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Seismic evidence for crustal underplating beneath a large igneous province: The Sierra Leone Rise, equatorial Atlantic

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ABSTRACT

Wide-angle seismic profiles reveal anomalously thick crust with a high-velocity (>7.3 km s^{-1}) zone under the Sierra Leone Rise, a major mid-plate elevation in the Atlantic lying between the Cape Verde platform and the Cameroon Volcanic Line. A profile recorded over the crest using an ocean-bottom seismometer and surface sonobuoys shows that beneath a 3 km water layer and 1 km of sediments, the basement extends to 16–20 km below sea level. Most velocity-depth values fall outside the expected range for Mesozoic–early Cenozoic ocean floor and stretched continental crust. The detection of 7.3–7.5 km s^{-1} material beneath thick, lower-velocity volcanics suggests that magmatic underplating of the crust has occurred. A prominent change in velocity gradient 10–12 km below sea level may mark the transition to underplated material emplaced during the late Cretaceous–early Cenozoic. A pronounced change in Moho depth lies on the line of a long offset fracture zone extending from the African margin, implying underplating was influenced by a pre-existing discontinuity in the lithosphere. Other seismic lines show 7.0–7.2 km s^{-1} basement above the underplated zone extending into water depths of almost 5 km. This is probably the intrusive foundation of early-formed crust over a mantle hot-spot. It is suggested that the development of the Sierra Leone Rise is distinct from other Atlantic hot-spot features to which it has been linked because of its setting in a region of intense lithospheric shear.

1. Introduction

The Atlantic contains many elevated platforms more than 300 km in extent which are believed to have resulted from copious outpourings of basic volcanics. Whether these large igneous provinces have a common structure and whether they trace out plate motions over mantle hot-spots or lie above hot-lines that follow the upwelling limbs of Langmuir-like convection cells in the mantle, or are related to ridge tectonics over anomalous mantle are questions that have catalysed both vigorous debate and field observations (Morgan, 1972; Bonatti and Harrison, 1976; Anderson et al., 1992; Coffin and Eldholm, 1994; Ito et al., 2003; Fairhead and Wilson, 2005; Koppers, 2011; Ernst, 2014). Important to our understanding of these features is their deep seismic structure. Seismic imaging offers a means of distinguishing thickened igneous basement, formed with or without magmatic underplating, from normal oceanic crust uplifted by the buoyancy of a mantle hot-spot (Holbrook, 1995; Holbrook et al., 2001).

Recent seismic investigations of some of the large volcanic platforms in the Atlantic (Fig. 1) suggest that significant underplating has not occurred. The Madeira-Toré Rise (Peirce and Barton, 1991) and the region around Tenerife, Canary Islands (Watts et al., 1997), are underlain by thickened, but not underplated, oceanic crust. A large-offset seismic experiment in 2.5–4.5 km water depth on the Cape Verde platform (Pim et al., 2008) has indicated the presence of normal oceanic crust and normal upper mantle velocities, suggesting dynamic support from a mantle plume. With closely-spaced shot points they do not find evidence for the thick crust reported by Lodge and Helffrich (2006) from earthquake observations. Deep reflection profiles across the Cameroon Volcanic Line just north of the Equator (Meyers and Rosendahl, 1991; Meyers et al., 1998) have also revealed normal oceanic crust that has been elevated about 2 km above the level of the surrounding basins.

Midway between the Cape Verde Platform and the Cameroon Volcanic Line lies the Sierra Leone Rise, a broad regional swell in the equatorial Atlantic separated from the African continental margin by a deep channel (Emery et al., 1975; Figs. 1–3). It is about 600 km long and 400 km wide at the 4000 m isobath. The crest rises about 2.5 km above the abyssal plain in the Sierra Leone Basin and consists of a wide plateau covered with ~900 m of late Cretaceous and younger pelagic sediments which have been sampled at DSDP Site 366 (Fig. 3) (Lancelot et al., 1977). To the west and north, the regional smoothness of the basement surface is broken by large seamounts of Eocene age (53–58 Ma; Jones et al., 1991; Skolotnev et al., 2012).

According to reconstructions of continental separation in the equatorial Atlantic magmatic activity on the Sierra Leone Rise was focussed

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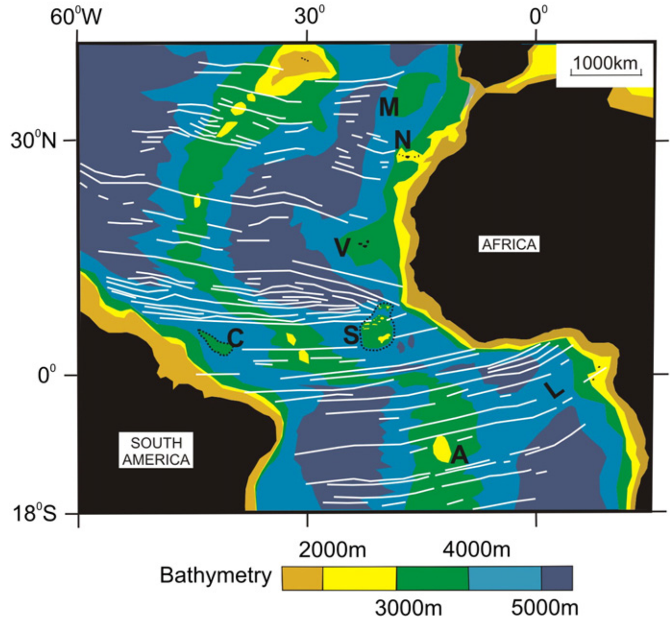

Fig. 1. The Sierra Leone Rise (S) in relation to mid-plate elevations and fracture zone distributions in the central Atlantic as mapped using satellite gravity by Matthews et al. (2011). M—Madeira-Toré Rise. N—Canaries. V—Cape Verde. C—Ceará Rise. L—Cameroon Line. A—Ascension.

