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Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins: implications for salt tectonics and source rocks

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Abstract

Seaward-dipping reflectors (SDRs) represent flood basalts rapidly extruded during either rifting or initially subaerial sea-floor spreading. Evaporites can form on this basaltic proto-oceanic crust, as in the Afar Triangle today. Evidence for SDRs in South Atlantic deep-water regions comes from proximity to the uniquely large Paraná–Etendeka volcanic province onshore, the Tristan and Gough hot spots, drilled volcanic rocks, and seismic profiles showing SDR provinces more than 100 km wide, as much as 7 km thick, and thousands of kilometers long. SDRs are clearest adjoining the Aptian salt basins. However, we speculate that SDRs are also present but seismically obscured below the salt basins. We argue that the conjugate Aptian salt basins are post-breakup, not pre-breakup; they were separated from the start by a mid-oceanic ridge; distal salt accumulated on proto-oceanic crust, not rift basins. This hypothesis is supported by: seismic stratigraphy and structure; magnetic anomalies; plate reconstructions; and hydrothermal potash evaporites. An important implication for exploration is that thick basalts, rather than rift-age source rocks, may underlie distal parts of the salt basins.

Keywords: Flood basalt; Passive margin; Seaward-dipping reflector

1. Background

1.1. Introduction

As exploration of divergent margins advances through deep and ultra-deep water, the nature of the continental-oceanic boundary becomes increasingly relevant to petroleum systems. For example, it is vital to determine the structural and stratigraphic context of subsalt lacustrine source rocks in basins containing both clastic rift fill and flood basalts.

This paper reviews volcanic rifted margins in general, then focuses on the role of igneous rocks in continental breakup and margin development in the South Atlantic. We survey massive suites of subaerial flood basalts that occur on continental crust, across the continent-ocean transition, and as part of the early-formed oceanic crust. Then we discuss how salt structures obscure these igneous provinces and speculate on their full extent. Finally, we examine the role of salt tectonics during continental breakup and argue that the Aptian evaporites of the South Atlantic are postrift and thus do not pre-date the onset of sea-floor spreading.

1.2. Large igneous provinces and mantle plumes

Large Igneous Provinces (LIPs) rapidly create large volumes of crust, especially in ocean basins and their divergent margins. LIPs comprise mafic rocks that are not formed by normal sea-floor spreading. They occur as onshore continental flood basalts, flood basalts

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imaged as seaward-dipping reflectors, oceanic plateaus, submarine ridges, seamount groups, and ocean-basin flood basalts. LIPs also include rocks equivalent to those listed above in intrusive settings; thicker-than-normal (20–40 km) oceanic crust near continental margins, and lower crustal, underplated bodies having high *P*-wave velocities below continental margins (Coffin & Eldholm, 1994; Eldholm, Skogseid, Planke & Gladczeko, 1995).

The main focus of this paper is on LIPs associated with continental breakup in the South Atlantic. LIPs are highly episodic, mostly forming in short-lived (< 1–3 Ma) pulses of high-volume magmatism (White, 1989). For example, 6×10^6 km^3 of magma were emplaced over an area of $> 1.3 \times 10^6$ km^2 in only 3 Ma along the rifted margins of the North Atlantic volcanic province (Coffin & Eldholm, 1994). The LIPs relevant to this paper form in volcanic rifted margins where crust extends and abundant magmatism is fed by mantle plumes (Burke & Dewey, 1973; Morgan, 1983; Coffin & Eldholm, 1994). Although most LIPs are related to mantle plumes, plumes do not seem essential for breakup and the formation of volcanic margins (Eldholm et al., 1995). Furthermore, some plumes underlie plates without dispersing them (for example, the giant Ontjong Java and Kerguelen plumes; Coffin & Eldholm, 1994). Spatial relationships can be misleading, though. For instance, melts can move laterally away for vast distances from the plume center as lava flows (> 750 km for Columbia River basalts; Tolan, Reidel, Beeson, Anderson, Fecht & Swanson, 1989) or dykes (> 1500 km for McKenzie dyke swarm in Canada; LeCheminant & Heaman, 1989).

The comparative roles of extension and mantle plumes in volcanic rifted margins are much debated (White & McKenzie, 1995). Most authors envisage that melt is generated rapidly by adiabatic decompression of a rising mantle plume. The quantity of melt depends on the amount of lithospheric extension, subtle temperature increases (50–100°C) in the asthenosphere, thickness of lithosphere before rifting, and the duration of rifting (Bown & White, 1994; Eldholm et al., 1995). Most significantly, the subsidence produced by lithospheric extension alone (McKenzie, 1978) is offset along volcanic margins mainly by: (1) addition to the crust of igneous material produced by decompression and (2) dynamic support by the hot, low-density mantle plume (White & McKenzie, 1989). The impinging plume creates a bulge in the Earth's surface 800–2000 km wide and 1–4 km in relief. This swell increases gravitational potential, which promotes lateral stretching (rifting) in its crest (White & McKenzie, 1995). Any unrelated rift system cutting across a hot spot would have enhanced extension and volcanism. As the plume head starts to spread and melt lithosphere, continental flood volcanism begins suddenly over an area as much as 2000–2500 km across (White & McKenzie, 1989). Voluminous tholeiitic basalts escape from the mantle and load the crust. This flood is typical during breakup and initial sea-floor spreading but can also start before rifting began (as in the Afar plume; Davison et al., 1994).

1.3. Seaward-dipping reflectors

The most distinctive LIPs of volcanic rifted margins are seaward-dipping reflectors (SDRs). These were first recognized on the continental margins of the Norwegian Sea (Hinz & Weber, 1976; Mutter, Talwani & Stoffa, 1982; Roberts, Backman, Morton, Murray & Keene, 1984a; Roberts & Schnitker, 1984b) and are now known to be widespread. Most drilling refraction surveys on SDRs have been done in the North Atlantic.

SDRs represent subaerial basalt flows erupted close to sea level. SDR sequences are immense. As much as 20 km thick, their width varies from tens to hundreds of kilometers; between Greenland and Iceland, the SDR belt is as much as 300 km wide (Hinz, Mutter, Zehnder & NGT Study Group, 1987; Larsen & Jakobsdóttir, 1988). Their mostly continuous length reaches almost 2500 km on the East Greenland margin (Eldholm & Grue, 1994). SDRs form by brief but voluminous extrusion. For example, along the Greenland rifted margin, subaerial lavas extruded profusely but briefly over 2 million years (Larsen & Jakobsdóttir, 1988). In contrast, the Iceland plume has persisted subaerially for > 60 Ma. The major part of SDR provinces lies landward of the oldest identifiable sea-floor magnetic anomaly. They generally form a magnetically subdued band, which results from extrusion within a single polarity interval or from stacking of flood basalts.

The North Atlantic SDR provinces have three main layers of crust (Eldholm et al., 1995). (1) Upper crust comprises flood basalts and interbedded sediments. P-wave velocity increases rapidly downward from 3.7 to > 5.0 km/s in the upper 1 km then increases more gently below. Velocities reach 6.0–6.5 km/s in the deepest SDRs. Significantly, the boundary between oceanic Layer 2 and Layer 3 cross-cuts the SDRs. Thus, rather than being a primary igneous feature, this boundary may represent a metamorphic facies change that shifts up and down as heat flow and other variables fluctuate. (2) Middle crust, which could consist of dykes overlying gabbro, has a velocity of 6.5–6.7 km/s at the top. (3) A lower crustal body has high (> 7 km/s) velocity and very gentle velocity gradient. These rocks could be MgO-rich intrusions created by breakup magmatism or could comprise stretched continental crust at granulite facies.

The seismic character of SDRs varies greatly. Variations in continuity, dip, amplitude, reflection pattern, and thickness are controlled by: (1) volume and rate of magmatic production, (2) the volcanic environment (vent geometry, relation to sea level, etc.), (3) any synvolcanic and postvolcanic deformation, and (4) rate and amount of subsidence (Eldholm et al., 1995). Nevertheless, SDRs have several distinctive features (Figs. 1 and 2). These seaward-dipping reflectors are convex up; dips steepen seaward from subhorizontal nearest the surface to 9–30° at their base (Roberts et al., 1984a; Roberts & Schnitker, 1984b). Individual reflectors can be traced for up to 11 km downdip. SDR flows average only 6 m thick, which is too thin to create individual reflectors (Barton & White, 1997). SDRs may represent a complex interference pattern between stacks of thin basalt flows and some thick individual flows (Eldholm et al., 1995). Interbedded volcaniclastic sediments and tuffs and weathered flow contacts provide further impedance contrasts (Roberts et al., 1984a; Roberts & Schnitker, 1984b). On strike-parallel profiles, reflectors are typically subhorizontal (Barton & White, 1997), except where complicated by volcanoes or oblique fissures.

Sedimentary reflectors conformably overlie the SDR basement. SDRs disappear downward into noisy reflections, where the geology is obscure. SDRs partly overlie stretched continental crust (Skogseid & Eldholm, 1995), but deep, rotated fault blocks are rarely imaged because masses of melt weaken and remobilize the crust. Landward, SDRs onlap continental crust, indicating that their source was seaward. Off Norway and Rockall, SDRs overlie undisputed oceanic crust and pass laterally and diachronously into normal oceanic crust (D.G. Roberts, personal communication 1999). Some continental margins, such as the Rockall margin off Norway, have double belts of SDRs, both of which wedge out landward into thin, flat-lying sequences (Barton & White, 1997). The landward SDR pile was emplaced above what is interpreted to be stretched and intruded continental crust, probably before breakup. The oceanward SDR belt separates stretched continental crust and true oceanic crust and was probably emplaced when subaerial sea-floor spreading began. Oceanic crust is typically about 7 km thick (White & McKenzie, 1995) and has a hummocky surface, including steep-sided volcanic mounds (Eldholm & Grue, 1994). Oceanic crust is opaque, containing only short or chaotic reflectors obscured by diffractions.

SDRs are subaerial flood basalts of oceanic composition; the term "proto-oceanic crust" (Meyers, Rosendal & Austin, 1996a) is thus appropriate. Interbedded sediments and weathered flow tops indicate that they are extruded above sea level on a thermally induced

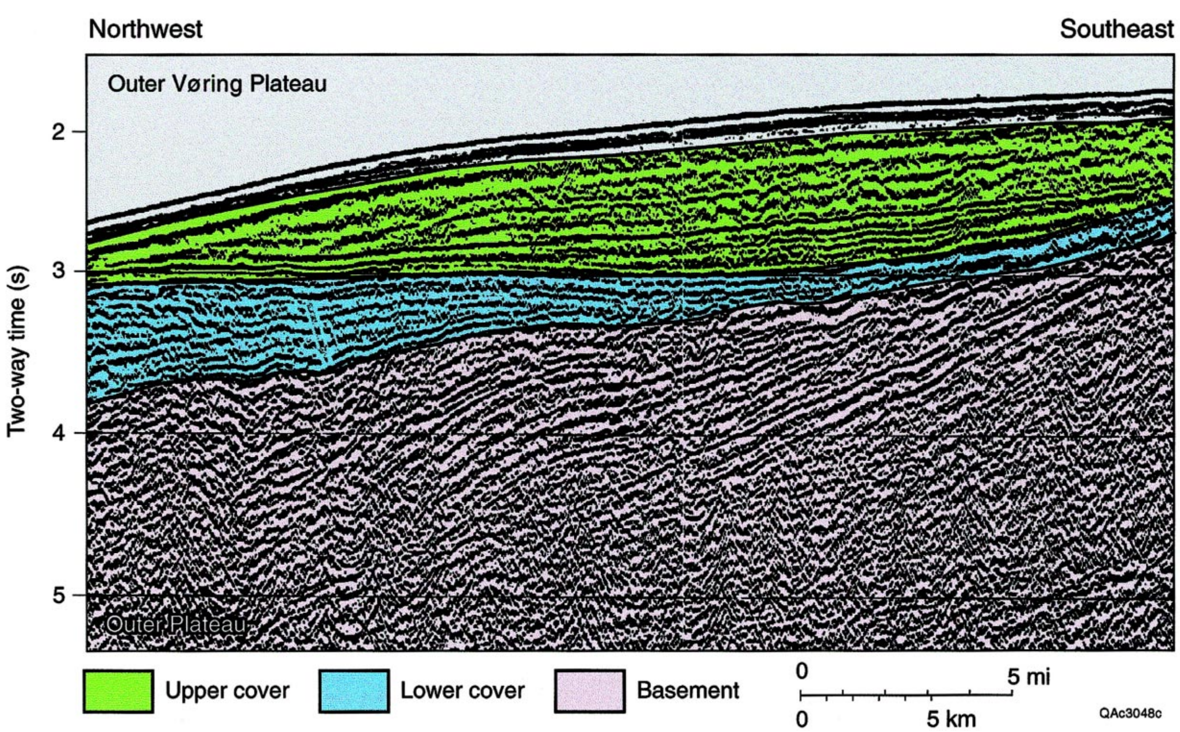

Fig. 1. Seismic profile of a typical wedge of seaward-dipping reflectors (SDRs) in the basement; this oblique dip line is from the Outer Vøring Plateau on the continental margin of Norway (after Mutter et al., 1982).

