Cunha plume and decreases southwards (Fig. 3) (e.g. Blaich *et al.* 2009; Hirsch *et al.* 2009). The SDRs emplaced along this conjugate province are symmetrical (e.g. Talwani & Abreu 2000), implying that the continent–ocean transitional domain is also symmetrical (Fig. 3a). In addition, fault blocks are inferred to be present in the upper crust within the continent–ocean transitional domain along both conjugate margins (Fig. 3a) (Gladczenko *et al.* 1998; Talwani & Abreu 2000). The landwards boundary of the continent–ocean transitional domain along this province is closely associated with a prominent positive magnetic anomaly (Fig. 2) (Blaich *et al.* 2011).

The central province of the South Segment, between the Salado Transfer Zone and the conjugate Colorado–Hope transfer system, is characterized by a continent–ocean transitional domain that, on the Argentine margin, appears to be narrow and relatively constant. In addition, the distribution of SDRs varies extensively and systematically along the Argentine margin, where the largest volumes of melts are emplaced close to the transfer zones and are decreasing internally within the individual margin segments, with a general northwards diminishing trend toward the Salado Transfer Zone (Franke *et al.* 2007, 2010). Moreover, Blaich *et al.* (2009) confirmed that the emplacement of extrusive basalt flows along the Argentine margin is associated with magmatic high-density lower crustal, which, in turn, indicates a general decrease in thickness and volume of magmatic products northwards.

The continent–ocean transitional domain along the conjugate South Africa margin is narrow close to the conjugate Colorado–Hope transfer system and broadens considerably northwards, following the prominent and positive magnetic anomaly trend (Figs 2 & 3b, c). The observed along-strike asymmetry on the central province of the South Segment is expressed by the northward increase in thickness and volume of the extrusive/intrusive magmatic products on the South Africa margin (Fig. 3b, c). This consequently leads to the width increase of the interpreted continent–ocean transitional domain northwards, which is conjugate to a continent–ocean transitional domain that is narrow and relatively constant (Fig. 3b, c). In addition, the double branch of the Large Marginal Anomaly (LMA) observed along the South Africa margin (Fig. 2) (Moulin *et al.* 2010) is only present south of the Salado Transfer Zone. The striking dissimilarity between the northern province and the central province of the South Segment suggests that the Salado Transfer Zone marks a distinct along-margin boundary in the distribution and volume of break-up-related magmatism.

On the central province, south of the Salado Transfer Zone (Fig. 2), the influence of the Tristan da Cunha plume can be questioned. This is because the distance of the SDRs observed on the Argentine and its conjugate South Africa margin exceeds the approximately 2000 km diameter of influence of a 'hot spot', as suggested by White & McKenzie (1989). Moreover, the volume of break-up-related magmatism along the Argentine margin is diminishing towards the north (Franke *et al.* 2007, 2010), followed by a southwards decrease in the magnesium composition in the crust along the conjugate margin off South Africa (Trumbull *et al.* 2007). Finally, the abrupt change in the volume of emplaced break-up-related magmatism, from a 'magma-poor' affinity south of the conjugate Colorado–Hope transfer system (southern province) to a 'magma-dominated' margin northwards (e.g. Blaich *et al.* 2009; Franke *et al.* 2010), leads us to consider alternative models that account for the gradual along-margin variations in the thermal regime of the lithosphere and sublithospheric mantle (plume-driven model). In this setting, the northwards unzipping of the rift zones, where the transfer zones acted as lithospheric discontinuities at the onset of rifting, may have substantially influenced the along-margin-varying emplacement of break-up-related magmatism (Franke *et al.* 2010). It was further suggested that the Argentine margin experienced a pulsed volcanic history, where an episodic emplacement of the individual SDRs is observed (Franke *et al.* 2007). In this way, the pulses of volcanism were controlled by interrupted rifting allowing the build-up of heat and followed by massive outpouring of melt successively for each segment. Furthermore, small-scale convective instabilities during rifting are capable of explaining the origin of volcanic margins with moderate volumes of melts (Simon *et al.* 2009). Therefore, the central province of the South Segment may not characterize a 'magma-dominated' end-member margin.

