

38. TECTONIC CONSTRAINTS ON THE HOT-SPOT FORMATION OF NINETYEAST RIDGE¹

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ABSTRACT

This paper examines the constraints on the tectonic setting of Ninetyeast Ridge, based on a compilation of bathymetric and magnetic data from the basins surrounding Ninetyeast Ridge in the Indian Ocean that includes the magnetic profiles collected under way during ODP Leg 121. Magnetic data in the Central Indian Basin demonstrate that the spreading center immediately west of Ninetyeast Ridge jumped to the south by a total amount of 11° between 68 and 46 Ma, implying that parts of the mirror image of Ninetyeast Ridge on the Antarctic plate were transferred onto the Indian plate. The obliquity of Ninetyeast Ridge relative to the fracture zone pattern and the occurrence of an Eocene extinct spreading axis in the Wharton Basin suggest that the northern part of Ninetyeast Ridge was emplaced by intraplate volcanism on the Indian plate, whereas the middle and southern parts of the ridge were emplaced along transform plate boundaries.

The northward drift of the Indian plate over a single hot spot is the most plausible origin for Ninetyeast Ridge. Based on a recent kinematic model for the relative motions of the Indian, Antarctic, and Australian plates, we present a simple model that reconciles most of the available observations for Ninetyeast Ridge: paleomagnetism, distribution of basement ages, geochemistry, and geometry. In addition, the model predicts a slow westward migration of the Kerguelen/Ninetyeast hot spot with respect to the Antarctic and Australian plates between the Late Cretaceous and early Oligocene (84 to 36 Ma). Allowing the hot spot to move slowly permits an excellent match to both the position and age of the volcanism along Ninetyeast Ridge and also provides a model for excess topography on the Kerguelen Plateau. Finally, comparisons of published hot-spot reference frames suggest that the Kerguelen/Ninetyeast hot spot also migrated with respect to the Atlantic and western Indian Ocean hot spots.

INTRODUCTION

Ninetyeast Ridge is one of the major submarine ridges in the Indian Ocean. This remarkably linear and nearly meridional ridge extends over more than 4000 km, from 5°N to 31°S, varies in width from 100 to 200 km, and is elevated about 2 km above the surrounding basins, the Central Indian Basin to the west and the Wharton Basin to the east (Fig. 1). Another 1000 km of the Ninetyeast Ridge is covered by the Bengal Fan north of 5°N. Ninetyeast Ridge is joined at its southern end to Broken Ridge, which is oriented N90°E. Broken Ridge and the Kerguelen Plateau are a conjugate pair of tectonic features that were separated by Eocene rifting and subsequent seafloor spreading along the Southeast Indian Ridge.

Various models have been proposed for the formation of Ninetyeast Ridge. This feature has been viewed as an uplifted fragment of oceanic crust (Francis and Raitt, 1967; Laughton et al., 1970) or as the result of convergence and overthrusting of the two adjacent basins (Le Pichon and Heirtzler, 1968) linked to a spreading reorganization of the Southeast Indian Ridge in the Eocene (McKenzie and Sclater, 1971). The small-amplitude free air gravity anomaly over the ridge (<100 mgal; Le Pichon and Talwani, 1969) implies a locally compensated structure that was subsequently faulted (Bowin, 1973). Ninetyeast Ridge has also been interpreted as a paleospreading center (Veevers et al., 1971) and as a fracture zone related to the northward drift of India (McKenzie and Sclater, 1971). Following Legs 22 and 26 of the Deep Sea

Drilling Project (DSDP), which sampled along the length of the ridge (von der Borch, Sclater, et al., 1974; Davies, Luyendyk, et al., 1974), there is now a consensus that Ninetyeast Ridge resulted from excess volcanism on the edge of the Indian plate. However, a variety of different sources has been hypothesized. For some authors, the excess volcanism originated from a fixed hot spot that progressively built Ninetyeast Ridge on the Indian plate as it drifted northward (Morgan, 1972, 1981; Peirce, 1978; Duncan, 1978, 1981; Curray et al., 1982). A two-hot-spot origin (Luyendyk and Rennie, 1977) and a leaky transform fault-spreading ridge junction (Sclater and Fisher, 1974; Sclater et al., 1974) have also been invoked, as well as a combination of the two processes (Luyendyk and Davies, 1974; Johnson et al., 1976).