surface swell (references in Barton & White, 1997, p. 531). The extrusive setting of SDRs can be visualized from modern analogs such as neovolcanic Iceland (Pálmason, 1980), which formed on 15–20-km-thick, hot lithosphere above a mantle plume. Extensive flows spew subaerially from volcanoes and fissure swarms parallel to the rift axis in regions 40–100 km long and 5–20 km wide (Barton & White, 1997). Each region is fed by central volcanoes 15–40 km wide (Gudmundsson, 1995). Their calderas are commonly capped with hyaloclastites (explosive fallout), which could explain their unreflectivity (Barton & White, 1997). The flows pile up at rates of 1000–5000 m/Ma, mostly in the first 1 Ma of the 3 Ma typical duration (Barton & White, 1997). Seaward-retreating magmatic vents lie downdip of the SDRs. The convex-upward curvature and seaward dip of the lavas probably result from differential subsidence caused by loading by younger flows farther seaward (Pálmason, 1980; Hinz, 1981; Mutter et al., 1982). (SDR divergence appears too extreme to be accounted for by differential cooling over such a brief time.)

As the volcanic margin migrates off the plume, basaltic outpouring declines. The continental margin cools and subsides below sea level. Without topographic barriers, much of the igneous province is inundated by seawater. The accreting center submerges as LIP volcanism wanes. Flood volcanism is impossible under water because lavas freeze rapidly. Thus, submarine sea-floor spreading begins to form true oceanic crust, complete with magnetic stripes caused by reversals. Meanwhile, the adjoining continental margin may remain isostatically elevated because of underplating (White & McKenzie, 1989).

As the subaerial basalts subside, restricted circulation of inundating seawater can lead to the formation of evaporites directly on proto-oceanic basalts. Perhaps the most vivid modern example of this is the Afar region of Djibouti in the Horn of Africa. In this region, where the Ethiopian plume, the Red Sea rift, and the Aden spreading ridge all meet subaerially, evaporites are found accumulating directly on proto-oceanic basalt crust (Fig. 3). A prime example is the evaporites around Lake Assal. This is the deepest point in Africa, 168 m below sea level. Only the barrier provided by a volcanic pile less than 0.3 Ma old prevents the area around Lake Assal from being submerged (Manighetti, Tapponnier, Courtillot, Cruszow & Gillot 1997). With these kinds of topographic dams, seawater periodically spills in and evaporates subaerially to form salt below sea level. These evaporites are coeval with proto-oceanic spreading. They form part of the postrift package, whose accommodation space is provided by crustal thinning, cooling, magma withdrawal, and SDR wedges loading continental margins (Benson, 1999).

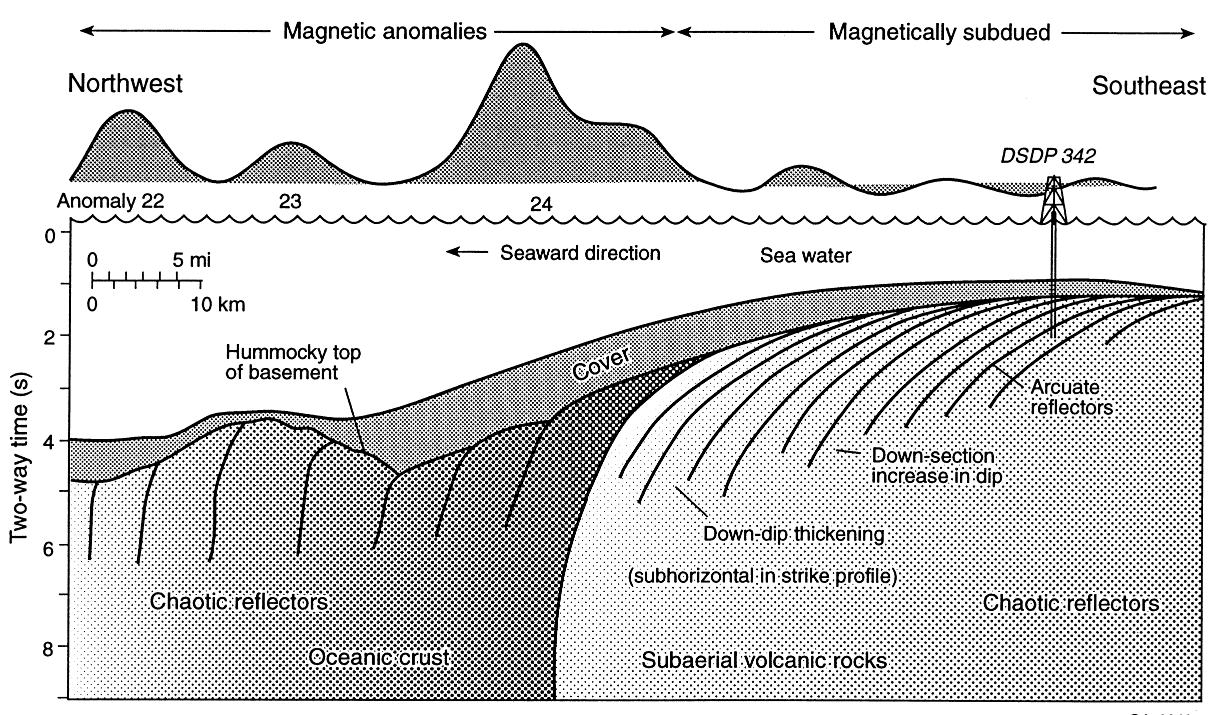

Fig. 2. Schematic features of SDRs on the Outer Vøring Plateau, offshore Norway (after Mutter et al., 1982). Magnetic anomalies are based largely on lines C165–166. Chron 24 at 56 Ma roughly dates the SDR sequence.

2. South Atlantic breakup

2.1. Rifting history

As Pangea dispersed, the Atlantic Ocean opened in three main phases: first, the southern North Atlantic, then the South Atlantic, then the Equatorial Atlantic. In the South Atlantic, rifting and the onset of sea-floor spreading generally became younger northwards, like an opening zipper. This idea is supported by the following two paragraphs although data quality varies greatly.

Least reliable is the onset of rifting, which is recorded by the oldest rift fill. Because of their depth, the oldest strata are rarely drilled offshore. Thus, estimates for the onset of rifting vary widely for any particular basin by as much as 20 Ma. Estimates for the onset of rifting have the following ranges in African basins, listed from south to north: Cape, 220–200 Ma (Light, Maslanyi & Banks, 1992); Orange, 160 Ma (Erlank et al., 1984) to 144 Ma (Guiraud & Maurin, 1992); Lüderitz–Walvis, 126 Ma (Nürnberg & Müller, 1991); Benguela–Kwanza–Congo–South Gabon, 144 Ma (Teisserenc & Villemin, 1989; Guiraud & Maurin,

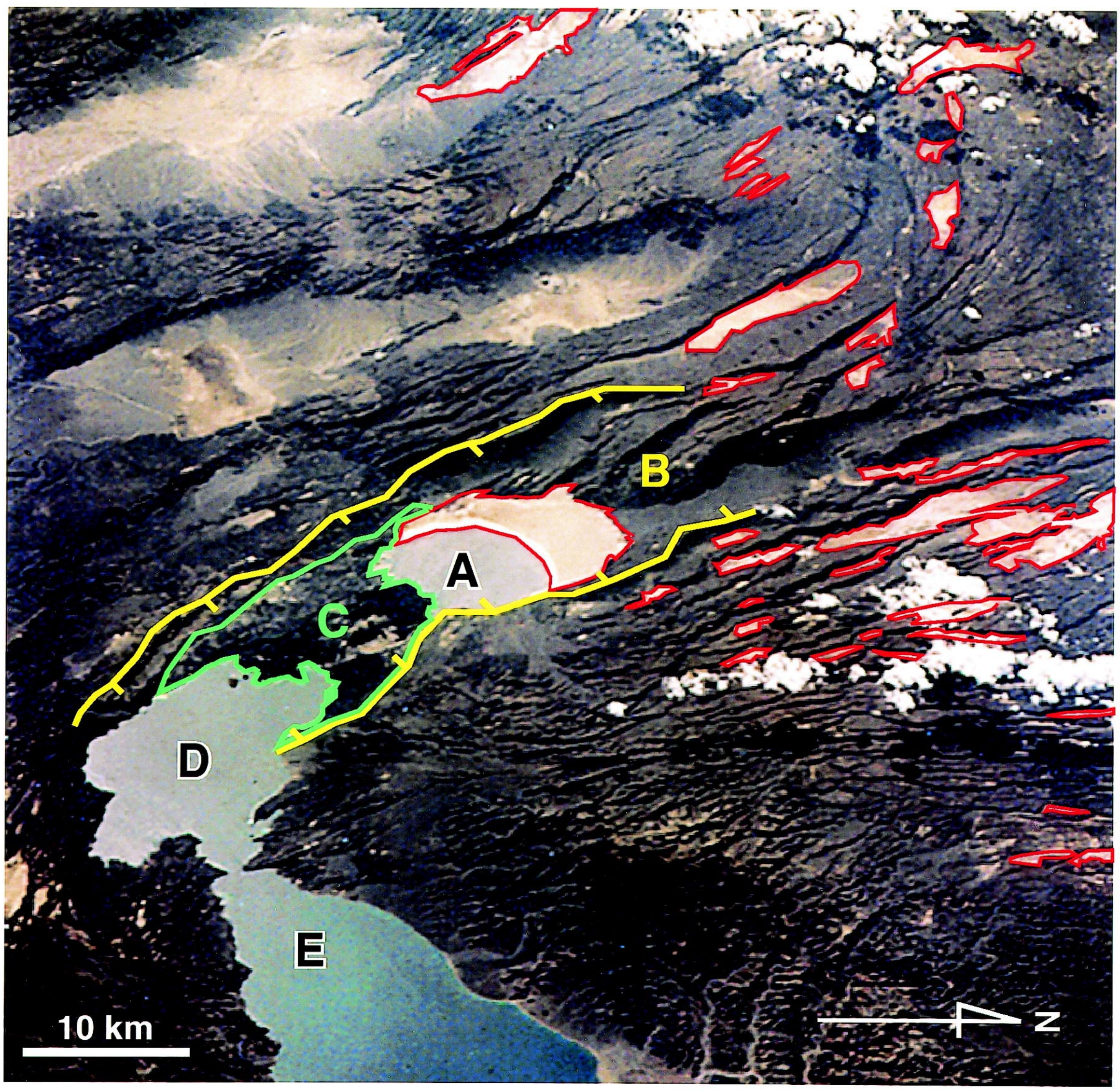

Fig. 3. The Afar triple junction in Djibouti, Horn of Africa. Evaporites accumulating subaerially below sea level appear as pale patches, outlined in red, on dark flood basalts representing proto-oceanic crust. The evaporites are especially prominent around the shores of Lake Assal (A) but also occur in half-grabens. Lake Assal occupies the interior (eastern) end of the Assal rift (B) behind a barrier of lavas <0.3 Ma old (C), which separate Lake Assal from Ghoubbet (D) and the Gulf of Tadjoura (E) containing the obliquely propagating, left-stepping Aden spreading axis. Shadowed fault scarps yield mainly left-lateral fault-plane solutions. Space shuttle photograph STS 41G-35-104, courtesy of NASA, was shot in 1984. Geology based on Manighetti et al. (1997). Scale applies to foreground only.

