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ABSTRACT

The 21–25-km-thick crust of the southern Kerguelen Plateau consists of three units: (1) a ≤2.3-km-thick sedimentary cover; (2) a 3–6-km-thick basaltic layer with velocities ranging from 4.5 to 6.2 km/s; and (3) a 15–17-km-thick lower crust with velocities from 6.6 to 6.9 km/s, including a 3–6-km-thick transition zone located at the base of the crust. The low-velocity transition zone has an average velocity of 6.7 km/s and exhibits several internal wide-angle reflections. The velocity-depth structure of the crust differs significantly from that of other hotspot-related oceanic plateaus and suggests that the southern Kerguelen Plateau may be a fragment of a volcanic passive margin composed of a thinned continental crust overlain by basalt flows.

INTRODUCTION

The Kerguelen Plateau is a 1.6 × 10^6 km^2 large submarine feature trending north-northwest in the southern Indian Ocean. It is surrounded by oceanic basins except to the south, where the 3500-m-deep Princess Elisabeth trough separates it from the Antarctic continental margin (Fig. 1). A large sedimentary basin, the Raggatt basin, lies on the top of the southern Kerguelen Plateau in water depths of ~1500 m.

In the 1970s the main scientific debate about the Kerguelen Plateau concerned its continental or oceanic origin. Granitic and syenitic plutonic complexes in the Kerguelen archipelago were presented as evidence for a continental origin of the islands (Nougier and Lameyre, 1973). Results from further petrological and geochemical studies conducted on the archipelago flood basalts (Watkins et al., 1974) and on the basaltic basement of the southern Kerguelen Plateau sampled during Ocean Drilling Program (ODP) Leg 120 (Storey et al., 1992) suggest that the plateau was emplaced at a spreading axis over a hot mantle plume, during initiation of sea-floor spreading between India and Australia-Antarctica, at ~110 Ma. This interpretation is also consistent with plate kinematic reconstructions (Royer and Coffin, 1992) and geophysical investigations conducted at sea (Coffin et al., 1990; Schaming and Rotstein, 1990).

The study by the Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM) and the Mission de Recherche des Terres Australes et Antarctiques Françaises (T.A.A.F.) provided the first high-quality, long-range ocean-bottom seismometer (OBS) data over the submarine Kerguelen Plateau. Herein we present the main results of two wide-angle seismic profiles shot over the southern Kerguelen Plateau in the Raggatt basin and a comparison with the deep structure of other large igneous provinces.

SEISMIC DATA INTERPRETATION

Profiles 4 and 5 were obtained in the Raggatt basin (Fig. 1) along multichannel seismic lines RS02-24 and MD48-5, respectively (Coffin et al., 1989). The seismic source was an untuned array of eight 16 L air guns shot at ~180 m spacing. Receivers were five three-component digital OBSs deployed evenly along each 160-km-long profile.

The OBS5 record along line 4 exhibits (Fig. 2) sedimentary arrivals between 2 and 4 km, high-amplitude arrivals (Pbb) refracted in the basaltic basement (layer BB) between 5 and 35 km, and quasilinear arrivals (Plc) refracted in the lower crust (layer LC) between 35 km and 145 km. A prominent Moho reflection (PmP) is observed from 35 to 145 km with a critical distance of 70 km. Between the Plc and PmP waves, several low-amplitude reflections (Pr) (Fig. 2) are observed, suggesting the presence of a reflective zone (layer RZ) between the base of layer LC and the Moho. No significant variation is observed from one OBS section to another along line 4, suggesting that the crust does not vary laterally along this north-northwest–trending line.

Line 5 exhibits seismic arrivals similar to those of line 4 but shows significant lateral variations (dipping interfaces).