The tectonic objectives of Ocean Drilling Program (ODP) Leg 121 focused on improving our understanding of the origin and tectonic history of Ninetyeast and Broken ridges. Three sites (756, 757, and 758) were drilled on top of Ninetyeast Ridge at different latitudes (Fig. 1) to collect additional geochemical and petrological evidence about the origin of the ridge and its relationship with Broken Ridge and the Kerguelen Plateau. Determination of isotopic ages and paleomagnetic inclinations from the sedimentary and basement rocks recovered at these sites further constrains the northward motion of India and the tectonic setting of Ninetyeast Ridge and the surrounding basins. Interpretation of these data and other relevant older data indicates that the ridge is the trace of the Kerguelen/Ninetyeast hot spot (Duncan, this volume; Klootwijk et al., this volume). The basement paleolatitudes for Site 756 are anomalously low (about 45°S vs. the expected 50°S), however, and this may be related to the complex history of plate boundaries in this portion of Ninetyeast Ridge (see the following discussion).

This paper presents a new compilation of magnetic and bathymetric data available in the Central Indian Basin and Wharton Basin, including the magnetic profiles collected under way during ODP Leg 121. We examine the tectonic, paleomagnetic, and age constraints in favor of a single hot-spot origin of Ninetyeast Ridge. Based on Royer and Sandwell's (1989) kinematic model for the Indian, Antarctic, and Australian plates that in-

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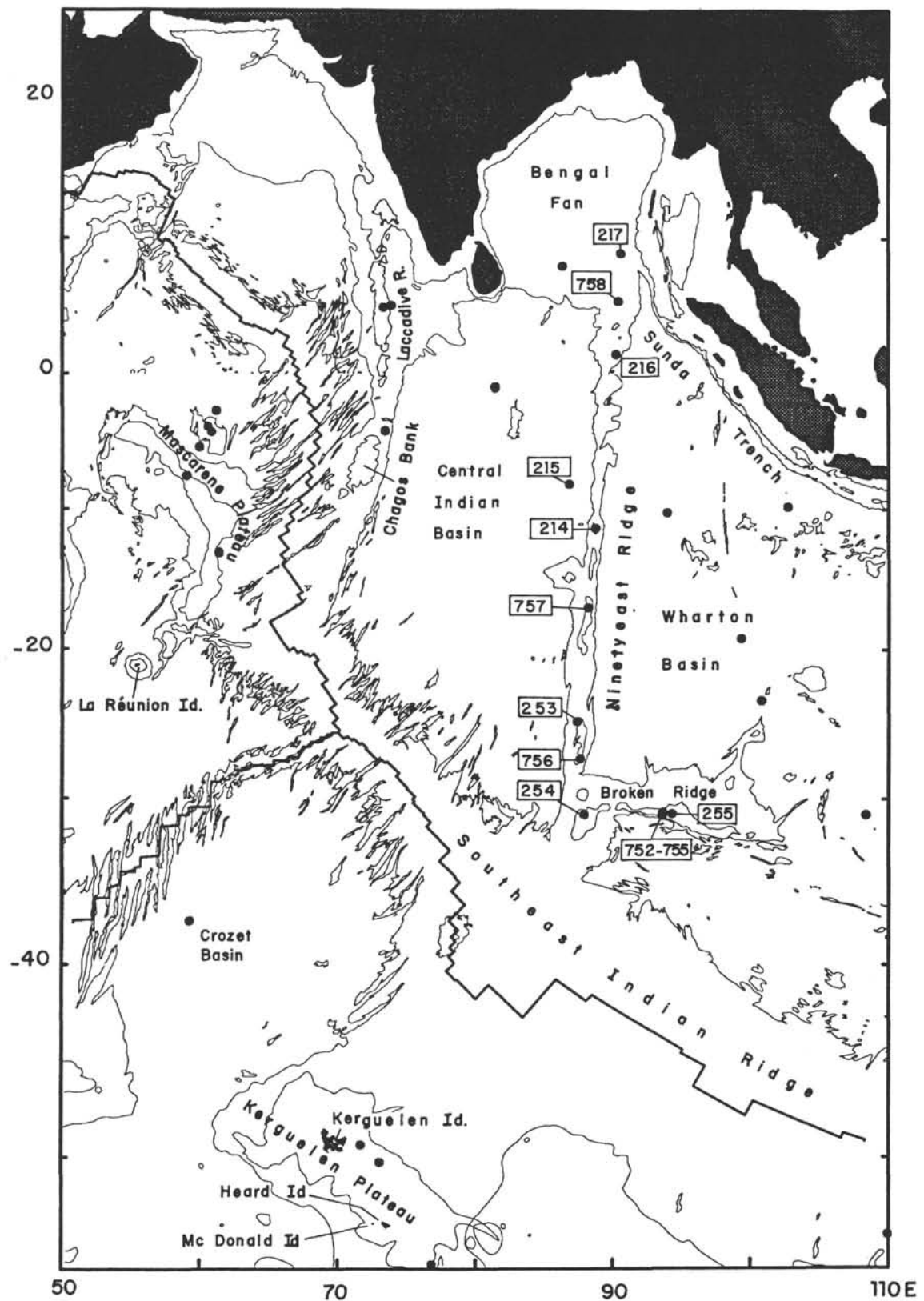