in the transition between the late Jurassic Atlantic and the newly opened South Atlantic (Sibuet and Mascle, 1978; Jones et al., 1995; Vogt and Jung, 2005; Moulin et al., 2010). This is a region of closely-spaced transforms, which include the large-offset Guinea Fracture Zone immediately north of the Rise and the St Paul transform to the south (Figs. 1, 3). Fig. 2 shows the locations of magnetochrons C31 (~68 Ma; late Maastrichtian; Gradstein et al., 2004), C34 (~84 Ma; Santonian) to M0 (~125 Ma; early Aptian) on flow lines south of the Guinea Fracture Zone. To the north the late Jurassic–early Cretaceous M-series from M25 (~155 Ma; late Oxfordian) to M0 record the spreading history off Africa before the opening of the South Atlantic (Cande et al., 1989). Some authors have suggested, in the absence of deep seismic data, that the Sierra Leone Rise and its conjugate in the western Atlantic, the Ceará Rise (Fig. 1), formed at the axis of the Mid-Atlantic Ridge as a result of anomalously high rates of mantle melting arising from regional changes in plate motions (Kumar, 1979; Vogt and Jung, 2005). Others have proposed that it is made up of uplifted oceanic crust above a mantle hot-line that extended into central Africa, one of several related mantle lineaments that include the Walvis Ridge, Cameroon Volcanic Line, the Cape Verde platform and the Canaries (Meyers et al., 1998). In view of the uncertainties surrounding the origin of this prominent igneous feature we have determined its velocity structure using wide-angle seismic data to examine its evolution in relation to the development of large igneous provinces in the central Atlantic.

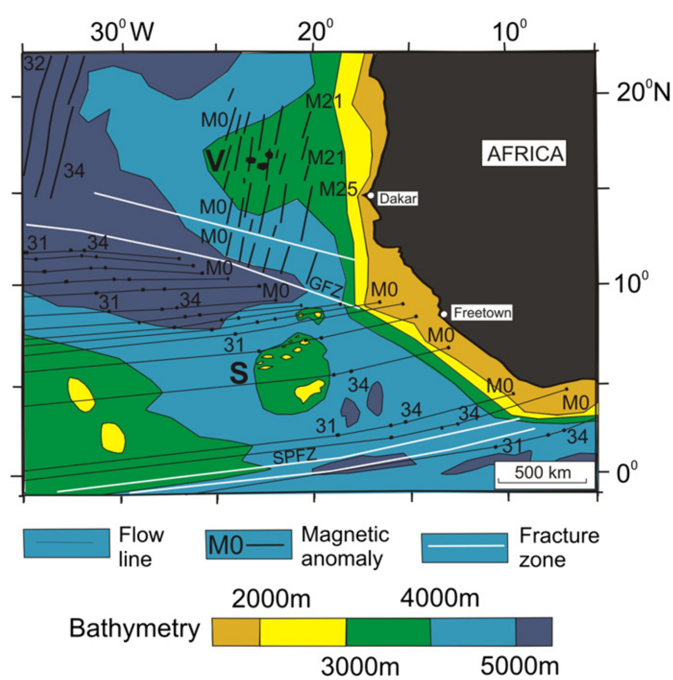

Fig. 2. Magnetic anomalies in the vicinity of the Sierra Leone Rise. GFZ—Guinea Fracture Zone. SPFZ—St Paul Fracture Zone. The late Jurassic–early Cretaceous M-series anomalies north of the Guinea Fracture Zone are taken from Cande et al. (1989). Further south the positions of magnetochrons M0 (~125 Ma; early Aptian; Gradstein et al., 2004), C34 (~84 Ma; Santonian) to C31 (~68 Ma; late Maastrichtian) are shown on flow lines based on stage poles derived from South Atlantic fracture zone trends and magnetic anomalies (Jones et al., 1995).

2. Seismic acquisition

Seismic profiles were recorded over the crest and on the periphery of the Sierra Leone Rise. The longest profile (1, Fig. 3; Fig. 4a) runs over the summit plateau. An ocean bottom seismometer (OBS) was laid in a water depth of 2908 m at the centre of the line (Table 1). The OBS, with a basic design described by Francis et al. (1975), employed a 3-component seismometer and two hydrophones (1–40 Hz) as sensors. Clear headwaves from Geophex explosive charges fired at 2.5–4.0 km intervals were recorded out to ranges of 85 km to the NE and SW (Fig. 5). To provide greater subsurface ray coverage, free-floating Aquatronics sonobuoys with hydrophones 37 m below the sea surface were deployed near the centre and at the two ends of the line (Buoys 1, 2 and 3: Figs. 4a, 5). All seismic arrivals were corrected to a sea level datum using velocimeter measurements of sound speeds in the water column. In addition, an airgun reflection profile was recorded close to the line of shots to determine the thickness of the sedimentary cover and to match reflectors to lithological units sampled at DSDP 366 (Lancelot et al., 1977). Two main sedimentary layers can be distinguished, with velocities of 1.82 and 2.30 km s^{-1} (Fig. 4b).

Shorter (18–40 km) seismic profiles running parallel to local isobaths were shot at positions 2, 3 and 4 (Fig. 3; Table 1) to determine the upper crustal structure at the margins of the Sierra Leone Rise. Water depths for each profile are given in Table 1. Free-floating Aquatronics sonobuoys were again deployed to receive arrivals from small Geophex charges detonated at intervals of 1.0–1.5 km. During the shooting filtered (10–50 Hz and 300–600 Hz) signals were recorded together with the shot instant from the ship's echo-sounder transducer. Fig. 6 shows traces from the 10–50 Hz hydrophones. On the panels for lines 2 and 3 the first sonobuoy deployed is labelled B1. On completion of the forward shots the profiles were reversed by laying a second buoy (B2). Line 2 reached a range of 33 km on the SE margin of the Rise. Headwaves on line 3 on the northern side were received out to a range of 40 km. Line 4 on the western boundary is a split profile shot with two sonobuoys (B1, B2) placed near the centre of the transect. Data from the OBS and sonobuoys are supplemented by three two-ship profiles of Sheridan et al. (1969) located in the Sierra Leone Basin at positions D–F in Fig. 3.