Results of the Traveltime Inversion

A two-dimensional velocity model (Fig. 3) was derived from an iterative inversion of traveltimes (Zelt and Smith, 1992). The result of the inversion shows a 1.0–2.3-km-thick sedimentary cover having velocities ranging from 1.7 to 3.4 km/s. The thickness of layer BB

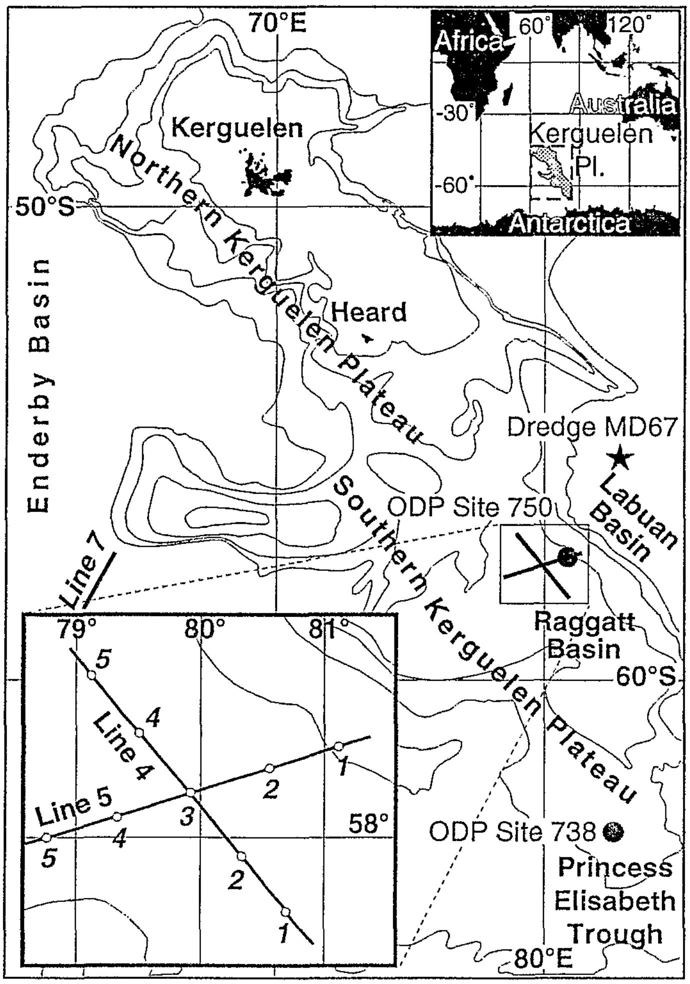

Figure 1. Bathymetric map of Kerguelen Plateau showing refraction lines 4, 5 (Raggatt basin), and 7 (Enderby basin). Upper inset shows location of Kerguelen Plateau in Indian Ocean. On main map circles mark location of Ocean Drilling Program (ODP) Sites 738 and 750; star indicates where continental samples were dredged in Labuan basin. Lower inset shows detailed OBS positions for lines 4 and 5 (circles).

varies from 3.6 to 6.5 km; velocities range from 4.8–5.2 km/s at the top of the layer to 5.8–6.3 km/s at the bottom, and the average vertical velocity gradient is 0.2/s. The transition between layers BB and LC is at an average depth of 9 km.

Layer LC can be parameterized with no lateral variation of velocity. This allows the vertical velocity gradient to be computed by inverting the Plc traveltimes. Along lines 4 and 5, velocities at the top of layer LC are 6.64 and 6.55 km/s, and vertical gradients are 0.022 and 0.039/s, respectively (root mean squares are 0.035 and 0.054 s and χ^2 are 0.5 and 1.18, respectively). Higher values of the vertical gradient led to a discrepancy between the computed and observed traveltimes for ranges >80 km.