Figure 1. Bathymetric chart of the Indian Ocean (2000- and 4000-m isobaths) after Fisher et al. (1982) and Laughton (1975); after Schlich et al. (1987) for the Kerguelen Plateau. DSDP and ODP drill sites are shown by dots.

cludes new interpretations of the magnetic anomaly pattern in the Wharton and Australian-Antarctic basins, a single hot-spot model is developed. Finally, we compare this model with absolute reference frames based on the Atlantic and western Indian Ocean hot spots.

TECTONIC CHART OF THE BASINS SURROUNDING NINETYEAST RIDGE

Central Indian Basin

West of Ninetyeast Ridge, the Central Indian Basin is dominated by east-west magnetic anomalies offset by north-trending fracture zones (Fig. 2). The age of the Central Indian Basin decreases from north to south, from Late Cretaceous (Chron 34) to the present day. The strike of the magnetic lineations shifts abruptly from N90°E to N135°E within the middle Eocene (Chron 20–18) (McKenzie and Sclater, 1971; Sclater and Fisher, 1974; Sclater et al., 1976; Patriat, 1987; Royer and Schlich, 1988). A major left-lateral offset of about 9° in the Late Cretaceous and Paleocene magnetic anomaly pattern is observed at the 85°E Fracture Zone (Sclater and Fisher, 1974). This fracture zone matches in the Late Cretaceous and Paleocene (Royer and Sandwell, 1989) with the major fracture zone observed southwest of the Kerguelen Plateau on the satellite altimeter data (e.g., Haxby, 1987; Sandwell and McAdoo, 1988), which will be referred to as the Kerguelen Fracture Zone.

The numerous magnetic profiles that have been collected west of the 85°E Fracture Zone since the early interpretations of McKenzie and Sclater (1971) and Sclater and Fisher (1974) help in refining the magnetic anomaly and fracture zone pattern (Fig. 2). However, the crustal ages immediately west of Ninetyeast Ridge, between 85°E and 90°E, are still poorly known. Between 1°N and 3°S, Peirce (1978, p. 300, fig. 8) identified anomalies 30 and 31 (Fig. 2) and, tentatively, anomalies 32 and 29 on either side. We propose on Figures 3A and 3B an alternate interpretation with a small ridge jump to the south occurring just after Chron 30. As observed by Sclater and Fisher (1974) and Peirce (1978), there is about 11° of extra crust between 85°E and 90°E. There, the distance from Chron 30 to Chron 20 is 11° larger than in the compartments west of the 85°E Fracture Zone (Fig. 2). Furthermore, a similar amount of crust is missing in the Crozet Basin, east of the Kerguelen Fracture Zone, between anomalies 34, 33, and 32 and anomaly 18 (Schlich, 1982; Patriat, 1987). This is evidence for the occurrence of several ridge jumps to the south. It seems likely that these ridge jumps were related to the proximity of the Southeast Indian Ridge axis to the volcanic plume, in accordance with Morgan's (1972) model.