1992) to 140 Ma (Brice, Cochran, Pardo & Edwards, 1982); North Gabon, 125–122 Ma (Teisserenc & Villemin, 1989); Rio Muni–Douala-Benue, 119 Ma (Nürnberg & Müller, 1991). Along the conjugate Brazilian margin, the earliest rifting was non-systematic: the oldest known rift fill (145–134 Ma) lies far north in the Reconcavo, Espirito Santo and Potiguar Basins, coeval with conjugate African basins but much later than African basins farther south (Davison, 1999).

The end of rifting can be established by the age of the sag basins immediately above the breakup unconformity or by the oldest magnetic anomaly in adjoining oceanic crust. North of the Walvis Ridge and Rio Grande Rise (the trails of the Tristan and Gough hot spots), early ocean opening apparently coincided with the long, normally magnetized period of the Cretaceous Quiet Zone (119–85 Ma) (Müller, Royer & Lawver, 1993) so is poorly constrained by magnetic reversals. Estimates for the end of rifting and the onset of sea-floor spreading have the following ranges in African basins, listed from south to north: Cape–Orange–Lüderitz, 137 Ma (Austin & Uchupi, 1982; Gladczenko, Hinz, Eldholm, Meyer, Neben & Skogseid, 1997; Peate, 1997) to 130 Ma (Nürnberg & Müller, 1991); Walvis, 126 Ma (Gladczenko et al., 1997); Benguela–Kwanza–Congo–Gabon, 127 Ma (Brice et al., 1982) to 117 Ma (Teisserenc & Villemin, 1989; Guiraud & Maurin, 1992; Karner & Driscoll, 1998); Rio Muni-Douala, 118 Ma (Nürnberg & Müller, 1991); Benue, 80 Ma (Nürnberg & Müller, 1991).

These ages provide crude but useful benchmarks to calibrate the tectonic setting of extension, magmatism, stratigraphy and salt tectonics. Our conception of the stratigraphy and crustal units of a generic South Atlantic volcanic margin is schematically shown in Fig. 4. Conceptual data were derived from the North Atlantic volcanic provinces and from many proprietary and published reflection-seismic lines across the South Atlantic margins. Three aspects of this diagram are especially important. First, the SDR sequences fan out seaward from a point above a crustal outer high. Second, the Aptian salt (or age equivalent) is shown as pinching out seaward, probably over volcanic crust in the SDR province. The limit of continental crust can be assigned to the seaward limit of the deepest visible reflector at the base of the SDR pile. However, the continental-oceanic boundary is typically a broad zone rather than a mappable line, and it is difficult to infer crustal type from seismic velocities alone (White & McKenzie, 1989). Third, the base of the Aptian salt or age equivalent was later deformed in one or more steps, the largest of which is the flexure known as the Atlantic Hinge.

2.2. Onshore magmatism

The SDRs form the thickest component of the South Atlantic igneous provinces (Figs. 4 and 5), whose entire known volume, including continental flood basalts, is at least 2×10^6 km^3 (Peate, 1997). The Paraná–Etendeka province alone has a preserved volume of $>1 \times 10^6$ km^3 and an area of $>1.2 \times 10^6$

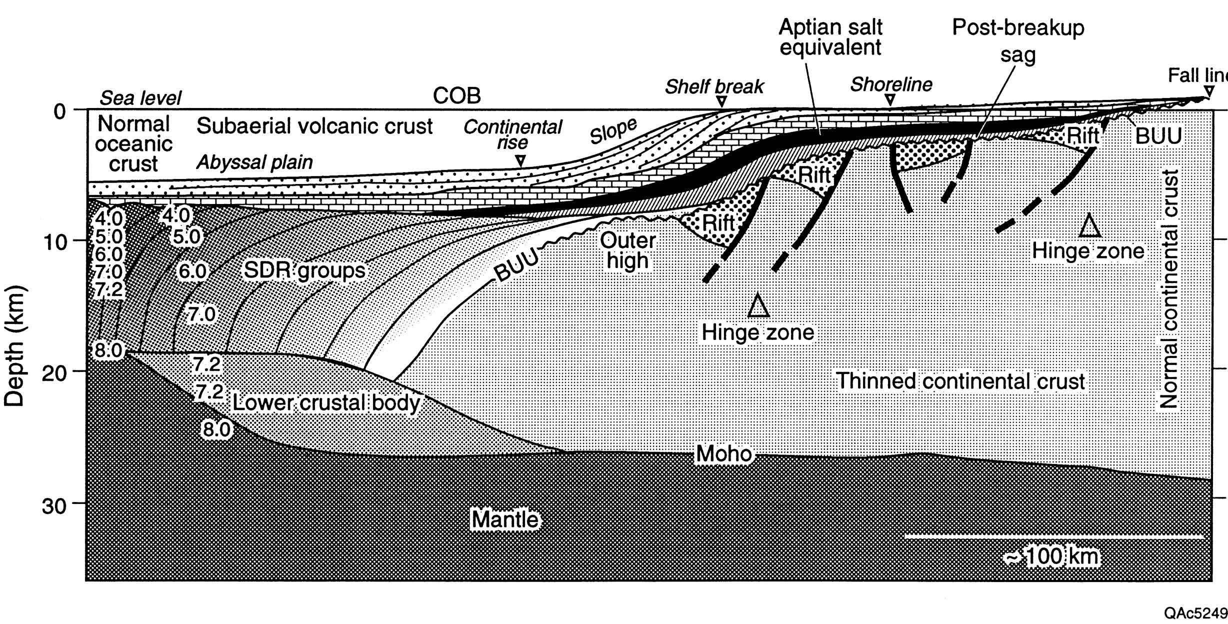

Fig. 4. Schematic cross-section of a generic volcanic rifted margin in the South Atlantic. Crustal units and dimensions are based on North Atlantic volcanic margins and on the Namibian margin (Gerrard & Smith, 1982; Gladczenko et al., 1997). Refraction data are sparse, so the P-wave velocities shown (4.0–8.0 km/s) are speculative. Salt-tectonics effects have been omitted for clarity. BUU, breakup unconformity; COB, the continental-oceanic boundary, varies in position from modern continental rise to shelf. Vertical exaggeration is roughly 4:1.

km^2 in South America (Cordani & Vandoros, 1967). This is the largest exposed basalt province in the world (White & McKenzie, 1989). The late-synrift Etendeka igneous rocks now preserved onshore are much less abundant than in the Paraná Basin. The Etendeka volcanic rocks are scattered along more than 1500 km of the West African coast from Walvis Bay to Luanda (Peate, 1997). The size and volume of onshore igneous rocks suggest equally massive volumes offshore.

The large thermal anomaly required for the volcanic rifted margins is linked to the Tristan hot spot (now active around Tristan da Cunha) and the Gough hot spot (now active around Gough Island). Active for 120 Ma, the plumes apparently left clear hot-spot trails that created the Paraná–Etendeka basalts, the South Atlantic volcanic rifted margins, the Abutment Plateau, the rest of the Walvis Ridge, and the conjugate Rio Grande Rise. The Tristan plume provided mostly conductive heat rather than asthenospheric material to the Paraná–Etendeka igneous province (Garland, Thompson & Hawkesworth, 1996).

The Paraná–Etendeka igneous province is lopsidedly concentrated on the South American Plate, far from the breakup zone along the conjugate coastlines. This striking asymmetry has been explained by: (1) a topographic barrier along the African margin (White & McKenzie, 1989); (2) an off-centre Tristan plume (O'Connor & Duncan, 1990); (3) asymmetric simple shear during rifting (Peate, 1990); (4) thin lithosphere below the Paraná Basin (Thompson & Gibson, 1991); and (5) a horizontal magmatic pressure gradient between the axial rift zone and the Paraná Basin (Harry & Sawyer, 1992).

The Paraná basin formed as a Late Ordovician intracratonic basin (Zalan et al., 1990). The main episode of flood basaltic volcanism lasted from 134 to 129 Ma, coeval with the end of the rift phase in the southern South Atlantic and with the synrift phase of the central South Atlantic; the oldest oceanic crust at this latitude is Chron M4 (127 Ma). Younger magmatism persisted along the coast from 128 to 120 Ma (Peate, 1997) during sea-floor spreading in the southern South Atlantic and latest rifting in the central South Atlantic. Timelines cut across Paraná compositional units, indicating that different magmas were erupted coevally in different places over several million years (Turner, Regelous, Kelley, Hawkesworth & Mantovani, 1994; Stewart, Turner, Kelley, Hawkesworth, Kirstein & Mantovani, 1996). However, in general, compositionally defined units dip toward the north, which suggests a northward-migrating magma source (Peate, Hawkesworth & Mantovani, 1992), possibly tracking the northward propagation of rifting (Peate, Hawkesworth, Mantovani & Shukovsky, 1990).

Volcanism was strongly bimodal, dominated by aphyric tholeiitic basalts. Some are reported to have

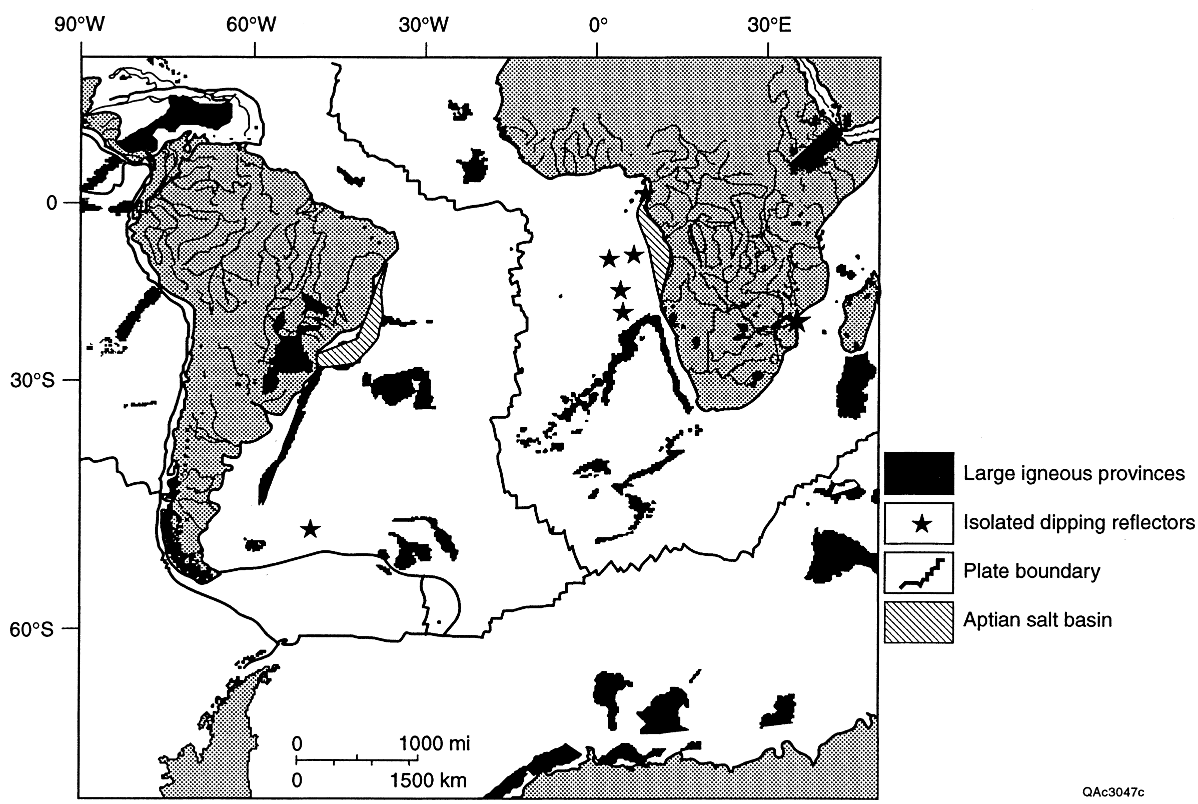

Fig. 5. Map of Large Igneous Provinces (LIPs) in the south-central Atlantic Ocean (courtesy of M. F. Coffin & L. Gahagan, 1998).