Along line 4 the proposed layer RZ was initially modeled as a homogeneous layer, to estimate its mean properties. The depth of the LC-RZ interface was computed using traveltimes of the reflection from the top of the RZ layer (Pr1) (Fig. 2B). The mean velocity of the RZ layer, the Moho depth, and the upper mantle velocity were computed simultaneously using the PmP and the Pn traveltimes. Layer LC is 14 km thick and has a velocity of 6.9 km/s at the maximum depth of 19.5 km. Underneath, the layer RZ is a low-velocity zone with a mean velocity of 6.7 km/s. Such a low velocity is required to match the delay between the postcritical traveltimes of the PmP and the traveltimes of the Plc (Fig. 2B).

Because Pr reflections in layer RZ are only observed at OBS3 along line 5, the lower crust is modeled as a single layer, 17 km thick, having velocities ranging from 6.6 km/s at 9 km depth to 7.1 km/s at 24 km depth.

The Moho depth is 23–26 km. Apparent velocities in the upper mantle are 8.6 km/s and 7.9 km/s along lines 4 and 5, respectively. These variations could be partly related to a dipping Moho because no Pn was observed on reversed record sections.

The high data density and the good ray-path coverage of the structure during the inversion allow accurate determination of velocities and thicknesses in the whole crust. We show, using the postcritical traveltimes of the PmP, that the presence of a high-velocity layer ($Vp > 7.2$ km/s) at the base of the crust is precluded by our data.

NATURE OF THE CRUST BENEATH THE RAGGATT BASIN

Comparison with Mean Oceanic Crustal Structure

The thickness of the igneous crust reaches 22 km below the Raggatt basin, similar to that of the northern Kerguelen Plateau (21