A major ridge jump probably occurred at about Chron 26 (~60 Ma) from approximately the vicinity of DSDP Site 215 to Osborne Knoll at 14.5°S (Fig. 4), when the Southeast Indian Ridge spreading center immediately west of the 85°E Fracture Zone reached the latitude of the volcanic source (Royer and Sandwell, 1989). As illustrated in Figure 3, other ridge jumps occurred at earlier times. Considering the latitude of Chron 20 at 85°E (Fig. 2), smaller ridge jumps occurred continuously or discretely afterward. These successive ridge jumps progressively eradicated and reversed the large offset along the 85°E Fracture Zone. From left-lateral in the Paleocene, the offset is right-lateral in the Eocene (Fig. 2). The proximity of a spreading center to the volcanic source that generated Ninetyeast Ridge is attested to by the mid-oceanic ridge basalt (MORB) component found in the Ninetyeast Ridge basalts at Sites 756, 757, and 758 (Peirce, Weissel, et al., 1989; Frey et al., this volume; Saunders et al., this volume; Weis and Frey, this volume). Another consequence of these ridge jumps is that the ages along the Ninetyeast Ridge, which would be expected to follow the ages of the adjacent oceanic crust closely, may not decrease monotonically from north

to south because parts of the Antarctic plate were transferred onto the Indian plate. Based on the ages at the drilling sites, Duncan (1978) derived an average rate of 9.4 ± 0.3 cm/yr for the migration of the Indian plate over the volcanic source. The ages for the Leg 121 sites (Duncan, this volume) are consistent with this prediction if one accepts the petrological arguments in favor of late-stage volcanism at Site 756 (Frey et al., this volume), which are supported by an unexpectedly low paleolatitude (Klootwijk et al., this volume).

Wharton Basin

East of Ninetyeast Ridge, the Wharton Basin presents a pattern of east-west magnetic anomalies similar to that in the Central Indian Basin. Early analyses of magnetic and bathymetric data (Sclater and Fisher, 1974) showed that the age of the Wharton Basin decreases from south to north, from Chron 33 (Late Cretaceous) to the youngest magnetic anomaly, which is tentatively interpreted as anomaly 17 (late Eocene). Based on the interpretation of new tracks in the Wharton Basin, Liu et al. (1983) and Geller et al. (1983) identified a fossil spreading ridge that became extinct in the middle Eocene at about Chron 19. This fossil ridge extends in a succession of right-lateral offsets from Ninetyeast Ridge to the Sunda trench at the equator. Conjugates of the magnetic anomalies in the southern Wharton Basin can be identified north of the extinct ridge; the oldest magnetic anomaly observed in the northern Wharton Basin corresponds to Chron 31 (Fig. 2). The pattern of magnetic anomalies and fracture zones shown in Figure 2 results from a new compilation of magnetic and bathymetric data available in this area.

The underway magnetic profiles recorded by *JOIDES Resolution* during Leg 121 confirm this interpretation (Figs. 5 and 6). Profile 1, en route between Sites 756 and 757, is parallel to the Ninetyeast Fracture Zone and appears severely disturbed by the magnetic signature of the fracture zone at 88.5°E (Fig. 5). Profile 2, between Site 757 and Cocos-Keeling Island, can be interpreted only with the help of better oriented profiles in its vicinity, but clearly outlines the fracture zone pattern (Fig. 6). Despite its obliquity to the fracture zone pattern, profile 3 between Cocos-Keeling Island and Site 758 (Fig. 6) displays several recognizable Eocene magnetic anomalies both south of the Wharton Basin fossil ridge between 11°S and 3°S and north of the extinct axis between 3°S and 3°N.