3. Results

The velocity model for Line 1 (Fig. 7b) was derived mainly by tomographic inversion of the first arrival travel times at the OBS and the three sonobuoys, supplemented by iterative finite-difference acoustic full-wavefield modelling (McMechan, 1985) for the Moho reflections (Fig. 5). Constraints on the thickness and velocities in the sedimentary cover are provided by the nearby reflection profile (Fig. 4). The

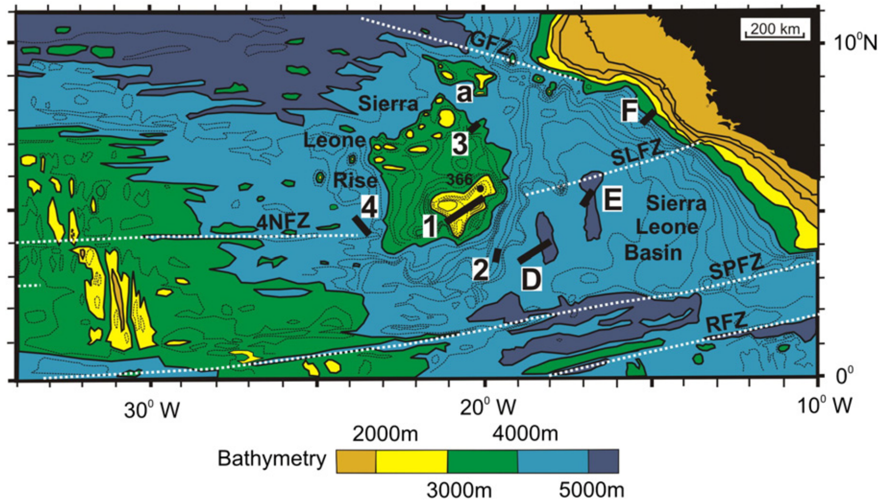

Fig. 3. Locations of long-offset seismic profiles. Profile 1 is a 170-km line recorded over the late Cretaceous sediment cover on the summit plateau of the Sierra Leone Rise using an ocean bottom seismometer placed at the centre in a water depth of 2908 m. Free-floating sonobuoys were deployed at the centre and ends of the line (see Fig. 4 and Table 1). Profiles 2, 3 and 4 on the periphery of the Sierra Leone Rise were recorded with sonobuoys (Table 1). Lines D–F in the Sierra Leone Basin are two-ship profiles shot by Sheridan et al. (1969). The position of Deep Sea Drilling Project site 366 (Lancelot et al., 1977) is shown. Bathymetry is derived from IBCEA (1999) and later soundings supplied by the National Oceanography Centre, UK, and the Lamont-Doherty Earth Observatory, USA. Seamounts on the northern flank of the Sierra Leone Rise (area a) are early Cenozoic in age. GFZ—Guinea Fracture Zone. SLFZ—Sierra Leone Fracture Zone. 4NFZ—Four North Fracture Zone. SPFZ—St Paul Fracture Zone. RFZ—Romanche Fracture Zone.

tomography uses the algorithm of Zhu and McMechan (1989) that predicts velocities within the region sampled by rays corresponding to first arrival paths. The tomography alternates between iterative velocity updates and retracing the rays to ensure internal consistency. The recording geometry produces a low ray sampling density in places (Fig. 7a) so parts of the model have some non-uniqueness associated

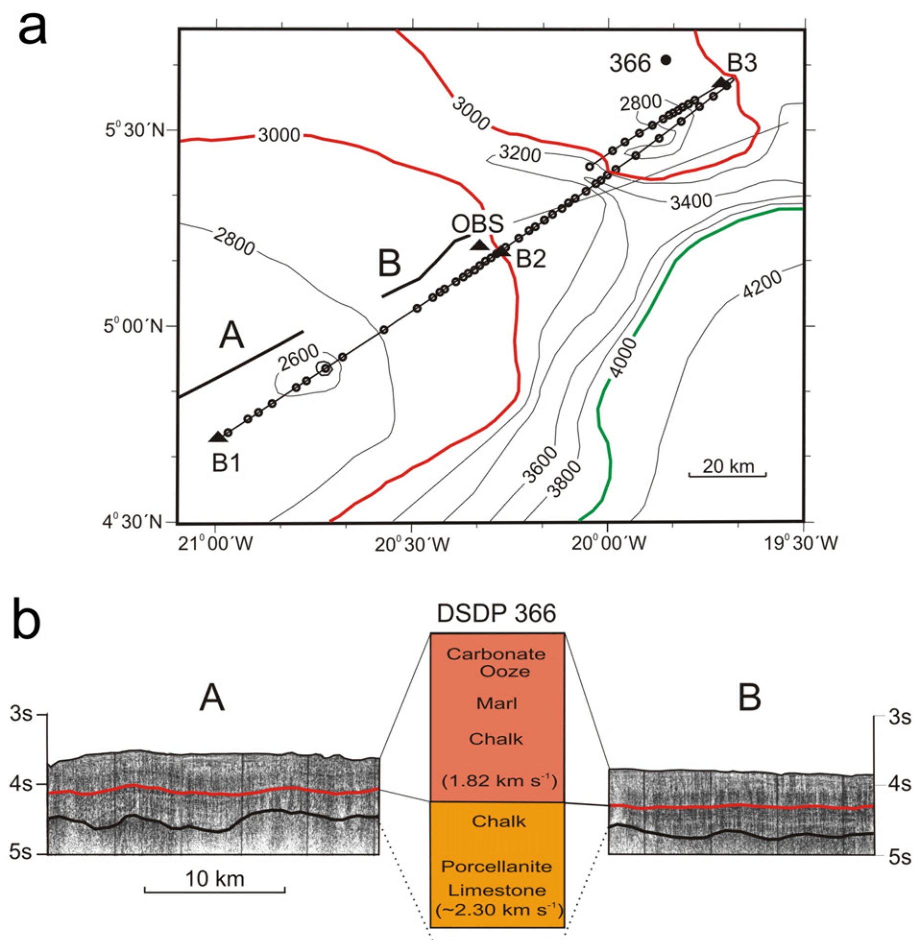

Fig. 4. (a) Shot and receiver positions on line 1 along the crest of the Sierra Leone Rise. OBS — Ocean bottom seismometer. B1, B2, B3 — sonobuoys 1, 2 and 3. Isobaths are in metres. (b) A and B are sections of an airgun reflection profile recorded close to the long-offset line. Two-way reflection times are shown. The correlation of the two main seismic units with the stratigraphy of the sediment cover at DSDP site 366 is also indicated.

Table 1
Location of seismic lines: Sierra Leone Rise.