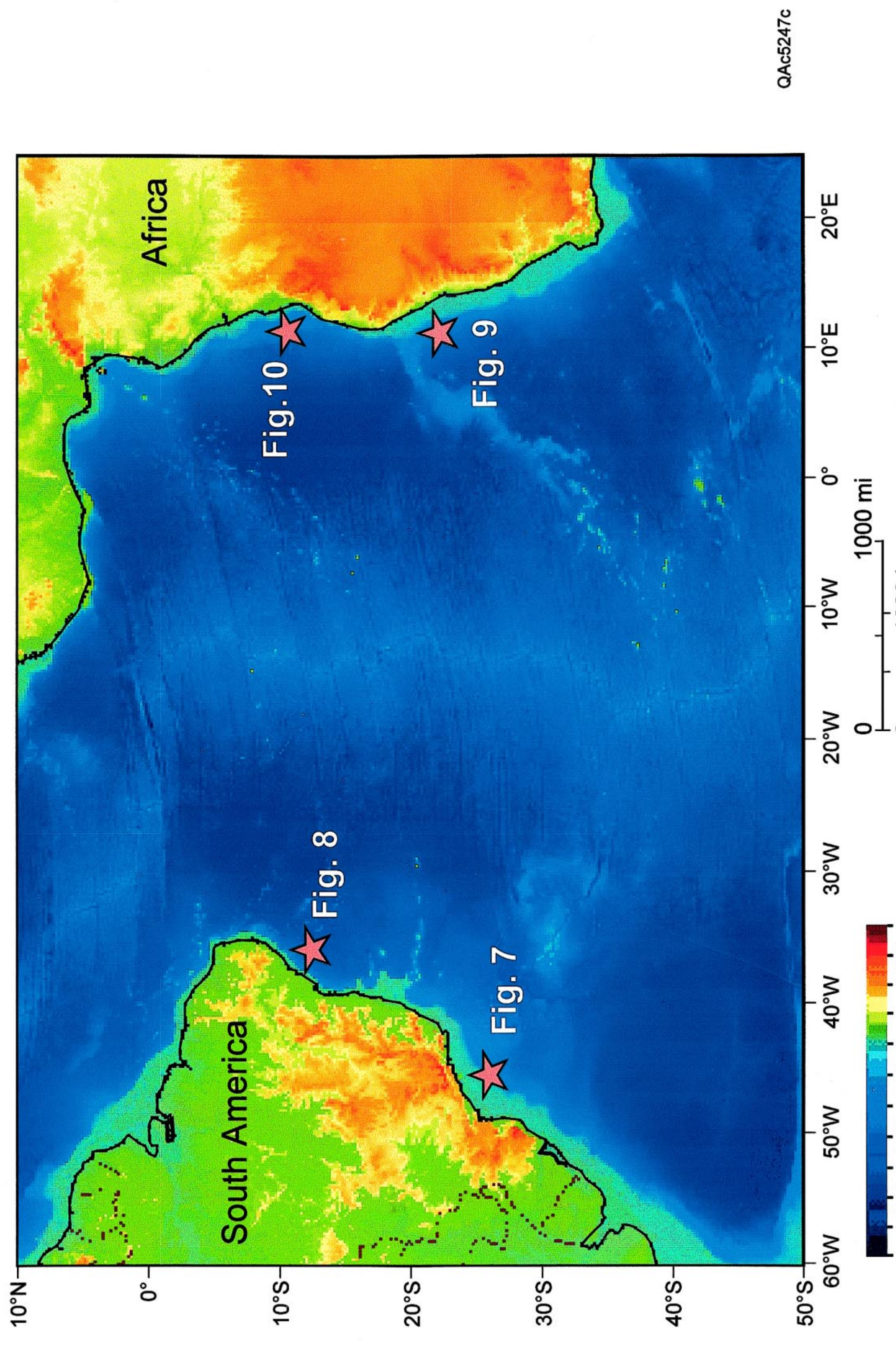

Fig. 6. Location of seismic lines (red stars) on a map of the bathymetry and topography of the South Atlantic Ocean and its continental margins.

flowed more than 340 km (Milner, Duncan, Whittingham & Ewart, 1995). Magnetic anisotropy indicates that in both provinces, lava flows were controlled by structures trending parallel to each coastline (Glen, Renne, Milner & Coe, 1997). That is consistent with extrusion along rifting or rifted margins. Rhyolitic eruptions (>1000 km^2) accompanied the final magmatic phase along both continental margins (Peate, 1997).

Onshore dyke swarms indicate that the lavas originally covered a greater area than preserved today. Dolerite dykes are concentrated in five areas. Four trend perpendicular to the coasts: (1) Ponta Grossa, Brazil, (2) Eastern Paraguay, (3) Morro Vermelho, Namibia, and (4) Etendeka, Namibia. This perpendicular trend suggests either failed rifts or inversion (Withjack, Schlische & Olsen, 1999). One swarm trends parallel to the coast: the Sao Paulo/Rio de Janeiro swarm, emplaced between 133 and 129 Ma, the peak of basalt extrusion. Generally, their ^{40}Ar–^{39}Ar ages and compositions are similar to those of the nearest lava flows. Numerous tholeiitic sills also intrude the Paraná sediments, attaining an aggregate thickness of 1 km (Peate, 1997).

2.3. Offshore SDR provinces

The offshore SDRs are far less well known than are the onshore igneous provinces. Although many wells (especially in the Campos Basin) terminate in flood basalts, the true extent of SDR sequences can only be hinted at on seismic profiles, which suggest that the offshore SDRs are much thicker (several kilometers) than the average lava thickness (only 0.7 km) in the onshore Paraná province (Leinz, Bartorelli & Isotta, 1968; Peate et al., 1992). In general, volcanic rocks are more common along the southern Brazilian margin than farther north. In the Santos and Campos Basins, the rift fill comprises mostly basalts and tuffs, whereas north of the latitude of the Paraná province, the rift fill is largely sedimentary (Szatmari, 1998). The best-known SDR provinces are the Barremian SDRs south of the Aptian salt basins (Fig. 5). On the Brazilian margin, the SDR province is about 3000 km long and 60–120 km wide, from north of the Malvinas Plateau (Lohmann, Hoffmann-Rolhe & Hinz, 1995) to the Santos Basin and possibly the Campos Basin. On the African margin, the SDR length is almost as great and up to 200 km wide (Hinz, 1981; Gerrard & Smith, 1982; Abreu, 1998). Four localities in the southern Atlantic (Fig. 6) illustrate examples of flood basalts. Drilling has confirmed two examples, but the thickness and age of the basalts is poorly known. Some basalts appear to be proto-oceanic crust (SDRs), whereas others seem to be late-synrift basalts extruded on thinned continental crust.

2.3.1. Pelotas Basin

The Pelotas Basin in southern Brazil and Argentina is south of the known limit of Aptian halite, although thin anhydrite equivalents are present in the Ariri Formation in the north (Abreu, 1998; Cainelli & Mohriak, 1998). Flood basalts are interpreted in two settings (Fig. 7a). About 800 m of seaward-dipping basalts were intersected at the bottom of the projected P-3 well (Fig. 7b). They were dated at 124 ± 8 Ma, indicating a late-synrift age (Mizusaki et al., 1992). The seaward tilt of the reflectors is attributed to rotation of late-synrift fault blocks along landward-dipping normal faults (Abreu, 1998; Cainelli & Mohriak, 1998). Under the continental rise, another belt of SDRs is at least 5 km thick (Fig. 7b and c); the belt is about 450 km long and 50–250 km wide along its length (Abreu, 1998). These SDRs are undrilled, but their location near the continental–oceanic boundary and their resemblance to drilled SDRs off the conjugate Walvis Basin suggest that they represent proto-oceanic, subaerial flood basalts. Similar interpretations have been made by Condi, Abreu, Bally and Sawyer (1996) and Cainelli and Mohriak (1998). These inferred flood basalts are overlain by Aptian-Turonian carbonates and intercalated shale, representing a shallow carbonate platform built during the drift phase (Abreu, 1998).

In both the Pelotas Basin and the conjugate Walvis Basin, SDR volcanism appears to have reduced subsidence of the margin, as would be expected with heating. In these basins, postvolcanic basement subsidence appears to be less in the north, where SDRs are wide, than in the south, where SDRs are narrow (Abreu, 1998). This is indicated by an inverse relationship between sediment thickness and width of SDR belt. In both basins, too, the SDRs dip northwards as well as seawards, perhaps recording a northward migration of the spreading centre as Pangea unzipped northward (Abreu, 1998).

To the south, off the Argentine continental margin, is a continuous SDR province 1500 km long, 50–100 km wide, and more than 5 km thick (Hinz, 1990).

The northern boundary of the Pelotas Basin is highly volcanic and aligned with the Rio Grande (Florianópolis) Fracture Zone, along which magma leaked to form the Sao Paulo Ridge. The volcanic rocks extend for ~500 km north of the Tristan plume trail into the Santos and Campos basins, where flood basalts (134–122 Ma), as much as 600 m thick, have been drilled below the Aptian salt. Their geochemistry and age are similar to the late-synrift Paraná volcanic rocks (Mizusaki et al., 1992). Just inboard of the seaward limit of Aptian salt in the Campos Basin, an SDR province has been interpreted by Cainelli and Mohriak (1998). Velocity effects associated with overlying salt bodies severely distort subsalt events, so it is unknown how far landward this SDR province extends.

2.3.2. Jacuipe Basin

The northern limit of known Aptian salt is in the Muribeca Formation on the Sergipe Basin shelf (Cainelli & Mohriak, 1998). In the Jacuipe Basin, which lies to the south, the salt appears to be thin or absent, indicating discontinuous salt. No signs of salt tectonics are visible in Fig. 8. Mohriak, Bassetto and Vieira, (1998) interpreted the Jacuipe facies immediately east of the distal rift basin (Fig. 8) as evaporites or slumped sediments. Immediately below the thin Cretaceous interval, well-defined seaward-dipping reflectors at least 6 km thick are visible almost down to the inferred Moho reflectors (Fig. 8b). This sequence is

