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South Atlantic volcanic margins

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Abstract: The Early Cretaceous South Atlantic continental break-up and initial sea-floor spreading were accompanied by large-scale, transient volcanism emplacing the Paraná–Etendeka continental flood basalts and voluminous extrusive constructions on the conjugate margins south of the Torres Arch–Abutment Plateau. On the North Namibia margin we interpret four main tectono-magmatic crustal units: (1) oceanic crust; (2) thickened oceanic crust covered by huge seaward-dipping wedges; (3) a *c.* 150 km wide break-up related rift zone partly covered by the dipping wedges; and (4) thicker continental crust, partly deformed by Palaeozoic extension, east of the Early Cretaceous rift. Similar settings also characterize other South Atlantic margin segments. We infer an up to 300 km wide and 2400 km long rift zone representing lithospheric extension leading to breakup and formation of the South Atlantic volcanic margins. Comparison with other volcanic margins demonstrates, in spite of local and regional differences, gross similarities in tectono-magmatic style, crustal units and dimensions.

Keywords: South Atlantic, Namibia, passive margins, volcanism.

Many rifted continental margins experienced massive, transient magmatic activity during final continental break-up and during initial sea floor spreading. These volcanic margins constitute a main category of transient large igneous provinces (e.g. Coffin & Eldholm 1994). An example is the South Atlantic Large Igneous Province (Fig. 1) emplaced during the Early Cretaceous break-up of South America and Africa. It comprises the Paraná–Etendeka continental flood basalt and offshore extrusive complexes recognized by seaward-dipping reflectors. The igneous activity during rifting and break-up has been ascribed to the Tristan da Cunha hotspot, which has a persistent plume trail along the Rio Grande Rise and Walvis Ridge (e.g. O'Connor & Duncan 1990; Turner *et al.* 1994). Here, we discuss the outer margin off North Namibia and relate its main tectono-magmatic features to other South Atlantic margins and to volcanic margins in general.

Namibia margin

We have interpreted a regional grid of commercial multichannel seismic lines off Namibia some of which reveal prominent seaward dipping reflectors and other tectono-magmatic features related to break-up. The margin south of the Abutment Plateau is divided into four tectono-magmatic zones (Figs 2–4): (1) oceanic crust; (2) thickened oceanic crust covered by seaward dipping reflectors; (3) a *c.* 150 km wide break-up-related Late Jurassic/Early Cretaceous rift, covered by the seaward dipping reflectors in the west, with lavas and intrusives farther east; (4) thicker continental crust. No typical zone 2 features are observed in Line 1 just north of the plateau (Fig. 2).

The irregular zone 1 basement surface changes into a smooth horizon, forming the top of the intra-basement seaward-dipping reflectors, in zone 2 (Figs 2–3). Faulting of zone 3 sediments records the Late Jurassic/Early Cretaceous rifting which culminated with break-up. We note, however, that the faulting is less clear in new German data. There is little evidence of syn-rift sediments, and an erosional rift unconformity indicates that the central rift was uplifted prior to break-up. We infer that a transient magmatic pulse created the seaward-dipping reflectors, partly by subaerial sea-floor spreading, as well as abundant extrusive and intrusive units within extended continental crust. The continent–ocean boundary is placed at the western termination of the rift unconformity which forms the base of the inner dipping wedge but is absent farther west (Fig. 2). The continental crust in zones 3–4 has undergone Palaeozoic extension, and the Permian Karoo sediments below the Etendeka volcanics (Erlank *et al.* 1984) may reflect a Permian eastward migration of the Paraná Basin (Zalán *et al.* 1991).

The most voluminous extrusives exist on the Abutment Plateau (Fig. 2) reflecting the proximity of the plume and persistent volcanism along the plume trail. The seaward dipping reflectors on the plateau terminate against other extrusive complexes with chaotic reflector patterns and steep-sided, flat-topped mounds. Such features may imply a change from subaerial to submarine volcanism (Planke pers. comm.). Thus, we concur with Goslin & Sibuet (1975) and Sibuet *et al.* (1984) in characterizing the western Abutment Plateau as plume-generated oceanic crust.