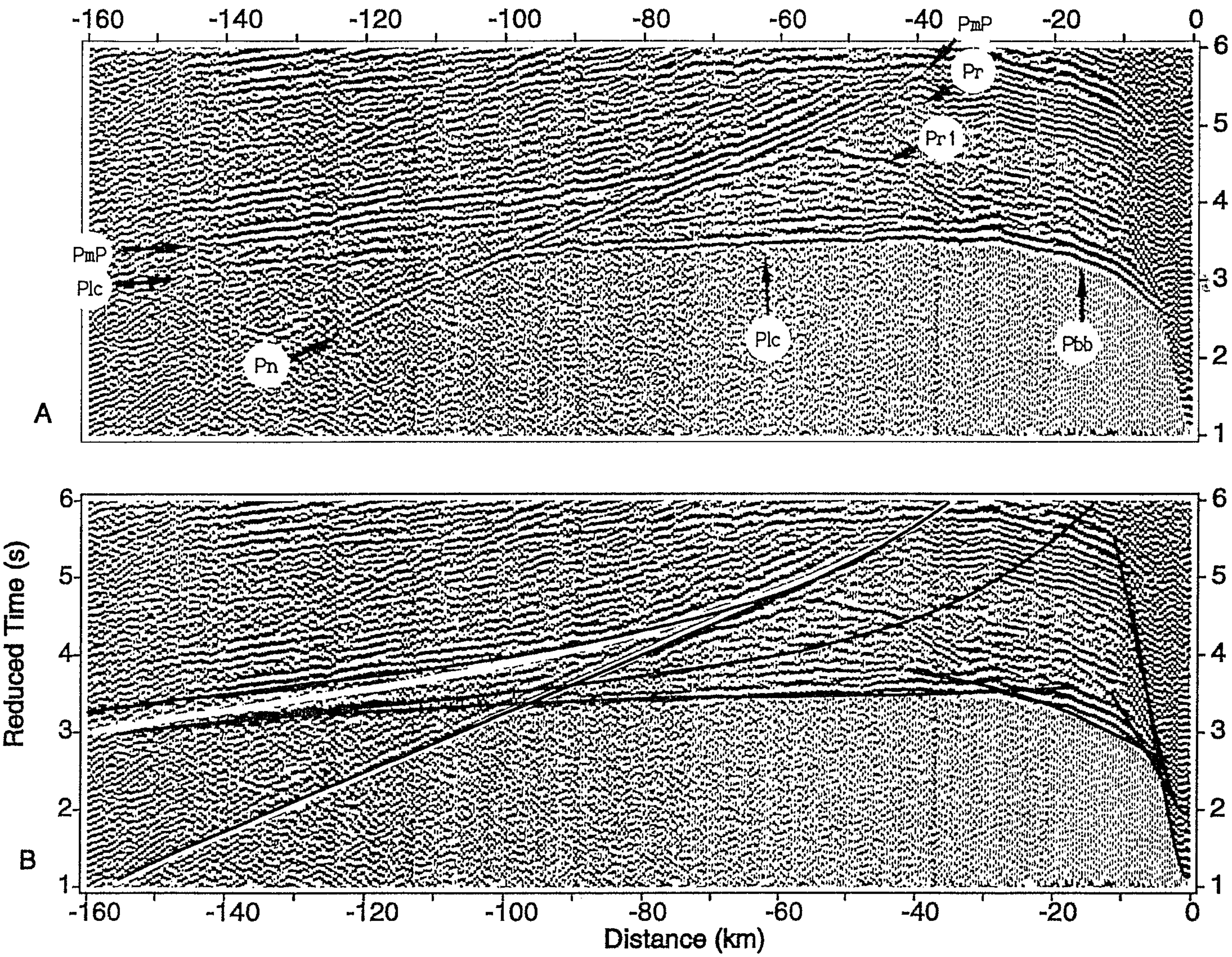

Figure 2. A: OBS5 record section for line 4, reduced to velocity of 6.5 km/s. Data have been bandpass filtered (5–15 Hz) and f-k filtered beyond 110 km to remove water-wave multiples. See text for description of prominent phases (PmP, Pn, etc.). B: Same section as A with superimposed traveltime curves (black) for final model. White curve shows PmP traveltimes computed for model without low-velocity zone at base of crust. Note delay between white curve and postcritical traveltimes of observed PmP.

km) (Charvis et al., 1993) and consistent with the average thickness of oceanic crust over mantle plumes (20 ± 1 km) (White et al., 1992).

In the southern Kerguelen Plateau, velocities observed in layer BB (4.8 to 6.3 km/s) are within the range of those observed in oceanic layer 2 (2.5 to 6.6 km/s) (White et al., 1992). The boundary between layers BB and LC is underlain by an increase of velocity from 5.8–6.3 to 6.6 km/s and by a major decrease of the vertical velocity gradient from ~0.2 to ~0.03/s. This is consistent with most oceanic crustal models where the boundary between layers 2 and 3, marked by an abrupt drop of the velocity gradient, corresponds to seismic velocities of 6.5–6.6 km/s (White et al., 1992; Mutter and Mutter, 1993).

The mean thickness is 5.0 km for layer BB and 16.2 km for layer LC. The comparison with the mean thickness for normal oceanic crust (2.11 ±0.55 km and 4.97 ±0.90 km, respectively, for layers 2 and 3) (White et al., 1992) yields thickening factors of 2.5 for the upper crust and 3.3 for the lower crust. This is consistent with Mutter and Mutter's (1993) analysis showing that thickening of layer 3 dominates crustal thickening.

Seismic velocities in oceanic layer 2 vary widely in oceanic crust and thus cannot indicate crustal type. The average seismic velocity in layer 3 increases as crustal thickness increases (Mutter and Mutter, 1993), which agrees with the observation that oceanic plateaus and ridges are characterized by high seismic velocities (7.0–7.6 km/s) at the base of the lower crust (Coffin and Eldholm, 1994). Using a model of decompressional melting, White and McKenzie (1989) estimated the thermal anomaly in the mantle needed to generate a 20-km-thick magmatic crust to be 150 °C. An increase in potential temperature during partial melting produces an increase in the percentage of MgO in the melt and an increase of the seismic velocities at a given depth in the derived igneous rocks (from ~6.9 to ~7.2 km/s at 10 km depth for 200 °C).