The occurrence of symmetric sets of magnetic anomalies in the Wharton Basin indicates that the northern Wharton Basin was part of the Indian plate. These data provide additional constraints on the relative motion between the Indian and Australian plates (e.g., Royer and Sandwell, 1989). A second observation concerns the location and orientation of Ninetyeast Ridge relative to the adjacent fracture zones. Ninetyeast Ridge is slightly oblique relative to the fracture zone pattern, suggesting that the primary control of the location of Ninetyeast Ridge was not the location of the fracture zones. As illustrated in Figures 2 and 6, as well as in figure 2 of Liu et al. (1983), only the northern extremity of the fracture zone called the Ninetyeast Fracture Zone parallels the edge of Ninetyeast Ridge. To the south, a different fracture zone, at 88.5°E, bounds the eastern flank of the ridge. Royer and Sandwell's (1989) reconstructions show that this fracture zone kept growing as the spreading ridge in the Wharton Basin migrated northward, whereas west of Ninetyeast Ridge, ridge jumps kept the spreading center at an almost constant position.

The reinterpreted structure of the Wharton Basin may also explain the morphology of Ninetyeast Ridge, which comprises three distinct domains (Sclater and Fisher, 1974). North of 5°S, the ridge is wide and is formed by discontinuous blocks; south of 5°S to Osborne Knoll, the ridge becomes narrow, linear, and continuous; and south of Osborne Knoll, it becomes significantly



Figure 2. Tectonic chart of the Central Indian Basin and Wharton Basin. Shaded rectangles correspond to normal reversals recorded by the ocean floor; numbers refer to the magnetic chrons. Fossil ridges (extinct spreading-ridge segments) are labeled FR and represented by heavy lines. Heavy dashed lines outline the fracture zones (F.Z.'s); light dashed lines are isochrons (Chrons 5, 6, 13, and 18; after Royer and Sandwell, 1989).

wider and slightly less linear. According to our interpretation (Fig. 2), the northern domain corresponds to the portion of Ninetyeast Ridge that was generated in the middle of the Indian plate (oceanic crust on both sides belongs to the Indian plate); the narrow and continuous domain was emplaced at the boundary between the Antarctic and Australian plates (or at the boundary between a short-lived microplate and the Australian plate); and the southern portion was emplaced near the fracture zone separating the Indian and Australian plates. The fracture zone marking this boundary

may have acted as a thermal barrier, limiting the extrusion of the plume.

PALEOMAGNETIC AND AGE CONSTRAINTS ON THE FORMATION OF NINETYEAST RIDGE

Paleomagnetic measurements performed on samples from DSDP Sites 213 through 217 clearly established that Ninetyeast Ridge was attached to the Indian plate and that both had drifted rapidly northward since the Late Cretaceous (Peirce, 1978). The