The seaward-dipping reflectors constitute voluminous crustal bodies, *c.* 100 km wide and up to *c.* 7 km thick. We record also several lower crustal reflectors at 8.5–13 s depth (Fig. 2). A Moho reflector at *c.* 9 s in zone 1 suggests a oceanic crustal thickness consistent with the global average (White *et al.* 1992). The seismic resolution is poor beneath the seaward-dipping reflectors, probably due to attenuation by the extrusive construction (Planke & Eldholm 1994). Farther east the nature of the deep reflectors is less obvious, but the shallowest may represent the top of the high-velocity lower-crustal body recorded at many volcanic margins (Eldholm *et al.* 1995). In the absence of wide-angle crustal velocities we have depth converted transects along Lines 2 and 3 applying interval velocities and deep crustal velocities from other volcanic margins. Gravity modelling of the transects shows that a high-density lower crustal body is consistent with the data available (Gladczenko 1994).

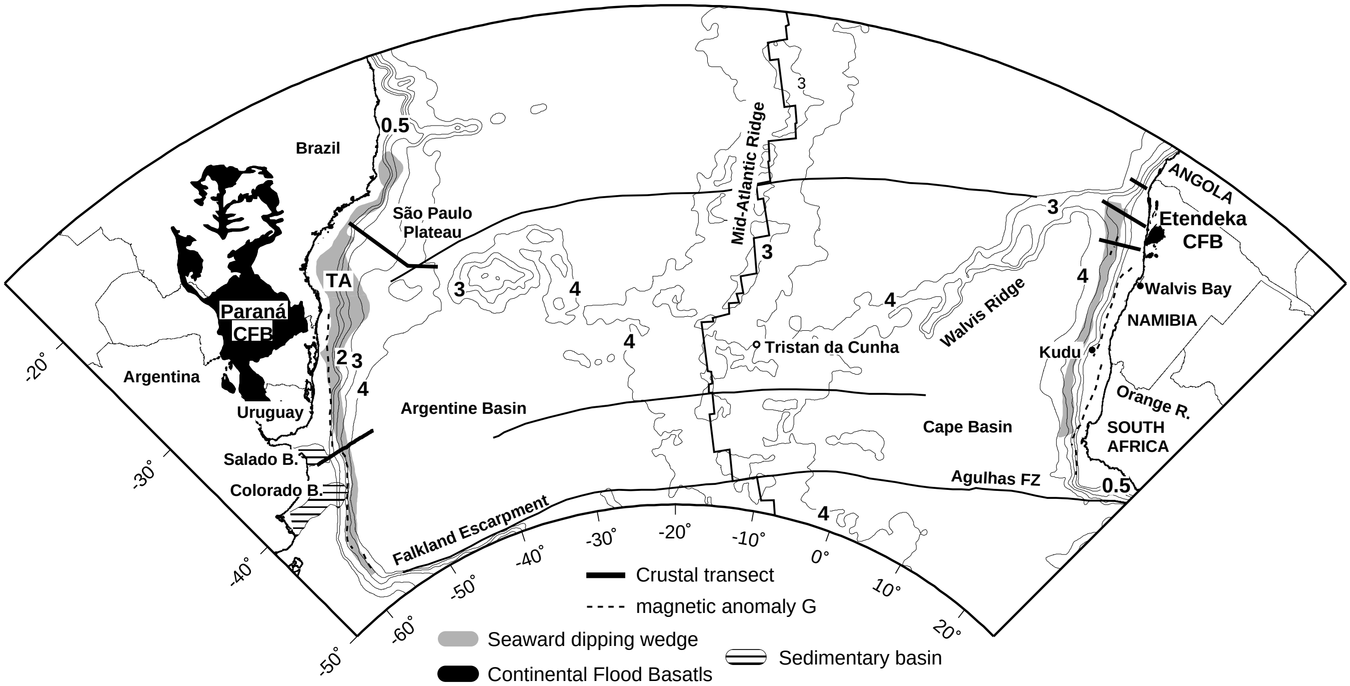

Fig. 1. Tectono-magmatic features related to the South Atlantic volcanic margins, compiled from: Rabinowitz & LaBrecque (1979), Austin & Uchupi (1982), Andreis *et al.* (1987), Cande *et al.* (1989), Milner *et al.* (1992), Turner *et al.* (1994), Gladczenko (1994), Hinz *et al.* (1995). The western seaward-dipping wedge north of the Torres Arch refers to drilled basalts (Goncalves de Souza 1991; Chang *et al.* 1992). CFB, continental flood basalts; TA, Torres Arch. Bathymetry in km (ETOPO-5 1988). Transects shown in Figs 2 and 6.