Line 1	Latitude (N)	Longitude (W)	Water depth (m)			
OBS	5° 12.43′	20° 19.81′	2908			
Buoy 1	4° 42.35′	21° 00.20′	2641			
Buoy 2	5° 11.62′	20° 16.80′	3021			
Buoy 3	5° 37.70′	19° 42.25′	2979			
Line 2	**Buoy position**			**Final shot position**		
	Latitude (N)	Longitude (W)	Water depth (m)	Latitude (N)	Longitude (W)	Water depth (m)
Buoy 1	3° 54.57′	19° 33.52′	4727	3° 44.08′	19° 35.73′	4751
Buoy 2	3° 37.96′	19° 36.36′	4720	3° 55.78′	19° 34.50′	4713
Line 3	**Buoy position**			**Final shot position**		
	Latitude (N)	Longitude (W)	Water depth (m)	Latitude (N)	Longitude (W)	Water depth (m)
Buoy 1	7° 36.05′	20° 03.05′	3950	7° 24.67′	20° 21.30′	3948
Buoy 2	7° 28.35′	20° 12.52′	3894	7° 33.33′	20° 05.90′	3853
Line 4	**Buoy position**			**Final shot position**		
	Latitude (N)	Longitude (W)	Water depth (m)	Latitude (N)	Longitude (W)	Water depth (m)
Buoy 1	4° 51.73′	23° 55.11′	4321	4° 42.78′	23° 50.95′	4407
Buoy 2	4° 50.41′	23° 48.33′	4385	5° 01.90′	23° 53.92′	4396

with them. Smoothing and both extrapolation and interpolation from the sampled regions into the non-sampled regions are used to construct a continuous model using the algorithm of Patel and McMechan (2003). Individual times can be better-fitted with models that have higher local variance in the less well sampled regions. We present in Fig. 7b a model that stably represents the larger-scale structural features.

The first arrival ray paths (Fig. 7a) do not penetrate to the base of the crust. However, Moho reflections were identified in the OBS and sonobuoy data out to ranges of 81 km so these have been incorporated into the model by iterative 2-D finite-difference modelling. While a difference in Moho depth to the NE and SW of the OBS is clear (Fig. 7b) details of the Moho geometry are not defined. In Fig. 5 the observed first arrivals and Moho reflections are superimposed on the synthetic seismograms predicted for the OBS data from the final velocity model in Fig. 7b. Similar modelling was carried out using the three sonobuoy data sets. The final composite model (Fig. 7b) accounts for all the observed times (Fig. 5) with an accuracy consistent with the uncertainty in picking arrival times (~0.050 s). All 127 arrivals from the OBS and sonobuoy data are fitted with a root-mean-square (rms) travel time misfit of 0.101 s. The rms misfits for basement headwaves and Moho reflections are 0.086 s and 0.112 s, respectively.

Below the sedimentary cover, the underlying crustal basement extends to depths of at least 16 km below sea level (Figs. 7b, 8). Large vertical gradients in P-wave velocity (~1.2 s^{-1}) characterize the upper kilometre, reducing to ~0.14 s^{-1} at depths of 9–10 km where velocities

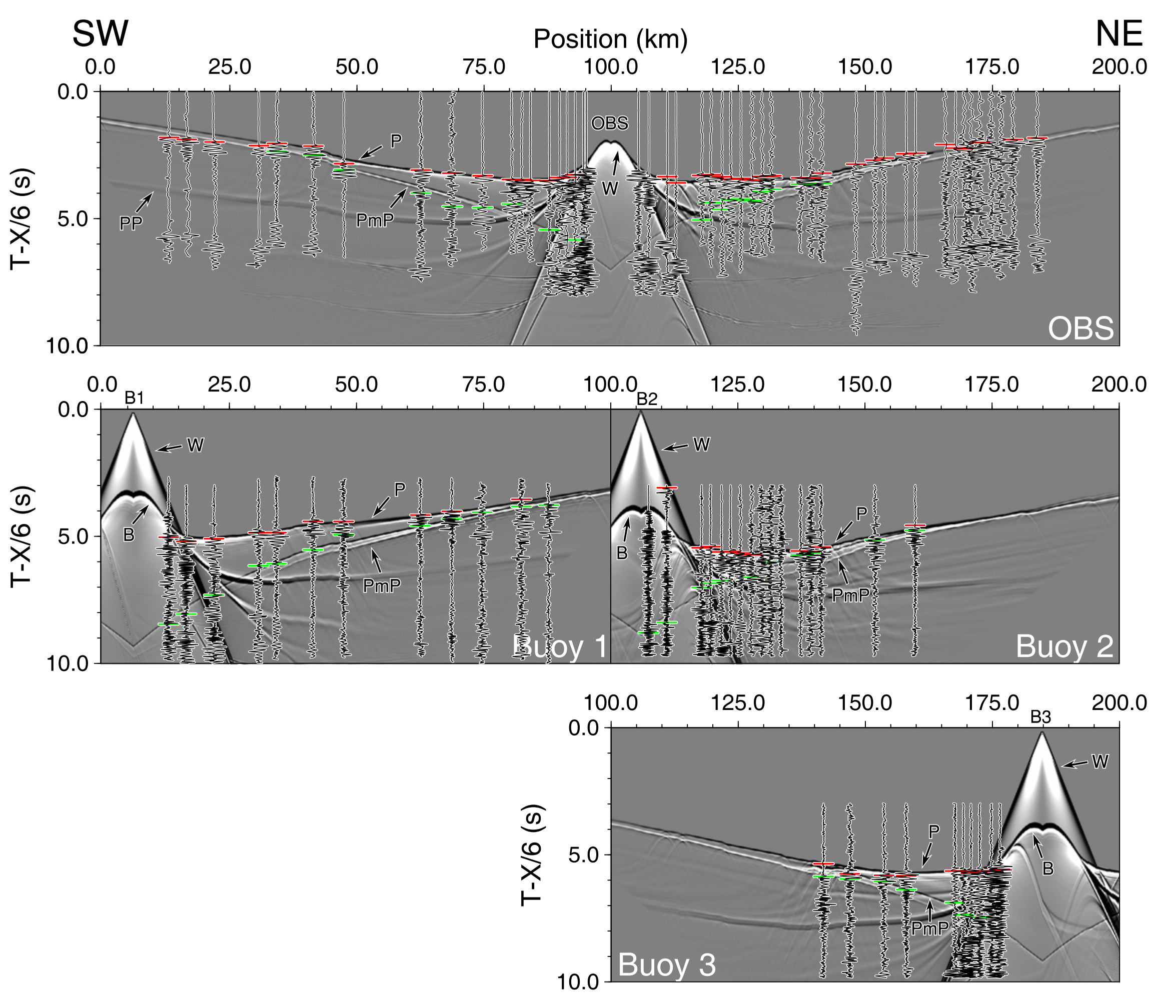

Fig. 5. Reduced-time plots of data recorded by the OBS and sonobuoys 1, 2 and 3 along line 1 (Figs. 3, 4). The traces are superimposed on synthetic seismograms computed for the OBS and sonobuoy locations in Fig. 7a, using the P-wave velocity model in Fig. 7b. First arrival picks (P) are shown in red and Moho reflections (PmP) in green. W — direct water wave. B — seafloor reflection. PP — multiple reflections of P from the sea surface.