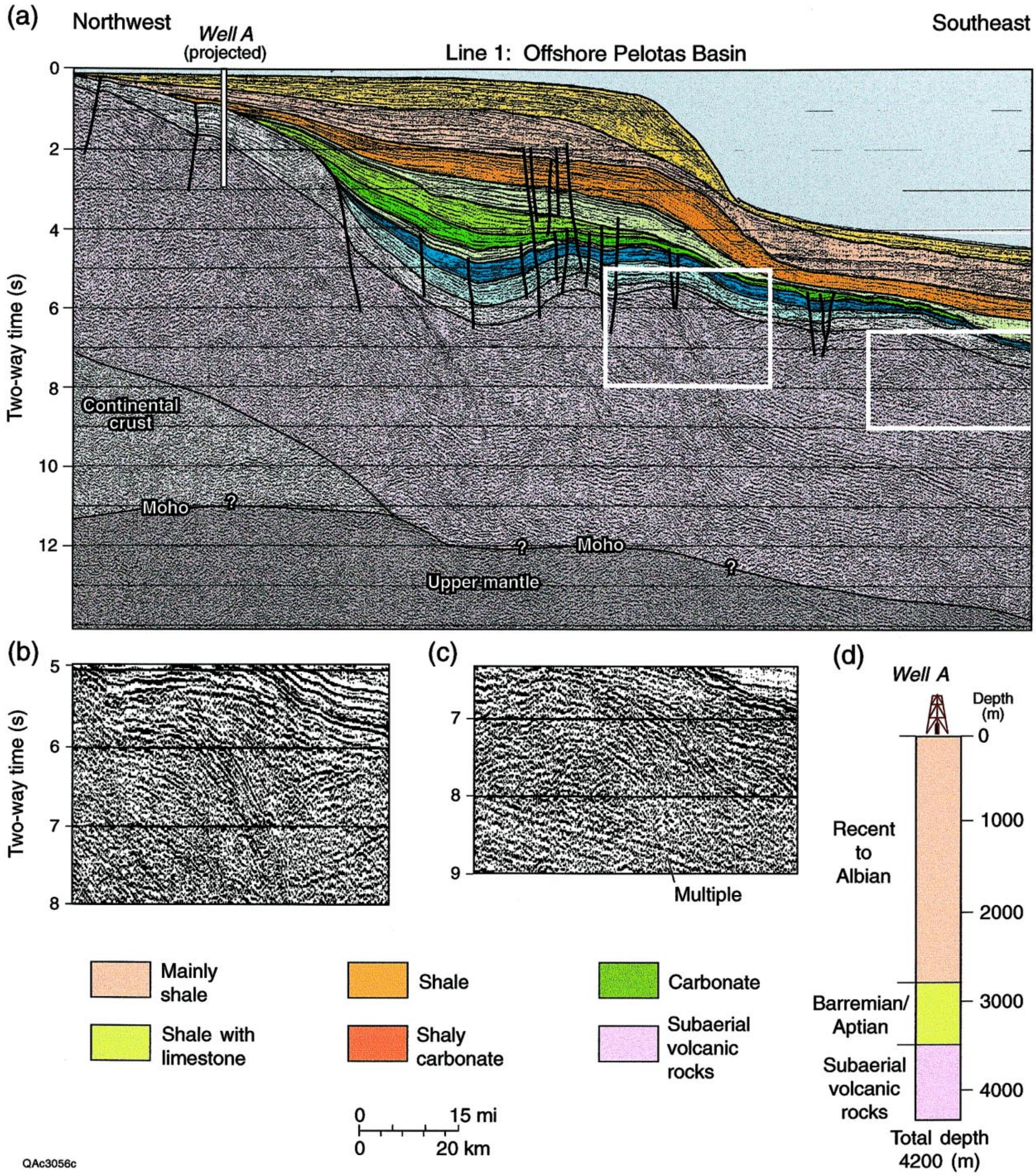

Fig. 7. (a) Seismic profile SS-2, referred to here as line 1 in the Pelotas Basin off southern Brazil. (b, c) Seismic details of SDRs from the areas outlined in white in profile (a). (d) Projected P-3 well data, showing subaerial volcanic rocks. This region is south of the Aptian salt basins. Data from Fontana (1996) and Cainelli and Mohriak (1998).

undrilled, but its geometry and position are typical of SDRs. We interpret it as proto-oceanic crust emplaced during or after continental breakup. Farther landward, the same interval thins abruptly into a thin, horizontally layered sequence that may represent slightly older volcanic rocks extruded on continental crust.

Mohriak, Robelo, Matos and Barros (1995) and Mohriak et al. (1998) also interpreted thick wedges of SDRs basinward in the Jacuipe and Sergipe Basins. Their gravity model included stretched continental crust only 5–6 km thick. That seems mechanically implausible because the stretching value (β ~7) is much more than the theoretical stretching limit of 4.5 for continental crust before complete separation (Dewey, 1982).

2.3.3. Walvis Basin

The Walvis Basin off northern Namibia contains an SDR province ~100 km wide and as much as ~7 km thick. One of the first SDR provinces reported (Hinz, 1981), this is part of a highly volcanic region between the Early Cretaceous (134–129 Ma, latest synrift) Etendeka flood basalts onshore and the Late Cretaceous (110–80 Ma, post-breakup) Walvis Ridge offshore (Tristan hot-spot trail). The SDRs extend southward to the Cape Basin (Austin & Uchupi, 1982; Gerrard & Smith, 1982). Gladczenko et al. (1997) interpreted four crustal units: (1) oceanic crust of normal thickness; (2) thickened oceanic crust, up to 15 km thick (Abreu, Condi, Bally, Sawyer & Droxler, 1996), comprising most of the SDR sequence and overlying the breakup unconformity; (3) a ~150-km wide Late Jurassic/Early Cretaceous rift zone partly covered seaward by a fringe of SDRs and landward by lavas and intrusions; and (4) thicker continental crust to landward, partly stretched by Paleozoic extension. As in the conjugate Pelotas Basin, the southern part of the Walvis Basin contains SDR sequences extended in the Cretaceous by landward-dipping normal faults, which become less common northwards (Abreu, 1998).

The projected well shown in Fig. 9c intersected roughly 500 m of basalt before drilling stopped. The seismic profile (Fig. 9a) suggests that the SDR province may comprise two zones. In the east, wedges of

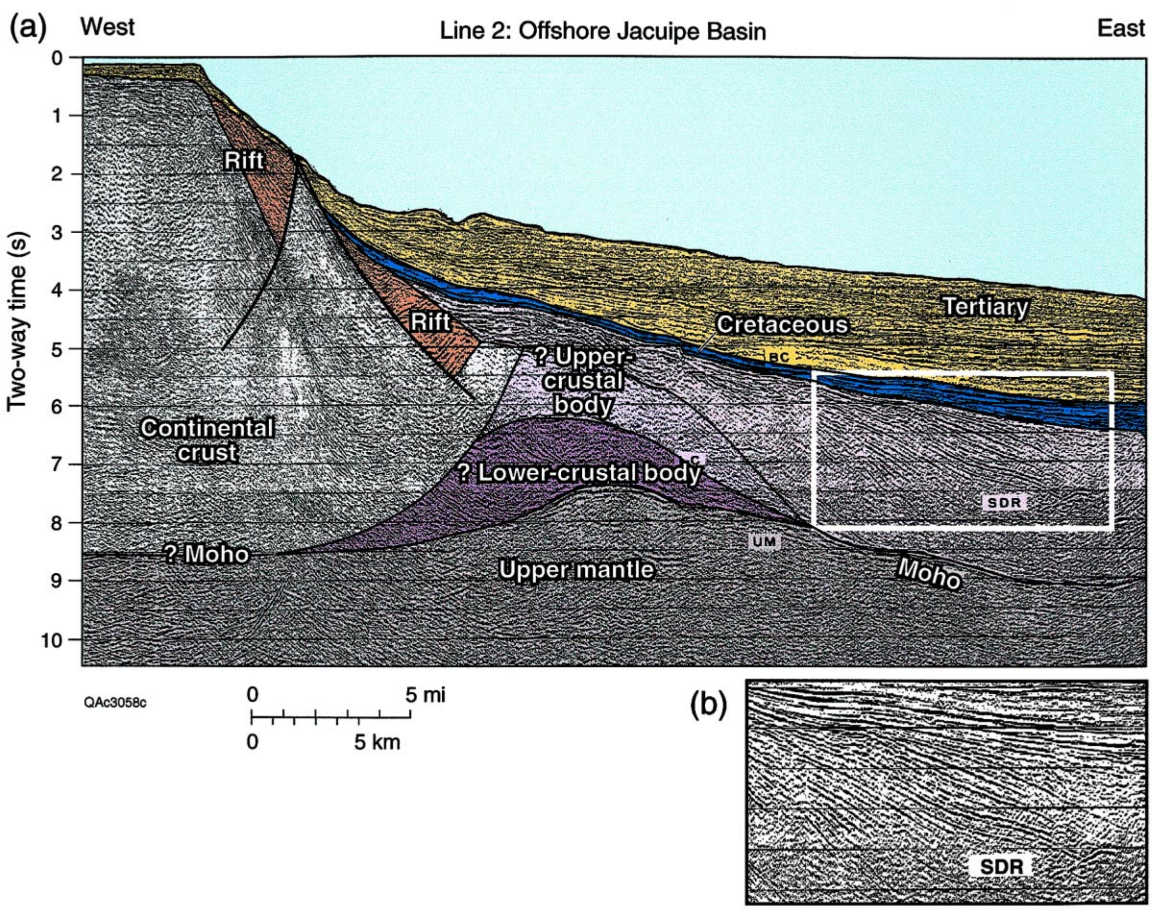

Fig. 8. Seismic profile of line 2 in the Jacuipe Basin off northeastern Brazil. (b) Seismic detail of SDRs from the area outlined in white in profile (a). Data from Mohriak et al. (1998).

lava or sediment expand seaward from the updip pinch-out of the 92-Ma maximum flooding surface (the "medial Hinge Line" of Maslanyj, Light, Greenwood & Banks, 1992). In the west, downward-steepening reflectors expand seaward (Fig. 9c) as proto-oceanic crust that merges seaward with oceanic crust.

2.3.4. Kwanza Basin

Although no convincing SDRs have been reported from the Kwanza Basin (Fig. 10a), basalts are certainly present. The well in Fig. 10b intersected nearly 1 km of basaltic volcanic rocks below the Cuvo Formation, a thin continental sag sequence conformably underlying the Aptian salt. We do not know how thick these basalts are or whether they represent proto-oceanic crust or synrift volcanic fill. Subsalt volcanic rocks were also reported by Dibner, Mitin, Rozhdestvenskaya, Seryakov and Ustinova (1986). We speculate that SDRs are present in offshore Angola but have not been recognized because salt structures have distorted the continuity of subsalt reflectors. SDRs are likely in offshore Angola because of proximity to mantle plumes at the time of breakup and to the Etendeka igneous province. Any SDRs present would underlie the Aptian salt; all other SDR examples in the South Atlantic north and south of the Aptian salt basins predate the Aptian interval. Continued volcanism during evaporite formation, which may be related to the nearby active and subaerial Walvis Ridge, is shown by tuffs intercalated with Aptian evaporites near Luanda (Brognon, 1971).

How much of the West African margin is underlain by SDR sequences is highly speculative. North of the Walvis Basin, the cover is thicker, and magnetic rever-

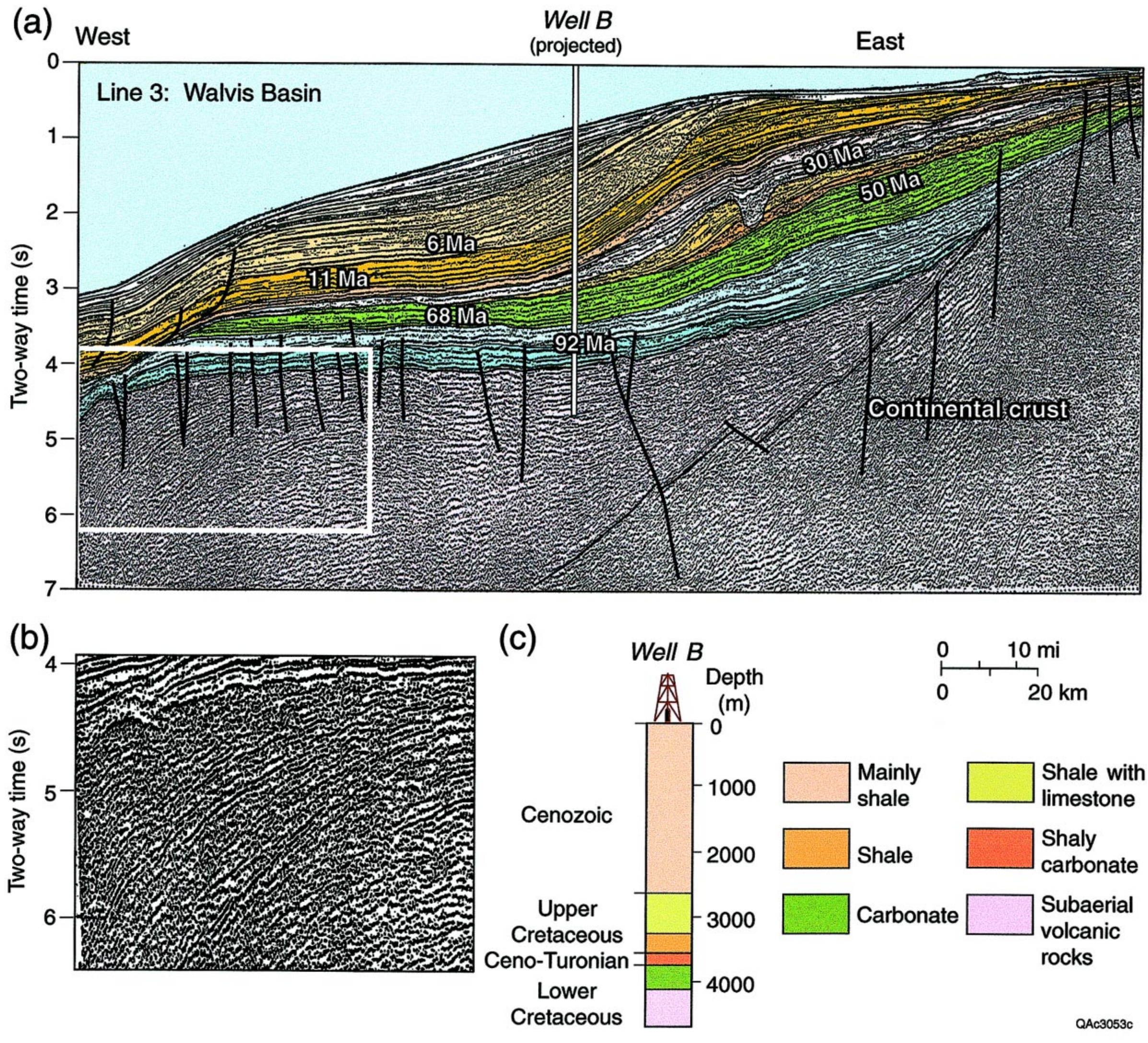

Fig. 9. Seismic profile of line 3 in the Walvis Basin, offshore Namibia. (b) Seismic detail of SDRs from the area outlined in white in profile (a), (c) Projected well data, showing subaerial volcanic rocks. This region is south of the Aptian salt basins. Data from TotalFina.