Seaward-dipping reflectors have been mapped along margin segments south of Walvis Bay (Hinz 1981; Austin & Uchupi 1982). Similar seaward dipping reflectors drilled on the Hatton Bank (Roberts *et al.* 1984), Vøring (Eldholm *et al.* 1987) and SE Greenland (Larsen *et al.* 1994) margins reveal subaerial and shallow submarine tholeiitic lava flows and interbedded sediments. Indeed, one of the commercial Kudu wells off Orange River (Fig. 1) drilled into the feather edge of a seaward-dipping wedge and encountered 100 m of mainly basaltic lavas (Gerrard & Smith 1983).

South America margin

The regional multi-channel seismic profiles acquired by Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) (Fig. 1) show that the 2400 km long rifted margin off southern Brazil, Uruguay and Argentina is characterized by igneous activity during rifting and break-up (Hinz 1990; Hinz *et al.* 1995). In particular, wedges of seaward-dipping reflectors are present along the entire margin south of the Torres Arch, and voluminous extrusive units have been mapped north of the arch to *c.* 20° S (Mohriak *et al.* 1990; Goncalves de Souza 1991; Chang *et al.* 1992), i.e they extend for about 500 km north of the plume trail.

The Argentine and Uruguay margins may be divided into four similar tectono-magmatic zones as those off Namibia (Figs 4–5). West of the seaward dipping reflectors Hinz *et al.* (1995) have mapped some basins which merge with the coastal and shelf Salado and Colorado basins (Fig. 1). Permian to Tertiary sediments have been drilled in the Colorado Basin (e.g. Andreis *et al.* 1987). Hinz *et al.* (1995) also describe narrow half-grabens of unknown age and nature west of the seaward dipping reflectors (Fig. 5a), as well as local deep crustal reflectors some of which may represent a block-faulted pre-rift substratum below the innermost seaward dipping reflectors. Nonetheless, neither multi-channel seismic nor velocity profiles provide reliable definition of mid-to-deep crustal features.

The maximum seaward dipping reflectors width is mapped on the Torres Arch between the main Paraná Continental Flood Basalts and Rio Grande Rise (Fig. 1), i.e. in a conjugate position to the Abutment Plateau. Farther north, on the broad 2000–3000 m deep Saõ Paulo Plateau, the distance between the shelf edge and unequivocal oceanic crust is in excess of 500 km compared with about 90 km on the conjugate margin (Leyden 1976; Davison this volume), cf. Line 1 (Fig. 2). The crustal nature of this region is not well understood, both continental crust (e.g. Guimarães *et al.* 1982) and thickened oceanic crust (Leyden *et al.* 1971) have been proposed. Furthermore, the plateau is underlain by salt layers, hiding the crustal features below (Fig. 5).

South Atlantic Large Igneous Province

Plate reconstructions indicate a stepwise, northward opening of the South Atlantic Ocean (Rabinowitz & LaBrecque 1979; Nürnberg & Müller 1991). The onset of sea-floor spreading is not well determined but it is commonly inferred that the ocean south of the Tristan da Cunha plume trail opened progressively during anomaly M11–M4 times, and during the Cretaceous Quiet Zone farther north. A linear magnetic anomaly, G, was used to delineate the continent–ocean boundary south of the plume trail (Talwani & Eldholm 1973; Rabinowitz & LaBrecque 1979) (Fig. 1). Modelling of seaward dipping reflectors off Argentina (Hinz *et al.* 1995) and elsewhere (Talwani *et al.* 1995; Steiner & Roeser 1996) show that they may produce high-amplitude, linear anomalies. The G anomaly correlates with the seaward dipping reflectors also