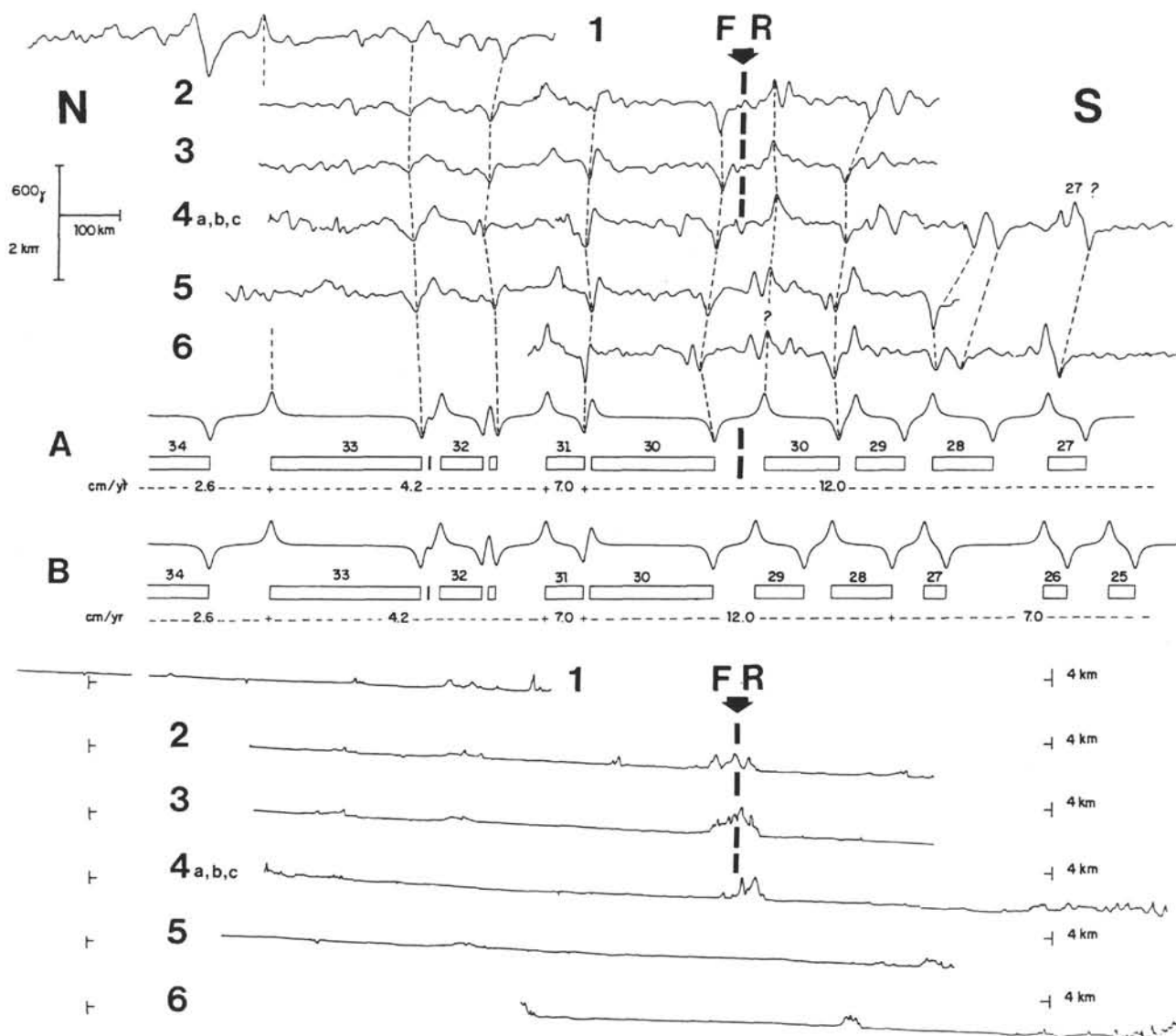
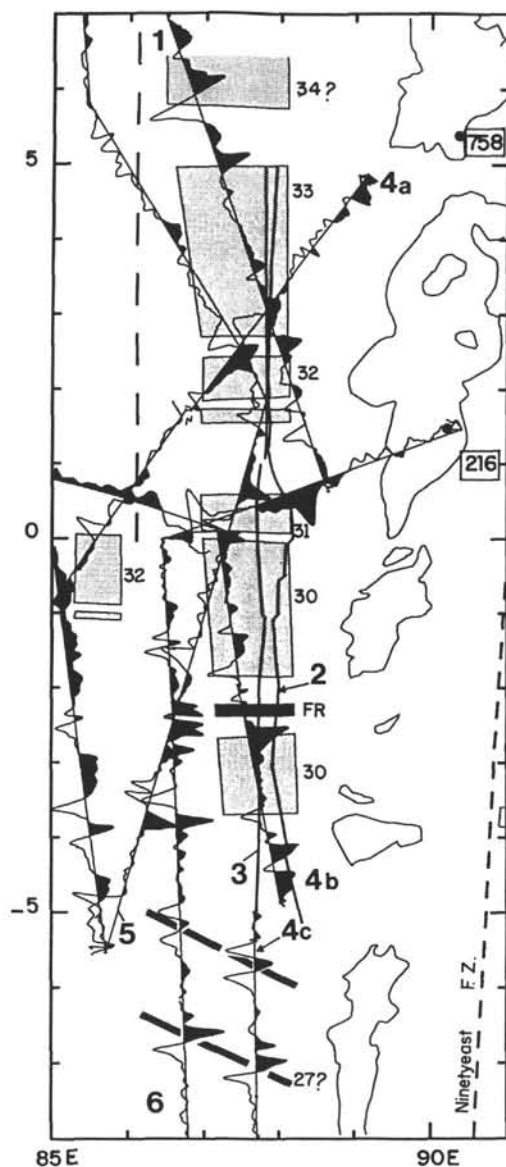