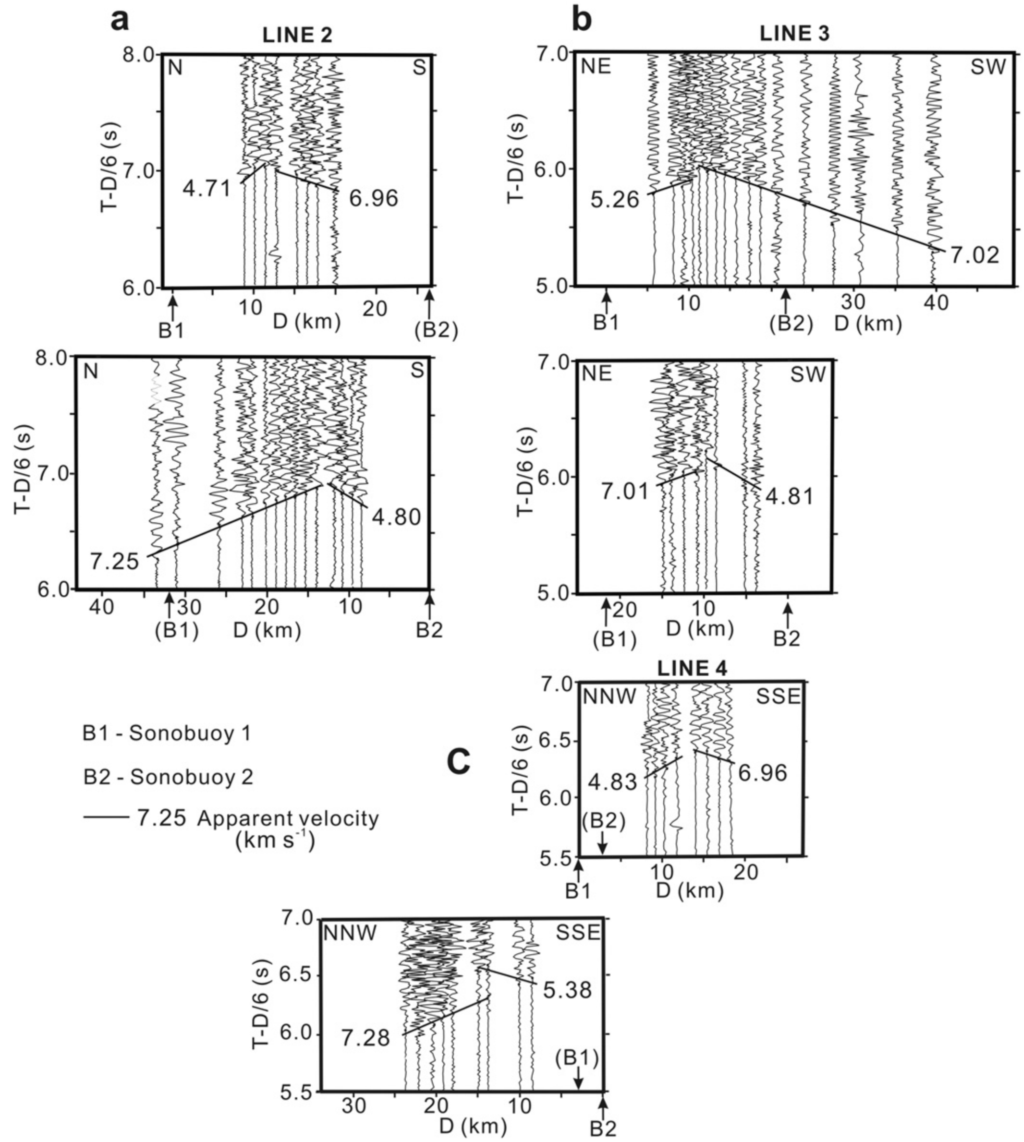

Fig. 6. a, b, c—Sonobuoy profiles 2, 3 and 4. Reduced time–distance plots of 10–50 Hz sonobuoy signals recorded along lines on the periphery of the Sierra Leone Rise (Fig. 3; Table 1). (a) Traces recorded from the first sonobuoy deployed (B1) on line 2 indicate apparent velocities of 4.71 and 6.96 km s^{-1} derived by least squares fits of arrival times. Reversing the line by shooting from a second buoy (B2) in the direction of B1 gives apparent velocities of 4.80 and 7.25 km s^{-1}. (b) On line 3 apparent velocities from traces recorded from B1 and B2 are shown. (c) Line 4 is a split profile recorded with sonobuoys B1 and B2 deployed near the centre of the line.

reach 7.2 km s^{-1}. A prominent increase in gradient is found just below 10 km, with velocities changing from 7.2–7.4 km s^{-1} over a depth increment of 0.7 km. This prominent feature of the crustal structure is marked by the conspicuous concentration of turning rays at this level (Fig. 7a).

Crustal velocities are well constrained by first arrival times to a depth of 13.5 km, where they reach ~7.5 km s^{-1}. To determine the basement thickness below we assume an average velocity of 7.54 km s^{-1} for the lower crust, the highest velocity constrained by the deep intersecting ray paths, and use observed Moho reflection times. This gives Moho depths varying between 16 and 20 km along the profile (Fig. 7b). In producing the synthetic seismograms, the velocity at the Moho is fixed at 8.1 km s^{-1}, a value that gives sufficiently high reflection amplitudes for comparison with observed travel times and amplitudes (Fig. 5).

The velocity structures beneath the shorter sonobuoy profiles around the edge of the Sierra Leone Rise (Profiles 2, 3 and 4; Fig. 3) have been derived from the apparent velocities and intercepts in Fig. 6 using the method of Mota (1954). Dipping plane-layer solutions reveal that below the 0.6–0.7 km sedimentary cover an upper basement layer, 1.1–1.8 km thick, is present with velocities typical of extrusive volcanics (4.7–5.1 km s^{-1}; Fig. 8, Table 2). They also show that the intrusive basement with a velocity of 7.1 km s^{-1} beneath the crest of the Rise extends to its periphery. Velocities below this section could not be determined from the sonobuoy lines.

