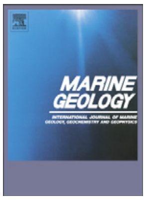
Marine Geology 365 (2015) 52–60

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo



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

E. John W. Jones [a,*], George A. McMechan [b], Xiaoxian Zeng [b]

[a] *Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK*
[b] *Center for Lithospheric Studies, The University of Texas at Dallas, 800W Campbell Road, Richardson, TX 75080-3021, USA*

ARTICLE INFO

*Article history:*
Received 22 March 2013
Received in revised form 10 March 2015
Accepted 12 March 2015
Available online 18 April 2015

*Keywords:*
Large igneous province
Seismic structure
Crustal underplating
Magmatic underplating
Hot-spots
Atlantic Ocean

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

---

[*] Corresponding author.
*E-mail address:* ejw.jones@ucl.ac.uk (E.J.W. Jones).

http://dx.doi.org/10.1016/j.margeo.2015.03.008
0025-3227/

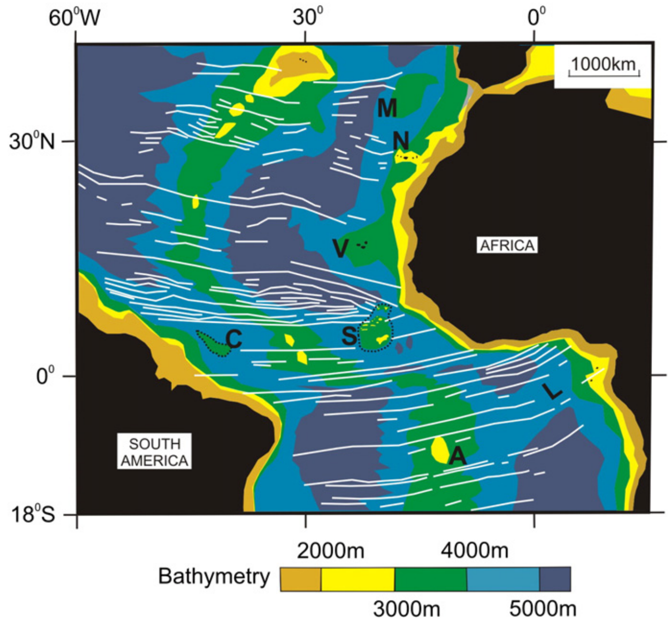


**Fig. 1.** The Sierra Leone Rise (S) in relation to mid-plate elevations and fracture zone distributions in the central Atlantic as mapped using satellite gravity by Matthews et al. (2011). M—Madeira-Toré Rise. N—Canaries. V—Cape Verde. C—Ceará Rise. L—Cameroon Line. A—Ascension.

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.

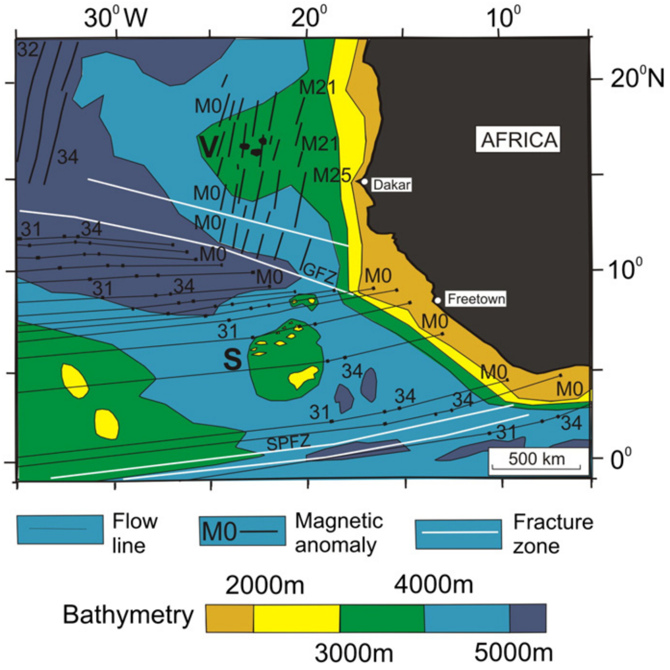


**Fig. 2.** Magnetic anomalies in the vicinity of the Sierra Leone Rise. GFZ—Guinea Fracture Zone. SPFZ—St Paul Fracture Zone. The late Jurassic–early Cretaceous M-series anomalies north of the Guinea Fracture Zone are taken from Cande et al. (1989). Further south the positions of magnetochrons M0 (~125 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