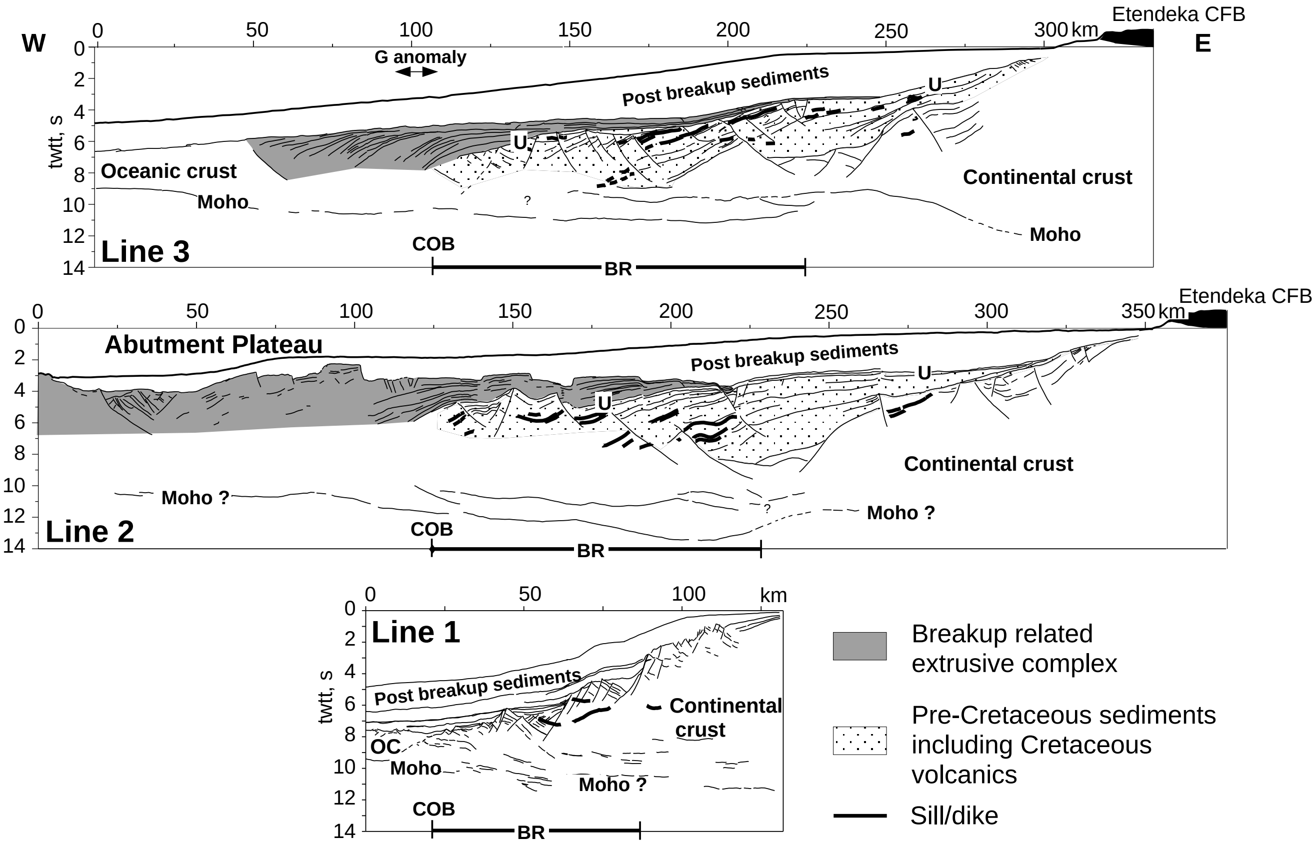

Fig. 2. Multi-channel seismic dip lines off northern Namibia acquired by PGS-Nopec. BR, break-up-related rift zone; COB, continent–ocean boundary; OC, oceanic crust, U, breakup unconformity. Only pre-drift structures and main tectono-magmatic zonation are included. Location in Figs 1 and 4.

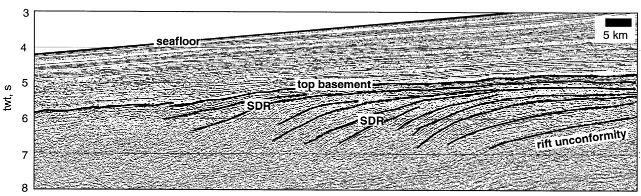

Fig. 3. Seismic example of seaward-dipping reflectors off northern Namibia. SDR, seaward-dipping reflector.

off northern Namibia (Fig. 2, 4). However, anomaly G of Rabinowitz & LaBrecque (1979) is located east of the seaward-dipping reflectors south of Walvis Bay where Gerrard & Smith (1983) ascribed its source to flows and sills over continental basement. Thus, the nature of the G anomaly should be re-examined, in fact the continuity of the seaward-dipping reflectors suggests coeval opening along 2400 km of the plate boundary, if the igneous activity is plume related.