4. Discussion

4.1. Seismic velocity variations

Variations in seismic velocity with depth beneath the crest of the Sierra Leone Rise and its environs are compared in Figs. 9 and 10 with those observed under normal oceanic crust (White et al., 1992), stretched continental crust (Christensen and Mooney, 1995) and other volcanic elevations. The igneous basement beneath the crest of the Sierra Leone Rise falls outside the range for uplifted oceanic crust of normal thickness or stretched continental basement (Fig. 9). It is not only 2–3 times thicker than the crust of the Sierra Leone Basin (Lines D–F; Figs. 3, 8) but includes a section, approximately 7 km thick, with velocities greater than 7.3 km s^{-1}. This zone lies beneath basement with

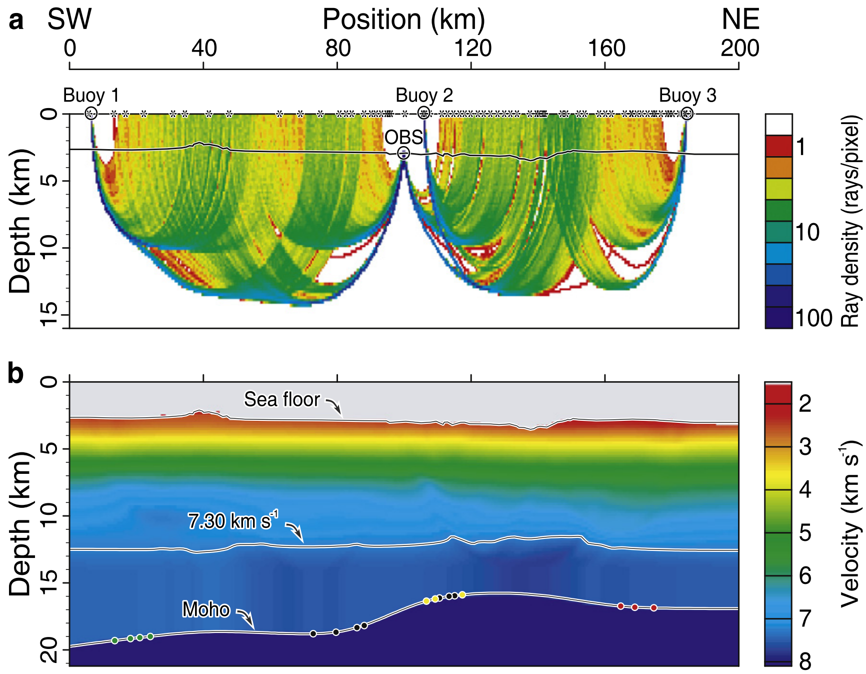

Fig. 7. (a) Shots (indicated by * symbols), receivers and seismic ray paths along Line 1. (b) P-wave velocity model used for computing the ray paths, with reflection points along the Moho coloured as follows: green—buoy 1, yellow—buoy 2, red—buoy 3 and black—OBS. The ray sample density distribution in (a) indicates the relative reliability of velocities in the model structure. The velocity grid for the tomography is discretized at 500 m horizontally and 200 m vertically; the velocity grid for the synthetic seismogram calculations has a 25 m increment in both directions.

velocities of 7.0–7.3 km s^{-1}, values which are appreciably higher than the 6.26 km s^{-1} characterizing oceanic Layer 3 in the central and northern part of the Sierra Leone Basin (Lines E, F, Fig. 8) suggesting that 7.0–7.3 km s^{-1} basement is the intrusive foundation of early-formed anomalous crust on the Sierra Leone Rise. Extending into water depths of more than 4.6 km at the periphery of the Rise (Lines 2, 3, 4; Fig. 8) the basement contrasts markedly with oceanic Layer 3 in the Sierra Leone Basin with its abnormally low velocity. In other regions Layer 3 velocities normally exceed 6.6 km s^{-1} (White et al., 1992). A distinctive feature of the Sierra Leone Basin observed on reflection profiles is widespread post-Eocene faulting of its sediment cover and basement which

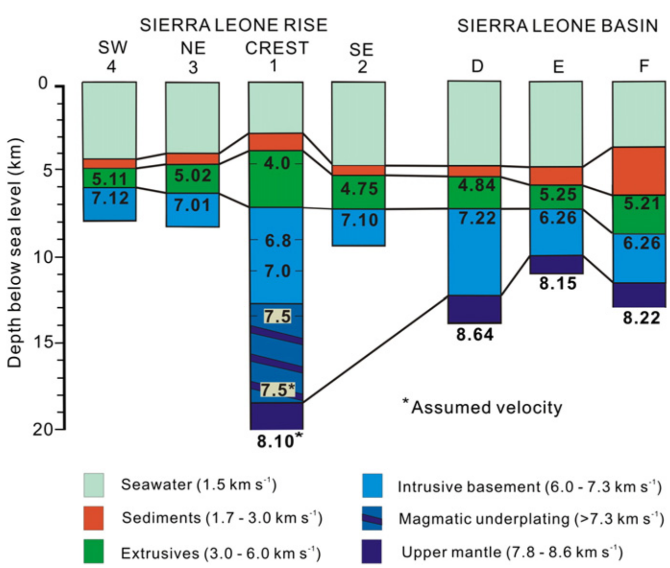

Fig. 8. Seismic structure of the Sierra Leone Rise and environs. Section 1 is the modelled structure from Fig. 7b which assumes a deep basement velocity of 7.54 km s^{-1} from 13.5 km depth to the Moho. Sections for profiles 2, 3 and 4 (Table 2) are derived from dipping plane-layer solutions for sonobuoy data in Fig. 6 using the method of Mota (1954). D, E and F are taken from the two-ship seismic data of Sheridan et al. (1969).

has been related to changing motions between the African and South American plates during the Cenozoic (Jones, 2003). Furthermore, airgun profiles from the basin reveal numerous sediment diapirs and local seismically transparent zones which suggest significant late-stage movement of crustal fluids. The low velocity for Layer 3 may thus reflect an unusually high porosity of the deep basement at the Layer 2/Layer 3 boundary resulting from the pervasive crustal deformation. Although borehole evidence is lacking to support this conclusion, it should be noted that analysis of downhole logs at ODP site 504B in the eastern Pacific (Pezard, 2000) has demonstrated that changes in crustal stress regime have led to reopening of cracks and fractures in the deep basement which has affected fluid circulation and crustal alteration at the Layer 2/Layer 3 boundary. More recent investigations of borehole samples from the same drill-site by Carlson (2014) indicate that velocity changes at this level are more strongly influenced by the crack-related porosity variations than by mineralogical changes brought about by circulating fluids.