Total rift evolution

Reconstruction of conjugate passive margins frequently indicates a marked asymmetry where a lateral offset in the high-strain zones within the crust and/or upper mantle is observed (e.g. Wernicke 1985; Lister *et al.* 1991). Furthermore, the asymmetry has been cited as evidence for detachment faulting that accommodates large strain until break-up (e.g. Lister *et al.* 1991; Driscoll & Karner 1998; Karner & Driscoll 1999). The analysis performed in this study clearly indicates along-strike tectonomagmatic asymmetry along the central province of the South Segment. In particular, the continent–ocean transitional domain of the South Africa margin is wide, and underwent a large amount of thinning and deformation, whereas the continent–ocean transitional domain along the Argentine conjugate margin is considerably narrower (Fig. 3b, c). Intracrustal detachment faulting is, therefore, invoked along the South Africa margin to explain the observed asymmetry (Fig. 10). The observed along-strike tectonomagmatic asymmetry along the central province of the South Segment may be attributed to the long and complex history of lithospheric extension, initiated long before break-up of the Gondwana supercontinent. Thus, the early stage of formation of the South Segment (i.e. the relief of the base of the lithosphere) may influence considerably the along-margin magmatic distribution where asthenospheric melts may preferentially move towards areas of accentuated crustal relief or ‘thin spots’ (Fig. 10) (e.g. Thompson &

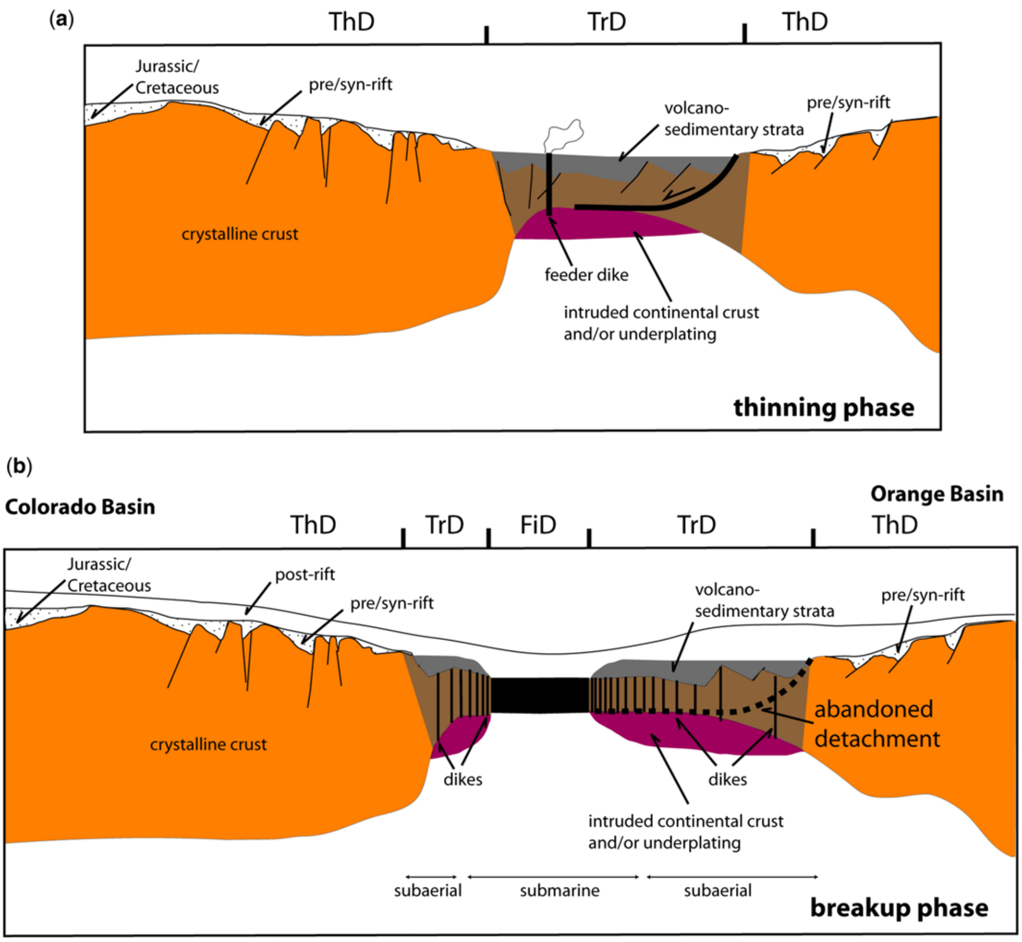

Fig. 10. Conceptual model showing the tectonosedimentary and magmatic polyphase evolution of the conjugate ‘magma-dominated’ South Segment (after Blaich *et al.* 2011). (**a**) Thinning phase, characterized by detachment faulting and possible depth-dependent stretching. (**b**) Break-up phase, volcanic activity associated with voluminous igneous rocks intruded into the lower crust followed by abandonment of the main detachment faults. The break-up phase is also associated with a large volume of subaerial and submarine flood basalts (see the discussion in the text). ThD, thinned crystalline crust domain; TrD, transitional domain; FiD; fully igneous crust.