Velocities in the lower crust of the Raggatt basin (between 6.6 and 7.1 km/s) are within the range of velocities reported in a 7-km-thick standard oceanic crust (White et al., 1992; Mutter and Mutter, 1993). However, according to our derived crustal thickness, the average velocity in the lower crust (6.875 km/s) is not consistent with the model of a thickened oceanic crust. For a 14-km-thick standard layer 3, Mutter and Mutter's (1993) statistical analysis indicates an average velocity of 7.3 km/s in layer 3. Velocities in the lower crust of the southern Kerguelen Plateau are even lower than the velocities in the 12-km-thick oceanic crust of the Enderby basin (Fig. 3) located west of the Kerguelen Plateau (Operto et al., 1994). The deep structure beneath the southern Kerguelen Plateau also differs significantly from that determined in the northern Kerguelen Plateau, which exhibits a classical crustal structure for an oceanic plateau with high seismic velocities (6.6–7.4 km/s) in the lower crust (Charvis et al., 1993). Furthermore, the low-velocity reflective layer of the central Raggatt basin is a very unusual feature in oceanic crust. In a few places, low-velocity zones are locally indicated at the base of a normal-thickness crust (e.g., in the western North Atlantic; Mithal and Mutter, 1989).

Comparison with Deep Structure of a Volcanic Continental Margin

The emplacement of the southern Kerguelen Plateau occurred during the early opening between India and Australia-Antarctica at ~110 Ma (Royer and Coffin, 1992). Several volcanic provinces, interpreted as related to the Kerguelen hotspot, developed near the continental margins: the Bunbury basalts in southwest Australia at ~130 Ma, the Rajmahal Traps in northeastern India at ~117 Ma, and the Prince Charles Mountains in Antarctica at ~110 Ma (Storey et al., 1992). The entire volcanic zone attributed to the Kerguelen hotspot has a size (a few thousand kilometres in diameter) similar to that of the North Atlantic Tertiary volcanic province, related to the Iceland hotspot (White and McKenzie, 1989). Moreover, the upper crust of the southern Kerguelen Plateau is composed of a basaltic layer including dipping reflectors that closely resemble those along volcanic passive margins (Schaming and Rotstein, 1990).

The Hatton Ridge margin, located in the northern Atlantic between Ireland and the Iceland Basin (White and McKenzie, 1989), consists of a rifted continental basin (the Rockall basin), a continental topographic high (the Hatton Ridge), and a volcanic margin composed of stretched continental crust overlain by basalt flows with dipping reflectors and underplated with igneous material with seismic velocities of 7.3 km/s (Fowler et al., 1989). Northwestward, the adjacent oceanic crust is thickened, but it thins abruptly toward the Iceland Basin. The deep seismic structure of the Raggatt basin is similar to that of the Rockall basin, which is underlain by stretched continental crust (Fig. 4). In both cases velocities in the lower crust range from 6.6 to 7.1 km/s at depths of 9 to 24 km.

CONCLUSIONS

The Raggatt basin crustal structure exhibits some characteristics of a thickened oceanic crust (thickness ratios, velocity gradients, velocity in the upper crust). Nevertheless, the low seismic velocity in the lower crust is not consistent with such models.