Having a basement core with velocities exceeding 7.3 km s^{-1} the Sierra Leone Rise shows similarities with the volcanic platforms around Hawaii and the Marquesas in the Pacific (ten Brink and Brocher, 1987; Caress et al., 1995; Leahy et al., 2010) and Kerguelen, La Réunion, Laccadive Island and the Ninetyeast Ridge in the Indian Ocean (Recq et al., 1990; Charvis et al., 1999; Grevemeyer et al., 2001; Gupta et al., 2010) where such high velocities have pointed to magmatic underplating by purely intrusive material or a mix of intrusions and preexisting basement. It differs from other mid-plate elevations in the eastern Atlantic which have been attributed to deep mantle plumes. The Cape Verde Platform (Pim et al., 2008) and the Cameroon Volcanic Line (Meyers and Rosendahl, 1991; Meyers et al., 1998) are floored by uplifted normal oceanic crust; the Madeira-Toré Rise (Peirce and Barton, 1991) and the Canaries (Watts et al., 1997) are underlain by thickened oceanic crust with an absence of deep crustal velocities greater than 7.3 km s^{-1}. Klingelhöfer et al. (2001) report that underplated crust may be present beneath Ascension but is no more than 1 km thick. However, a further study of a three-dimensional seismic dataset from the area did not find any evidence for magmatic underplating (Evangelides et al., 2004) (Fig. 10).

Table 2
Seismic structure from sonobuoy profiles: margin of Sierra Leone Rise.

Line number	Water layer		Sedimentary layer		Extrusive layer		Intrusive layer
	Thickness	Velocity	Thickness	Velocity[c]	Thickness	Velocity[d]	Velocity[d]
	km	km s^{-1}	km	km s^{-1}	km	km s^{-1}	km s^{-1}
2[a]	4.73	1.50	0.61	2.00	1.74	4.75 (±0.18)	7.10 (±0.11)
3[a]	3.95	1.50	0.70	2.00	1.74	5.02 (±0.27)	7.01 (±0.08)
4[b]	4.34	1.50	0.59	2.00	1.14	5.11 (±0.58)	7.12 (±0.46)

[a] Reversed profile.
[b] Split profile.
[c] Assumed value.
[d] ±Standard error.

Wide-angle reflections from the top of the high-velocity region located ~7 km beneath the Marquesas have been interpreted (Caress et al., 1995) as arrivals from a relict Moho marking the base of early-formed crust (M_R, Fig. 9). While there is a distinct increase in trace amplitudes about 2 s before Moho reflections come in at near-vertical incidence (Figs. 5, 7), the present data from the Sierra Leone Rise do not show convincing evidence for coherent mid-crustal reflections over significant distances. However, there is a pronounced increase in the vertical velocity gradient at ~7 km below the top of the basement (Fig. 9) from which much seismic energy is returned to the surface on both sides of the OBS (Fig. 7a). This region is the transition to the thick section with velocities exceeding 7.3 km s^{-1} and is interpreted as the top of a zone of magmatic underplating. The base is defined by pre-critical Moho reflections at shot–receiver ranges up to 66 km (Fig. 5). The shape and depth of the Moho are estimated by iterative modelling to fit the picked reflection times and relative amplitudes and indicate that the underplated section almost doubles in thickness over a distance of ~100 km (Fig. 7b), suggesting relatively low viscosities in the lower crust and upper mantle during the underplating process. At shallower levels crustal thickening has involved not only underplating but the addition of an expanded extrusive section under the crest of the Sierra Leone Rise (~3.0–6.0 km s^{-1}), with a thickness exceeding its elevation (Figs. 7b, 8).

The question of whether the conjugate of the Sierra Leone Rise in the western Atlantic, the Ceará Rise, is an underplated volcanic platform remains unanswered. A reversed seismic profile (Houtz et al., 1977) has revealed in the upper part of the igneous basement a sequence of low-velocity volcanics approximately equal in thickness to those found beneath the crest of the Sierra Leone Rise (Fig. 10). Below lies a 6.8 km s^{-1} layer of undetermined thickness. The deeper structure is presently unknown.

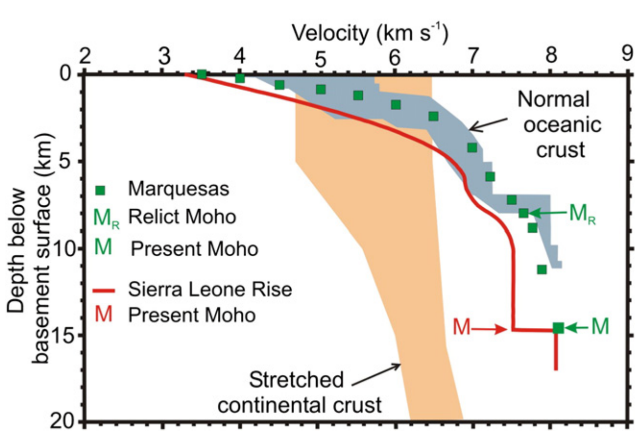

Fig. 9. P-wave velocities beneath the Sierra Leone Rise (kilometre 58, Fig. 7). The deep basement velocity below 9.5 km is assumed to be 7.54 km s^{-1}. The velocities for the central Marquesas platform are taken from Fig. 4 (kilometre −25) of Caress et al., 1995). Also shown are the bounds for stretched continental crust (Christensen and Mooney, 1995) and normal oceanic crust (29–140 Ma) (White et al., 1992).