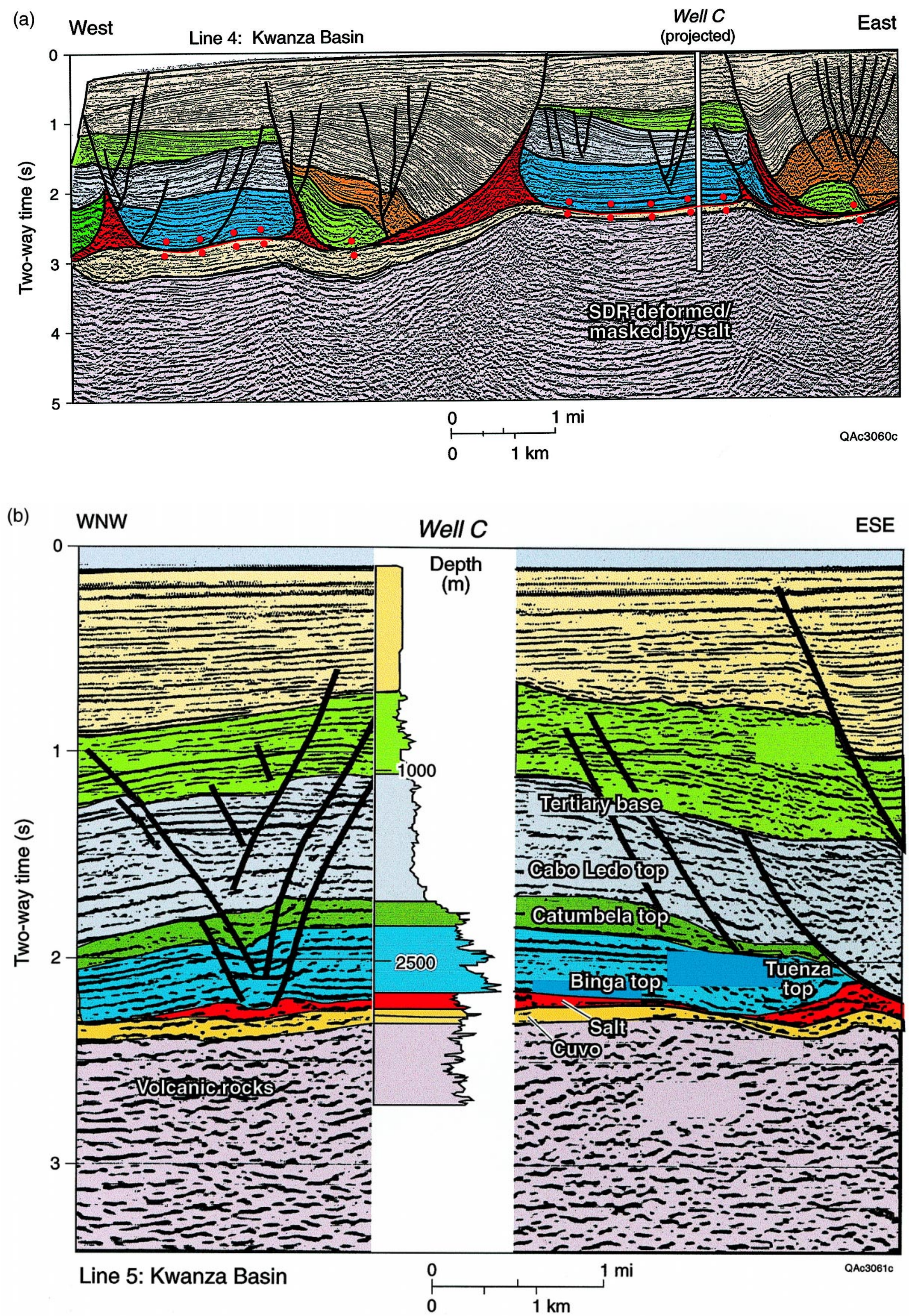

Fig. 10. (a) Seismic profile of line 4 in the Kwanza Basin, offshore Angola. (b) Similar seismic profile of line 5 and well data, showing volcanic rocks. Data from TotalFina.

sals are lacking in the Cretaceous Quiet Zone. Superimposed on the residual Bouguer anomaly map of Fig. 11 is the former area of three hot spots during continental breakup, assuming a plume-head diameter of 1200 km. This assumption is conservative: the present-day bulge in the sea floor around Iceland (Anderson, McKenzie & Sclater, 1973) and the reconstructed volcanic provinces just after ocean spreading began (White & McKenzie, 1989) both indicate a bulge about 2000 km wide over the Iceland plume. These large dimensions suggest that mantle plumes could have influenced almost all the West African margin. If so, SDRs could underlie much of the margin in the deep-water and ultra-deep-water regions. Unpublished industry seismic data indicate that SDRs are probably present off Equatorial Guinea, Gabon, and the northern Congo Basin, just north of the Kwanza Basin. These are areas where the Aptian salt is thin, so salt structures are smaller and less likely to mask the subsalt structure and stratigraphy. As seismic reflection data improve in quality, more and more divergent margins around the world appear to be volcanic (Coffin & Eldholm, 1992, 1994).

3. Discussion

3.1. Aptian salt tectonics

Wherever Aptian evaporites are present, even as thin layers, salt tectonism has played a major role in the deformation of postrift sediments. Due to salt's effectiveness as a detachment zone, structures above salt commonly differ radically from those below. In turn, the tectono-stratigraphic setting of salt deposition during or after rifting has equal importance to its role in deformation of the margin. Generally, little attention has been paid to the role of salt during breakup. In the South Atlantic, because of an uncertain tectonic setting, some authors have classified the Aptian evaporites as "transitional" between the rift and drift phases; placing the continental-oceanic boundary along the seaward edge of the salt reflects the same ambiguity. However, this ambiguity seems unnecessary because the evidence summarized below appears to make it clear.

One hypothesis is that the Aptian salt basins formed before Pangea broke up and sea-floor

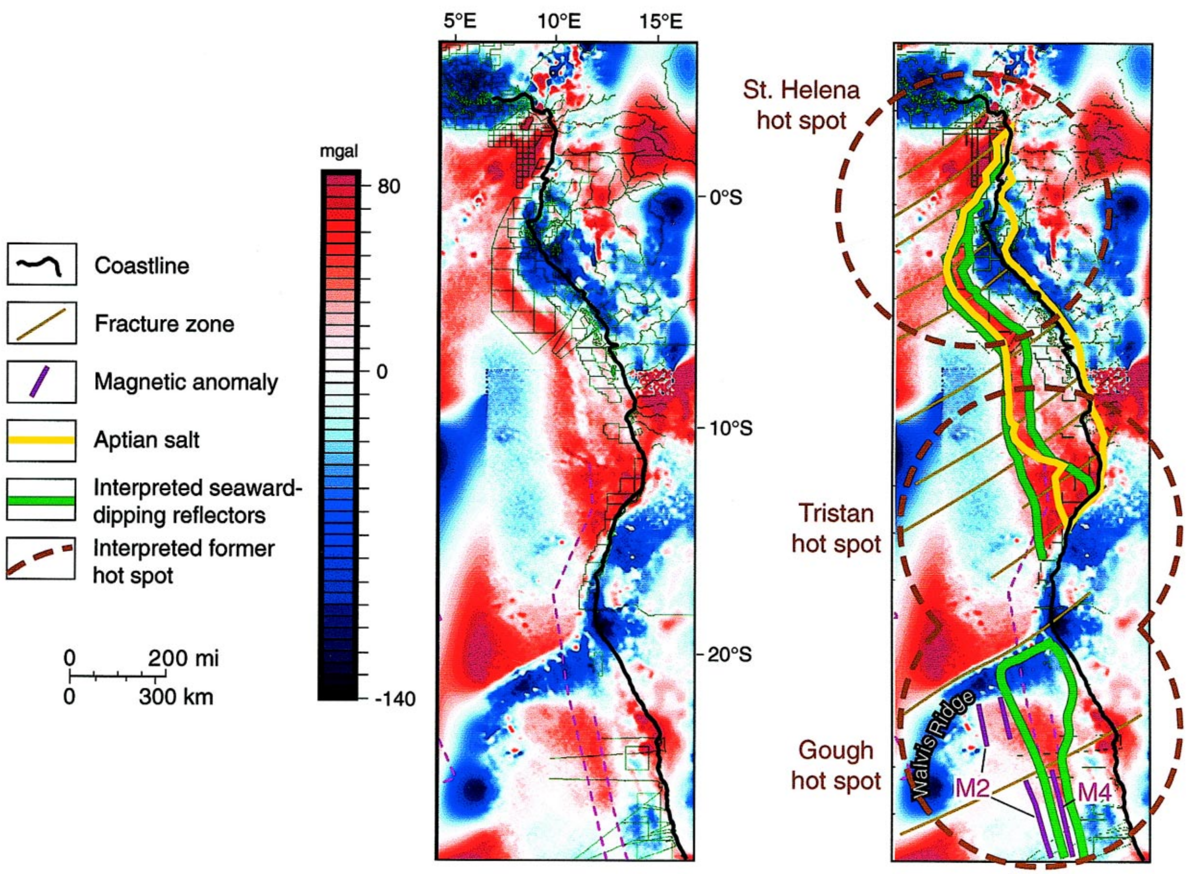

Fig. 11. Bouguer residual gravity map of the West African margin; uninterpreted on left, interpreted on right. Data reprocessed by TotalFina from offshore Sandwell satellite altimetry and onshore African Gravity Project.

spreading began (Evans, 1978; Ojeda, 1982; Guardado, Gambo & Lucchesi, 1989; Duval, Cramez & Jackson, 1992; Davison, 1999). We refer to this scenario as "pre-breakup salt". Fig. 12a shows that rifting would have had to occur both before and after salt deposition. The conjugate Aptian salt basins are assumed to have once formed a single giant salt basin that was later split by continental breakup.

An alternative hypothesis is that Aptian salt basins formed after the continents separated (Fig. 12b). In this "post-breakup salt" hypothesis, rifting ended before salt was deposited. The African and Brazilian salt basins would have been separated from the start. Several papers have favored this hypothesis (Nürnberg & Müller, 1991; Guiraud & Maurin, 1992; Karner, Driscoll, McGinnis, Brumbaugh & Cameron, 1997; Abreu, 1998; Fonck, Cramez & Jackson, 1998; Marton et al., in press), but none presents a systematic evaluation of both hypotheses. The following themes are relevant for weighing positive and negative evidence for each hypothesis: tectono-stratigraphy of salt; tectono-stratigraphy of SDRs; distal margin of salt basins; map pattern of salt basins. All these lines of evidence contradict the pre-breakup hypothesis and strongly favour a post-breakup origin for the Aptian salt basins of the South Atlantic margins.