We note that extrusives north of the Torres Arch (Goncalves de Souza 1991; Chang *et al.* 1992) are conjugate to a region of negative gravity anomalies on the outer Angola margin south of 14° S. Simple-shear rift extension and/or migration of the early spreading axis (Sibuet *et al.* 1984; Davison this volume) may explain the different character of these margin segments. Despite the absence of seaward dipping reflectors on Line 1 north of Abutment Plateau (Fig. 2), industry sources (N. Cameron pers. comm.) refer to seaward dipping reflectors off Angola. Rosendahl *et al.* (1991) and Mohriak *et al.* (1995) have interpreted seaward-dipping reflectors in Gulf of Guinea and Sergipe Basin off Brazil respectively. However, their seismic signatures are different from the prominent wedges farther south. The plate tectonic setting may explain the change in conjugate margin character north of the plume trail. The plume–lithosphere interaction facilitated break-up and decompressional partial melting beneath the strongly thinned lithosphere in the south, whereas less voluminous melts penetrated the thicker lithosphere to the north. Nonetheless, the proximity of the Brazil and Angola margins to the plume make us infer magmatic underplating and pervasive intrusions coeval with the complete break-up farther south.

The onset of sea-floor spreading was preceded by continental extension along the present margins. Uliana *et al.* (1989) and Nürnberg & Müller (1991) infer the initiation of rifting at *c.* 160 Ma, while dynamic modeling of lithospheric extension in the Paraná–Etendeka region suggests a rift duration of *c.* 25 Ma (Harry & Sawyer 1992). We estimate rift widths of *c.* 120 and *c.* 150 km off Namibia and Argentina, respectively; and that the up to 300 km wide and 2400 km long rift underwent extension for *c.* 25 Ma prior to break-up. Off Namibia, we record break-up intrusive rocks in pre-rift sediments at a distance of 100–150 km landward of the continent–ocean boundary and most of the break-up-related rift zone is covered by volcanic rocks.

Peate *et al.* (1992) and Milner *et al.* (1992) have estimated the volume of the Etendeka and Paraná Continental Flood Basalts to 0.07×10^6 km^3 and 1.2×10^6 km^3, respectively. If Line 3 (Fig. 2) is representative, the extrusive volume on the

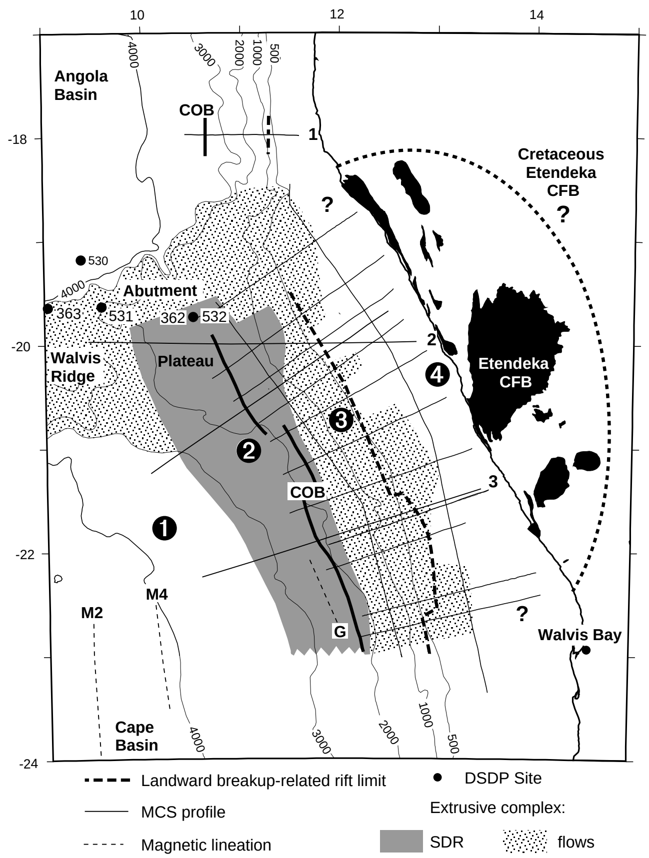

Fig. 4. Namibia margin tectono-magmatic zonation (1–4). Multi-channel seismic profiles from Intera-HGS ECL89/91 and PGS-Nopec surveys. Magnetic anomalies from Rabinowitz & LaBrecque (1979). CFB, continental flood basalts; COB, continent–ocean boundary; SDR, seaward-dipping reflectors. Bathymetry in m (GEBCO 1994).

northern Namibia margin is 0.2×10^6 km^3. Volume estimates farther south are uncertain, but appear smaller. We calculate volumes of 0.58×10^6 km^3 and 0.5×10^6 km^3 for the eastern and western margins, respectively. The entire South Atlantic Large Igneous Province, including the continental flood basalts, has an extrusive volume of at least 2.35×10^6 km^3. However, the onshore geology suggests that the Etendeka–Paraná Continental Flood Basalt province was larger than today (e.g. Erlank *et al.* 1984; Renne *et al.* 1996), probably continuing offshore (Fig. 4). A similar value, 2.0×10^6 km^3, has been calculated for the North Atlantic Volcanic Province (Eldholm & Grue 1994). On the other hand, the total extrusive volume for the US East Coast margin where no evidence for a plume is present and onshore extent of basalts is limited, is smaller (Gladczenko 1994).