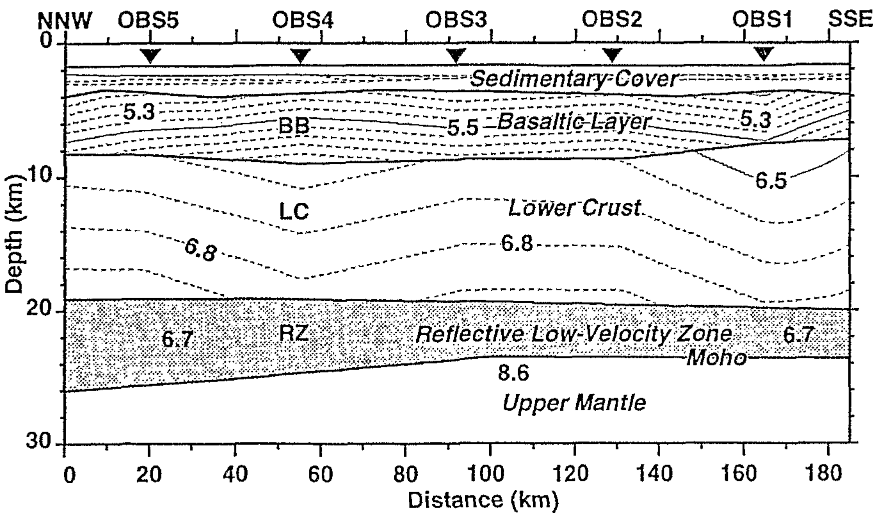

Figure 3. Final model across southern Kerguelen Plateau for line 4 with isovelocity lines at 0.1 km/s intervals. Heavy lines indicate interfaces between main units. BB is basaltic basement; LC is lower crust; RZ is reflective zone.

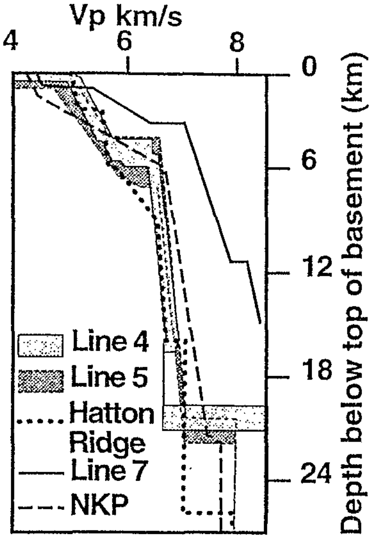

Figure 4. Comparison of velocity-depth functions of southern Kerguelen Plateau (this study) with northern Kerguelen Plateau (NKP), Hatton Ridge (Fowler et al., 1989), and Enderby basin (line 7).

The low-velocity reflective zone (layer RZ) can be compared with the reflective lower crust commonly observed beneath stretched continental areas, including volcanic passive margins. It probably consists of interlayered higher and lower velocity layers related to mafic intrusions during the emplacement of the basaltic basement and/or ductile shearing associated with extension (Holbrook et al., 1991). The lack of Pr reflections along the west-trending line 5 can be interpreted as a large-scale anisotropy, suggesting that reflections from layer RZ are dominated by shear zones.

The geochemical signatures of the southern Kerguelen Plateau basalts suggest that the magmatic source was contaminated by continental lithosphere (Storey et al., 1992). Furthermore, samples from Site 738 (Fig. 1) indicate that the southern end of the plateau may be underlain by continental crust (Alibert, 1991). Samples of granitic and metamorphic rocks were dredged on the top of the southern Kerguelen Plateau (Ramsay et al., 1986) and in the Labuan basin, northeast of the Raggatt basin (Fig. 1) (Montigny et al., 1993). In the Labuan basin, 70% of the 1.5 t of rocks recovered (only one dredge was acquired at this site) are continental; the rest are basalt and sediment (Montigny et al., 1993). These continental rocks could be interpreted as ice-rafted material from the Antarctic continent (Montigny et al., 1993) or as samples from the southern Kerguelen Plateau continental crust (Ramsay et al., 1986). The large percentage of continental material dredged in the Labuan basin (Montigny et al., 1993) argues in favor of continental crust in this area.

On the basis of these geochemical and geological data and our seismic data, we argue (but cannot prove) that the southern Kerguelen Plateau may be a fragment of a volcanic passive margin that was isolated during the nascent breakup of Gondwana. It remains unclear how and when this continental fragment was detached and whether this process was related to Kerguelen plume activity.

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