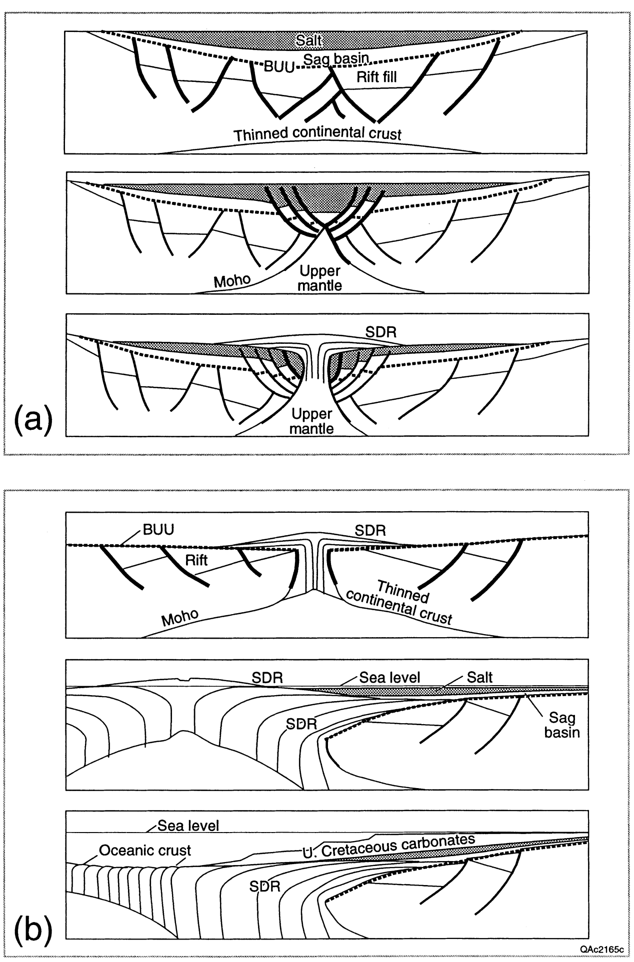

Fig. 12. Schematic evolutionary sections showing hypotheses for (a) pre-breakup Aptian salt, and (b) post-breakup Aptian salt. BUU, breakup unconformity. From Fonck et al. (1998).

3.1.1. Tectono-stratigraphy of salt

The Aptian salt demonstrably overlies the breakup unconformity in most of the Aptian salt basins. The base of the salt unconformably overlies tilted rift blocks of clastic or volcanic rocks. In places, the breakup unconformity is at the base of the salt (Davison, 1999); elsewhere, the unconformity underlies a sag sequence conformably overlain by salt (for example, Henry & Abreu, 1998). Only in parts of the Sergipe Basin does the final stage of rifting affect Aptian salt (Cainelli & Mohriak, 1998) because of northward propagation of continental breakup. Thus, rifting had ended and sea-floor spreading had begun by the time Aptian salt was accumulating (except for a small overlap of minor rifting in the Sergipe Basin). So if sea-floor spreading had begun by the time the Aptian salt started to accumulate (except in the extreme north), the African and Brazilian salt basins must have always been separated by the mid-oceanic ridge; we speculate below that this ridge was partly subaerial but below sea level.

3.1.2. Tectono-stratigraphy of SDRs

Wherever SDRs have been identified on both margins, they invariably predate the stratigraphic equivalent of the Aptian salt. Thus, whether or not SDRs actually underlie the salt basins (as we predict, but are seismically masked), SDRs formed before the salt accumulated. Nowhere is the salt or its time equivalent known to be overlain by proto-oceanic crust, which would be a corollary for pre-breakup salt. Any post-breakup basalts would have sunk into distal salt until the lavas froze and strengthened (Needham, 1978).

Flood volcanism both accompanies and follows rifting. The most distal SDR sequence is likely to post-date continental separation because the SDRs merge with oceanic crust. Thus, the SDR proto-oceanic crust should overlie the breakup unconformity (Fig. 12b; Gladczenko et al., 1997). For example, offshore basaltic volcanism in the North Atlantic and Baffin Bay regions was coeval with the onset of sea-floor spreading (see compilation by White & McKenzie, 1989). Since the SDR sequence commonly forms in only 1–3 m.y., the absolute ages of unconformities at the top and bottom of the SDR sequence could be indistinguishable, depending on the dating method. The breakup unconformity has been ascribed to several causes. However, along a volcanic rifted margin, one plausible cause is the erosion caused by thermal uplift above the impinging plume before full-scale flood volcanism. For example, along the margin of Greenland, marine shales are overlain by a basinwide unconformity created by rapid (< 5 Ma) prevolcanic uplift. This unconformity is overlain by fluvial sandstones derived from exhumed basement; these in turn are overlain by a marine synvolcanic succession in a rapidly subsiding basin (Dam, Larsen & Sønderholm, 1998). In the Kudu 9a-1 well in the Orange Basin, drift-phase eolian sandstones overlie and are intercalated with basalts of probable Barremian age (Gerrard & Smith, 1982).

3.1.3. Distal margin of salt basins

Pre-breakup salt would be thickest in the center of the giant parent salt basin where maximum subsidence occurred above the highly extended breakup zone. Thus, after breakup, the oceanward edge of a pre-breakup salt basin would be an abrupt, fault-bounded margin through the thickest salt. In contrast, post-breakup salt would wedge out distally against a sea-floor rising to the mid-oceanic ridge. Thin, autochthonous salt pinches out seaward over oceanic or proto-oceanic crust in the Lower Congo Basin (Lehner & de Ruiter, 1977), South Gabon Basin (Meyers, Rosendahl & Austin, 1996a) and North Gabon and Douala Basins (Meyers, Rosendahl, Groschel-Becker, Austin & Rona, 1996b). Elsewhere on the African margin (Lower Congo, Kwanza, and Benguela Basins), the autochthonous salt is tectonically thickened and is allochthonous along its leading edge, the Angolan Escarpment (Emery, Uchupi, Phillips, Bowin & Mascle, 1975). This tectonism obscures the original geometry of the salt.

We infer that post-breakup Aptian salt basins must have been confined distally by a subaerial mid-oceanic ridge in the proto Atlantic Ocean. The inference that the Brazilian and African salt basins were always separate follows logically from two propositions documented in the previous paragraphs. First, the Aptian salt is post-breakup (except in the extreme north where it is affected by the final stage of Sergipe rifting). Second, the stratigraphic equivalent of Aptian salt postdates the SDRs. Thus, the salt must have started accumulating after extrusion of SDRs and the onset of sea-floor spreading and the development of a mid-oceanic ridge. It is implausible that such a ridge could have split a giant salt basin. Evaporites accumulate as residual ponds in the deepest parts of a basin. So it is unlikely that salt could have buried the thermally elevated, actively spreading mid-oceanic ridge, especially where seawater was restricted — as is necessary for evaporites to form.

Are there modern analogues for subaerial mid-oceanic ridges? Almost all present-day mid-oceanic ridges are submerged, but this is a feature of old, wide oceans. A fitter analogy would be the subaerial parts of mid-oceanic ridges currently thermally elevated by an underlying mantle plume, such as the Djibouti Afar on the Aden Ridge (Fig. 3) or Iceland on the Reykjanes Ridge. The Afar hot spot bulge allowed synrift Messinian evaporites to form throughout the Red Sea while open-marine conditions existed farther south in the Gulf of Aden (Crossley, Watkins, Raven, Cripps, Carnall & Williams, 1992). As in Afar, the Aptian salt basins were confined to the south by the subaerial swell of the proto Walvis Ridge and Rio Grande Rise. These ridges separated open-marine conditions in the south from restricted marine conditions in the north. In the northern parts of both the Walvis Basin and the conjugate Pelotas Basin, where volcanism was most abundant, the initial oceanic crust kept close to sea level or at a shallow depth until almost the Turonian (91 Ma, some 20 million years after breakup; Abreu, 1998; Dingle, 1999). So it is likely that the mostly subaerial volcanic ridges acted as a dam. Gaps in the ridges would have allowed restricted access of seawater to the northern proto South Atlantic (Henry & Abreu, 1998). That would favor evaporitic conditions even after the oceanic crust had thermally subsided below sea level, as in the Messinian Mediterranean. However, simple evaporative drawdown would not suffice: assuming an average salt concentration of 3.5%, complete evaporation of the world's oceans would yield a salt layer only 60 m thick (Borchert & Muir, 1964). The equivalent salt thickness for a single evaporative drawdown in the proto South Atlantic would probably be less than 20 m, given the average water depth of the present South Atlantic (~4500 m) compared with the youthful depth typified by the modern Red Sea (~1000 m). Because the Aptian salt thickness averages at least 1000 m, at least 50 cycles of complete filling and evaporation would be required in the available 10 m.y. Open-marine conditions were only established in the middle-upper Albian (Dingle, 1999).

3.1.4. Map pattern of salt basins

The preferred hypothesis that the Aptian salt basins postdated continental breakup can also be tested by examining the basin fit in plate-tectonic reconstructions. We used the plate-kinematic model of Nürnberg & Müller (1991), which was based on gravity, magnetic and onshore geologic data and which achieved a close fit of plates by allowing intraplate strains and displacements along known crustal discontinuities. Fig. 13 is their restoration at 100 Ma (end of Albian). The two most important features of this map are the location of magnetic anomalies and the distribution of Aptian salt. First, the magnetic anomaly M0 (118 Ma) disappears northward underneath Aptian salt in the Santos and Kwanza basins on both sides of the Atlantic Ocean (Nürnberg & Müller, 1991). This disappearance suggests that at least part of the Aptian salt was deposited on oceanic crust. Second, the distribution of Aptian salt cannot be reconciled with the hypothesis of a single giant salt basin. The salt distribution is strikingly asymmetric, being much wider in the south and narrower in the north on the Brazilian margin than the African margin. At chron M0 (118 Ma), the northern South Atlantic was just beginning to open, with negligible oceanic crust. Most significantly, Fig. 14 shows that both salt basins cannot be fitted together into a giant precursor, even over stretched continental crust. The basins would have to overlap by roughly 220 km. This overlap is probably large enough to feature on any reasonable plate reconstruction. This huge overlap cannot be attributed to basinward-spreading of allochthonous salt sheets. Published and proprietary seismic lines on each margin show that the fringe of allochthonous salt is generally less than 30 km wide. The overlap can only be explained if the salt basins accumulated *after* breakup and distally overlie Aptian oceanic or proto-oceanic crust (Fig. 13). The center and proximal parts of the salt basins overlie stretched continental crust.

Circumstantial evidence of the association of Aptian evaporites with basalts is supplied by evaporite geochemistry and mineralogy, based on the work of Hardie (1983, 1990, 1996), summarized as follows. Evaporites can form from either seawater or hydrothermal brine. The geochemistry of halite is rarely diagnostic to distinguish between these two brine sources. However, potash evaporites are much more diagnostic of their brine source, even though they are rare, forming only in the final stage of seawater evaporation after limestone, dolomite, gypsum and halite have begun to precipitate. Potash evaporites form two groups. A rarer group rich in $MgSO_4$ forms by evaporation of seawater originating from rivers. The sulfate minerals, polyhalite, kainite, and kieserite are diagnostic. This group formed in the Vendian, Late Mississippian to Permian and Miocene to Quaternary.