4.2. Development of Sierra Leone Rise

Thick igneous basement beneath the Sierra Leone Rise and the presence of a conjugate elevation in the Western Atlantic, the Ceará Rise (Houtz et al., 1977; Kumar and Embley, 1977) (Figs. 1, 10), are consistent with high rates of magmatism over a mantle hot-spot and later rifting at the westward migrating crest of the Mid-Atlantic Ridge (Kumar, 1979). Magmatic activity began during the late Cretaceous soon after continent/continent contact ceased along the Guinea Transform (Sibuet and Mascle, 1978; Jones et al., 1995; Vogt and Jung, 2005; Moulin et al., 2010). It took place in an area characterized by an unusually dense group of fracture zones, clearly defined by bathymetry, magnetic anomalies and recent satellite gravity (Fig. 1) that mark regional changes in plate motion and the development of leaky transforms (Jones and Mgbatogu, 1982; Jones, 1987; Matthews et al., 2011). The initially high rates of magma supply did not persist long into the Cenozoic because the Sierra Leone Rise merges with the flanks of the Mid-Atlantic Ridge about 900 km from the axis (Figs. 1, 3). Continued hot-spot activity which does not appear to be expressed in the topography is evident from a broad geochemical anomaly west of the

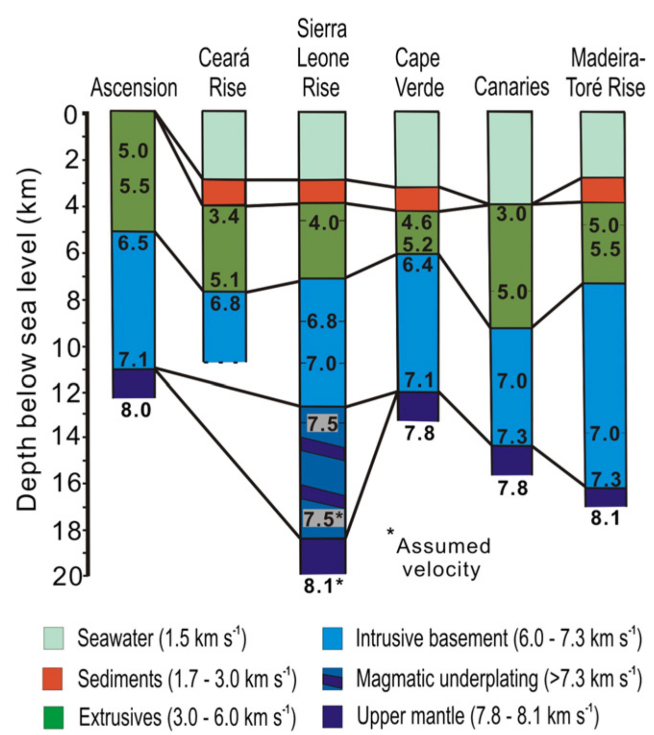

Fig. 10. Structure of mid-plate elevations in the central Atlantic. Seismic velocities are shown for Ascension (Evangelides et al., 2004), the Ceará Rise (Houtz et al., 1977), Sierra Leone Rise (Fig. 8), the Cape Verde Rise (Pim et al., 2008), Canaries (Tenerife) (Watts et al., 1997) and the Madeira-Toré Rise (Peirce and Barton, 1991).

Rise mapped using Pb–Nd–Sr isotopes and rare earths in dredged basalt glasses (Schilling et al., 1994) and from low shear wave velocities detected to depths of 250 km in this region (Silveira and Stutzmann, 2002; Heintz et al., 2005).

A feature of the Sierra Leone Rise is the presence of seamounts of Eocene age (53–58 Ma) on its northern flank which are appreciably younger than the late Cretaceous sediment cover on the summit plateau (Fig. 3; Jones et al., 1991; Skolotnev et al., 2012). It does not exhibit the age progression observed on the Walvis Ridge and other Atlantic elevations attributed to lithosphere moving over deep mantle plumes (O'Connor et al., 2012). This may be because the main episode of anomalous mantle melting was short-lived and was augmented in the early Cenozoic by edge convection (King and Anderson, 1998) associated with the large difference in age (>50 Ma) and thickness of the lithosphere across the Guinea transform at the northern boundary of the Rise (Vogt and Jung, 2005; Moulin et al., 2010). The late-stage activity extended from the Sierra Leone Rise further east along the Guinea Fracture Zone where it bounds the African margin (Bertrand et al., 1993). While the degree of melting associated with edge convection is the subject of debate (Armitage et al., 2013), intense shearing of the lithosphere at the site of primary hot-spot activity could have promoted the creation of pathways for the intrusion and then freezing of early melt below attenuated crust within the closely-spaced fracture zones (Cormier et al., 1984; Spathopoulos and Jones, 1993). Such pathways allowed the formation of a high density barrier to further rising melt and the growth of an underplated layer.

The ~4 km change in thickness of the high-velocity basement near kilometre 100 beneath the summit of the Sierra Leone Rise (Fig. 7b) lies on the western continuation of the Sierra Leone Fracture Zone (McMaster et al., 1973) that displaces the African margin by approximately 140 km at 7°N (Fig. 3). This suggests that build up of the zone of magmatic underplating was influenced by a major discontinuity in the lithosphere established at the time of continental separation. Intense lithospheric shear, such as we see in the vicinity of the Sierra Leone Rise, may account for the difference in deep crustal structure between the Rise and the mid-plate platforms of the Cape Verdes, Canaries and Madeira-Toré Rise and may be an important factor in determining the growth of magmatic underplating beneath mid-plate elevations in other oceanic areas.

5. Conclusions

Wide-angle seismic observations indicate that the crust of the Sierra Leone Rise is anomalously thick (13–17 km) and contains in its deeper sections a zone with velocities exceeding 7.3 km s^{-1}. The high values suggest magmatic underplating has occurred through the addition of purely intrusive material or a combination of intrusions and pre-existing basement. The top of the underplated region is marked by an increase in velocity gradient 10–12 km below sea level and its base is defined by Moho reflections. Velocity variations within the basement indicate that the Sierra Leone Rise did not form from uplift of normal oceanic crust or from stretched continental basement left behind during the early stages of separation of Africa from South America.

The development of the Sierra Leone Rise, with its core of high-velocity basement, has followed a path that differs from other mid-plate volcanic elevations in the eastern Atlantic, which are underlain by uplifted normal oceanic crust (Pim et al., 2008; Meyers and Rosendahl, 1991; Meyers et al., 1998) or thickened oceanic crust without significant magmatic underplating (Peirce and Barton, 1991; Watts et al., 1997). We suggest that the feature is distinct because it evolved by anomalous mantle melting, possibly associated with edge convection, beneath a region of intense lithospheric shear close to the crest of the Mid-Atlantic Ridge soon after continent/continent contact ceased along the main transform that bounded the newly opened South Atlantic. The growth of an underplated layer (>7.3 km s^{-1}) may have been promoted by the creation of a high-density barrier to rising melt in this intensely sheared region. The presence of strongly sheared lithosphere above a mantle hot-spot may be a vital factor leading to the development of high-velocity underplated zones here and beneath large igneous provinces elsewhere.

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