Gibson 1991). In addition, the existence of Palaeozoic basins and the location of mobile belts along the Pan-African fold belt may have exerted a major influence on the tectonic development and, consequently, on the magmatic distribution along the South Africa margin, giving rise to the observed tectonomagmatic asymmetry (e.g. Gladczenko *et al.* 1998).

The continuous nature of the SDRs along the South Africa margin precludes the possibility of ridge jumps being invoked to explain the observed asymmetry (e.g. Hopper *et al.* 2003). Therefore, the tectonomagmatic asymmetry observed along the central province of the South Segment (Fig. 3b, c) can be inferred to be caused by the initial continental stretching and accompanying magmatism rather than by the subsequent sea-floor spreading (Fig. 10) (e.g. White & Smith 2009). Therefore, the Tristan da Cunha plume on the central province may have influenced the volume of magmatism but did not necessarily alter the process of rifted margin formation (Gladczenko *et al.* 1998), further implying that the subsequent magmatism may have taken place within the inherited, asymmetrically stretched continental crust (Fig. 10) (e.g. White & Smith 2009). In this setting, apart from voluminous magmatism, the extensional evolution of 'magma-dominated' margins (e.g. the central province of the South Segment) may have much in common with 'magma-poor margins' (Fig. 10), except for the fact that there is no evidence of mantle exhumation along the conjugate margins in this segment of the South Atlantic, although some authors have interpreted mantle exhumation in the southern Santos Basin (Zalán *et al.* 2009). Similarly to White & Smith (2009) and Franke *et al.* (2010), we interpret the nature of crust at the continent–ocean transitional domain as a mixture of break-up-related intrusive and residual continental crust (Fig. 10). The consequent symmetrical sea-floor spreading may suggest that the steady supply of magma by dyking may release stress, allowing strain to occur at lower stresses than required for faulting (Ebinger & Casey 2001). In this way, extension of the crust by magmatic intrusion exceeds tectonic extension, leading to continental break-up and emplacement of a symmetric fully igneous crust (Fig. 10) (Ebinger & Casey 2001; Cornwell *et al.* 2006).

Conclusions

The integrated analysis of seismic reflection and refraction profiles, and potential field data, complemented by crustal-scale gravity modelling and plate reconstructions are used to study the evolution of the Central and South segments of the South Atlantic conjugate margins. The study elucidates structural elements and features that reflect the processes that lead to the rupture of the continental crust, in addition to refining and constraining the structural architecture and nature of the continent–ocean transitional domain. The latter is defined as the part of the lithosphere that is located between the clearly identifiable stretched crystalline crust domain and the first appearance of fully oceanic (i.e. fully igneous) crust formed by sea-floor spreading. The continent–ocean transitional domain along the 'magma-dominated' South Segment is characterized by a large volume of flood basalts that form a series of seawards-dipping reflections (SDRs) and high-velocity–high-density lower crust, which are associated with voluminous igneous activity during continental break-up and initial formation of oceanic crust, resulting in accretion of newly formed magmatic material to the lower crust. The northern province of the South Segment, between the Rio Grande Fracture Zone and the Salado Transfer Zone, is characterized by symmetrical SDRs and a symmetrical continent–ocean transitional domain. Furthermore, the melt volume along both conjugate margins decreases southwards. It is very likely that the Tristan da Cunha plume exerted an influence on the distribution of volcanic products along the 'magma-dominated' northern province of the South Segment.

The central province of the South Segment, between the Salado Transfer Zone and the conjugate Colorado–Hope transfer system, is characterized by along-strike tectonomagmatic asymmetry. In this setting, the continent–ocean transitional domain of the South Africa margin is wide, and underwent a great amount of thinning and deformation, whereas the continent–ocean transitional domain along the Argentine conjugate margin is considerably narrower. The asymmetry observed along the central province of the South Segment can be inferred to be caused by the initial continental stretching and accompanying magmatism rather than by the subsequent sea-floor spreading. Thus, the early stage of formation of the South Segment (i.e. the relief at the base of the lithosphere) may have influenced considerably the along-margin magmatic distribution where asthenospheric melts may preferentially have moved towards areas of accentuated crustal relief or 'thin spots.' The Tristan da Cunha plume on the central province may have influenced the volume of magmatism but did not necessarily alter the process of rifted margin formation, further implying that the subsequent magmatism may have taken place within the inherited, asymmetrically stretched continental crust. Thus, the central province of the South Segment may not characterize a 'magma-dominated' end-member margin. Furthermore, apart from voluminous magmatism and lack of mantle exhumation, the extensional evolution of 'magma-dominated' margins, such as the central province of the South Segment, may have much in common with 'magma-poor margins.'

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