The second, more common group is rich in KCl and $CaCl_2$ and poor in $MgSO_4$. This group cannot form by evaporation of seawater from rivers alone. The chloride minerals, sylvite, carnallite, tachyhydrite, and bischofite are diagnostic. This group formed in the Cambrian through Early Mississippian and Jurassic through Paleogene. $CaCl_2$ brines, that concentrate to form KCl minerals, originate from brines enriched in $CaCl_2$ by hydrothermal water-rock interaction. The most prolific host is basalt, hydrothermally altered to spilitic greenstone; albitization releases Ca into the brine, and chloritization absorbs Mg from the brine. As the brine wells up hydrothermally, the abundant Ca combines with any SO_4 present to precipitate gyp-

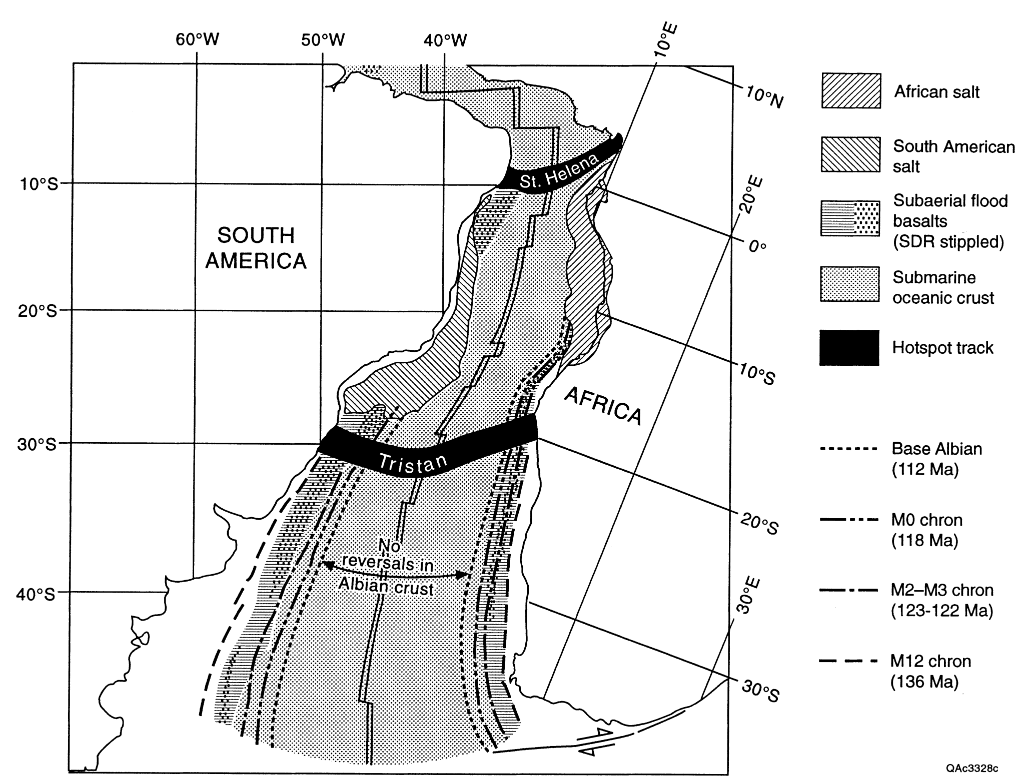

Fig. 13. Plate-tectonic reconstruction of a youthful South Atlantic Ocean at 100 Ma (end of Albian). Geographic coordinates are those of today. Aptian salt basins based on proprietary data. Plate positions and magnetic anomalies based on Karner and Watts (1982) and Nürnberg and Müller (1991).

sum at the surface; the brine in lakes remains enriched in Ca. Limestones would also be a prolific source of Ca, but these are rare below the Aptian salts of the South Atlantic.

The presence of tachyhydrite and similar chlorides does not prove the bedrock for the evaporites was basalt. However, the vast thickness, high temperatures and abundant plagioclase in flood basalts mean that these were likely to be the most prolific source of Ca. All the known Aptian potash evaporites in the South Atlantic formed from $CaCl_2$ brines enriched by hydrothermal alteration. The Sergipe–Alagoas Basin contains carnallite–sylvite–tachyhydrite tens of meters thick (Wardlaw, 1972). Aptian evaporites in Gabon contain carnallite–bischofite (Teisserenc & Villemin, 1989). The Lower Congo Basin contains carnallite–sylvite with bischofite–tachyhydrite 150 m thick (Belmonte, Hirtz & Wenger, 1965). Moreover, Pb-Zn-Cu mineralization was widespread during the Early to Mid Cretaceous along the South Atlantic margins. $CaCl_2$-rich brine is typically enriched in base metals because it contains roughly 8 times more chloride than seawater.

Clearly, the Aptian potash evaporites record hydrothermal interaction with a host rock that is probably basaltic. Such basalts could be the voluminous, rapidly emplaced SDR flood basalts. Spilitized basalts also form steadily at mid-ocean ridges. Alternation of KCl and $MgSO_4$ types of potash evaporites has been linked to secular variation in seawater because of variations in sea-floor spreading rates (Hardie, 1996). The Aptian had twice the modern spreading rate. Times of rapid spreading are marked by rise of sea level and seawater temperature, changes in marine carbonate chemistry, and other greenhouse effects. In such times, brines generated at mid-ocean ridges dominate those derived from river water, so hydrothermally derived KCl evaporites dominate. Thus, we cannot distinguish the setting (SDRs or mid-oceanic ridges) of the spilitized basalts that yielded KCl evaporites.

3.2. Implications for source-bed distribution in the South Atlantic

The possibly widespread existence of SDR sequences below salt in deep water has major implications for petroleum systems. Piles of flood basalts forming proto-oceanic crust several kilometers thick might be present where rift fill containing potential lacustrine source rocks was previously interpreted. The seismic resemblance of SDR sequences to rift fill is enhanced by the presence of normal faults where rifting affected the SDR sequence, such as in the Walvis and Pelotas basins and in Iceland (Larsen & Jakobsdóttir, 1988).

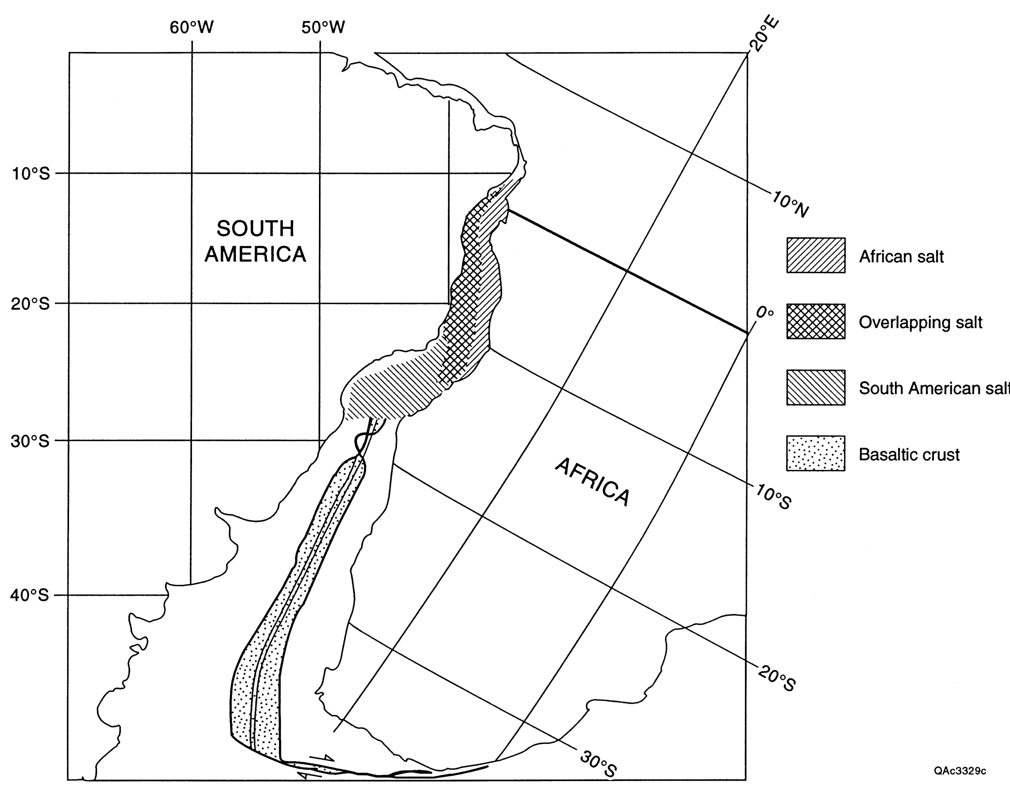

Fig. 14. Plate-tectonic reconstruction during the birth of the South Atlantic Ocean at 118 Ma (mid-Aptian). The unrealistic 220-km overlap of the Aptian salt basins suggests that the salt accumulated on oceanic crust younger than 118 Ma. Geographic coordinates are those of today. Plate positions based on Karner and Watts (1982) and Nürnberg and Müller (1991).

However, subsalt source rocks could occur above the SDR sequence. Standing lakes could develop above the SDR sequence, as in Afar (Fig. 3). Some of the deeper-water fields of the Campos Basin could be sourced by such beds in the Lagoa Feia Formation below the salt and oceanward of the main crustal hinge line.

Another favourable possibility is for Late Cretaceous source rocks above the salt. The topographic barriers provided by the initially subaerial Walvis Ridge and Rio Grande Ridge might also restrict circulation and provide anoxic conditions for distal marine shales.

4. Conclusions

Our paper attempts to reconnoiter the continental-oceanic boundary in the deep water of the South Atlantic Ocean, which is opening up in major exploration programs off West Africa and Brazil–Argentina. These regions are poorly known because of their inaccessibility and because salt structures mask subsalt seismic reflections, and seismic refraction data are meager. Thus, available evidence is sparse, widely scattered, and equivocal. Nevertheless, we hope that the following clues provide a guide and an incentive to improve our understanding of frontier exploration regions.

1. SDRs are just as common on volcanic rifted margins of the South Atlantic as they are in the North Atlantic. Evidence comes from: (1) the vast volumes of igneous rocks associated with the nearby onshore Paraná–Etendeka volcanic provinces, (2) the Tristan, Gough, and St. Helena hot spot trails, (3) seismic profiles showing SDR sequences as much as 200 km wide and 7 km thick, and (4) well intersections with basalts in a variety of synrift and postrift settings.
2. The clearest examples of SDRs in the South Atlantic Ocean are north and south of the main Aptian salt basins. However, we contend that SDRs are also present below the salt basins but have been seismically obscured by overlying salt-related structures. Supporting evidence includes: (1) the former existence of the Tristan, Gough, and St. Helena mantle plumes below these margins, (2) subsalt basalts of mixed origin intersected by wells, (3) clear images of SDRs on the northern and southern margins of the salt basins, and (4) SDRs of mixed clarity imaged below thin salt in deep and ultra-deep water.
3. The conjugate Aptian salt basins formed after not before continental separation. The salt basins were always separate and did not originally form a single giant salt basin. The separate salt basins accumulated distally on proto-oceanic crust, not rift basins. A post-breakup origin for the salt is supported by the stratigraphy and structure recorded on seismic lines: wherever observed, both SDRs and the breakup unconformity invariably underlie the Aptian salt or its stratigraphic equivalent except in the Sergipe Basin. A post-breakup origin is also supported by the distal pinchout of the salt basins on what appears to be typical oceanic crust, by the salt's relationship with magnetic anomalies and by plate reconstructions showing that the Aptian salt basins only fit together if they partly overlie oceanic crust. Otherwise, the salt basins are forced to overlap unrealistically by 220 km; this overlap cannot be accounted for by allochthonous salt tectonics. Circumstantial evidence is also provided by the geochemistry of $MgSO_4$-poor potash evaporites, which are derived by hydrothermal alteration of a host rock likely to be spilitized basalt.
4. The Aptian salt basins were associated with subaerial basalts and continental and shallow-water sediments. Evaporites accumulated in a basin that may have been below sea level but protected by the proto Walvis Ridge and Rio Grande Rise. Through gaps in this mostly subaerial ridge, seawater of the southern South Atlantic spilled northward repeatedly to supply the Aptian evaporites. The separate, conjugate evaporite basins were bounded distally by crust rising to the mid-oceanic ridge. Evaporites ponded on either side of the spreading center, which was probably at least partly subaerial in the proto South Atlantic.
5. An important implication for ultradeep-water exploration is that below the distal parts of the salt basins, thick piles of basalt may be present rather than subsalt rift fill containing lacustrine source rocks. If so, subsalt source rocks should be searched for either proximally in rift sequences or distally in lacustrine sag sequences like the Grey Cuvo Formation (Kwanza Basin) or the upper Lagoa Feia Formation (Campos Basin), which stratigraphically separate SDRs and overlying salt.

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