Global comparison

At present, the volcanic margins off E Greenland, Norway and UK are by far the best studied by integrated seismic surveys and drilling, while excellent seismic crustal information is available on the US East Coast margin (Holbrook *et al.* 1994*a*, *b*; Talwani *et al.* 1995). These studies have led to a first-order tectono-magmatic volcanic margin zonation, and evolutionary models which include (Eldholm *et al.* 1995): (1) lithospheric extension during a rift episode of finite duration leading to complete plate break-up and separation; (2) central rift uplift and increased igneous activity during late rifting and break-up, culminating with voluminous outpourings of basaltic lavas during break-up and initial sea-floor spreading; and (3) change to normal accretionary volumes with subsequent continental margin subsidence and maturation. The intense break-up magmatism is commonly associated with mantle plumes impinging on already thinned lithosphere, or on lithosphere under extension.

The data from the South Atlantic conjugate volcanic margins document the volcanic signature. In fact, the North Atlantic margin tectono-magmatic zonation, and the break-up-related igneous features may equally well apply to the South Atlantic. However, the absence of reliable deep crustal seismic data has precluded verification of high-velocity lower crustal bodies beneath the extrusive cover along the continent–ocean transition.

The increased asthenospheric melt potential in the early Cretaceous, documented by the Paraná–Etendeka Continental Flood Basalts, is ascribed to the Tristan da Cunha mantle plume. The plume location at break-up is unclear and

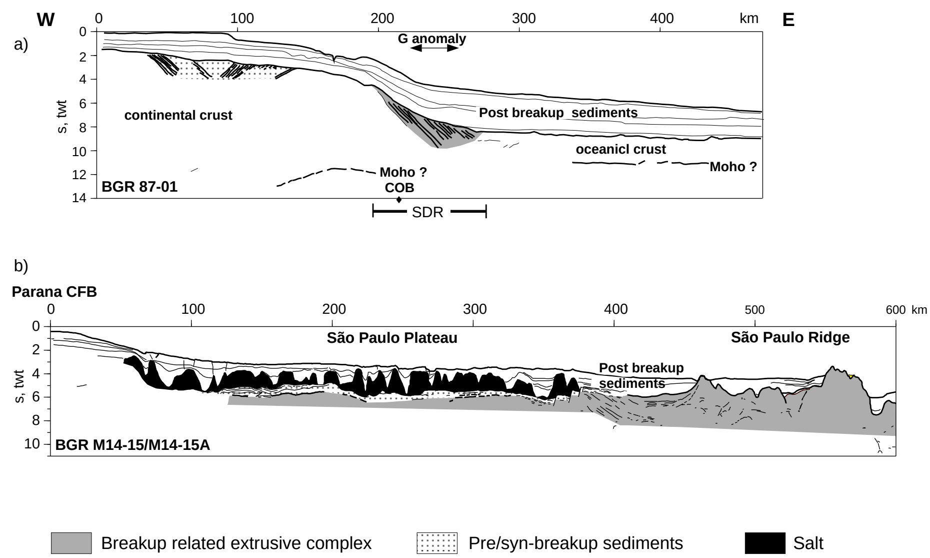

Fig. 5. Line drawings of BGR multi-channel seismic lines off Argentina (**a**) and Brazil (**b**). COB, continent–ocean boundary; SDR, seaward-dipping reflectors. Location in Fig. 1.

locations beneath southern Angola (Duncan 1984) or an eastward migration from the NW Paraná Basin have been suggested (Turner *et al.* 1994). The timing and location of volcanism may have been controlled by the mode of rifting and pre-existing weakness zones within the lithosphere (Harry & Sawyer 1992). With reference to the size of modelled plume heads after lithospheric impingement (White & McKenzie 1989; Hill 1991), the more than 2000 km long volcanic margin south of the Torres Arch–Abutment Plateau raises the question whether the plume is responsible for the entire South Atlantic Large Igneous Province. A combination of the Tristan da Cunha plume and locally increased asthenospheric melt potential along the southern part of the incipient Africa–South America plate boundary may satisfy the observations.

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