Figure 3. A. Detail of Figure 2 showing residual magnetic anomaly profiles over an extinct segment of a Paleocene spreading ridge (FR) west of Ninetyeast Ridge (outlined by the 3000-m isobath). Magnetic profiles are plotted at right angles from the ship tracks (positive values in black). The profiles interpreted in Figure 3B are labeled with bold numbers. B. Interpretation of magnetic anomaly profiles shown in Figure 3A: 1 = *Melville* 06; 2 = *Pioneer* 64; 3 = *Wilkes* 901; 4a = *Circe* 03; 4b = *Robert D. Conrad* 1708; 4c = *Robert D. Conrad* 1402; 5 = *Robert D. Conrad* 1709; 6 = *Glomar Challenger* 22. Magnetic profiles are projected onto N0°. Two synthetic models are shown: model A has a ridge jump of 163 km to the south at 66.4 Ma (between Chrons 30 and 29) and model B has a normal sequence of magnetic anomalies from Chrons 34 to 26. Chron numbers are indicated above the normal magnetic reversals from Kent and Gradstein's (1986) magnetic reversal time scale. Note the sharp increase in spreading rates at Chron 31. Model B is too slow between Chrons 30 and 29 to match the observed profiles. The fossil spreading ridge (FR) is clearly expressed in the seafloor topography. A ridge jump may have occurred at younger times on profiles 5 and 6.

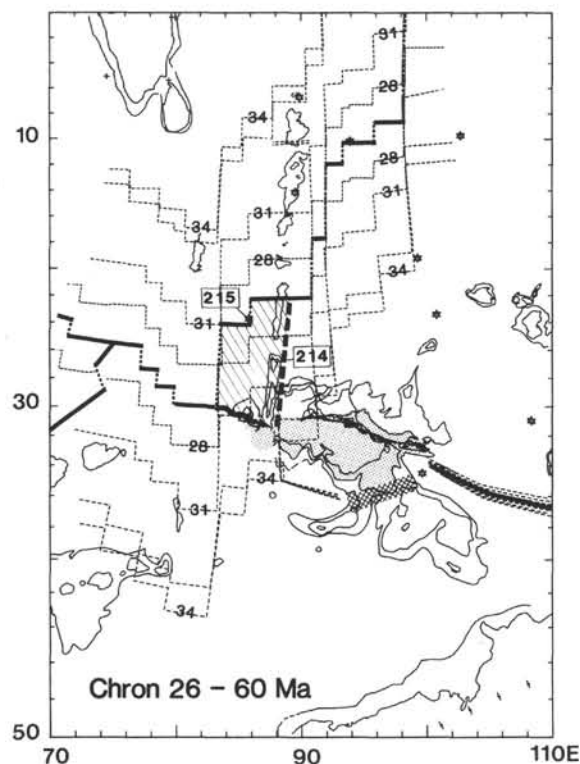


Figure 4. Reconstruction at 60 Ma (approximately Chron 26) from Royer and Sandwell (1989), suggesting that the Southeast Indian Ridge propagated through the 85°E Fracture Zone at the latitude of Osborne Knoll, when the ridge axis west of the fracture zone reached the latitude of the volcanic plume. The hatched area corresponds to the portion of the Antarctic plate that transferred onto the Indian plate. Dashed lines are isochrons and heavy lines represent the active spreading-ridge segments. Australia is fixed relative to its present-day coordinates.

basement paleolatitudes at these sites indicate that the volcanic source remained at a constant paleolatitude near 50°S, the present-day latitude of the Kerguelen hot spot.

Additional paleomagnetic results from the Leg 121 basalts confirm these results at Site 758. Site 757 has some paleolatitudes that agree with the latitude of Kerguelen and some that do not, apparently because of tectonic effects. Site 756, near the southern end of Ninetyeast Ridge, has paleolatitudes that are 7° to 9° too far north according to the hot-spot model (Klootwijk et al., this volume). However, the geochemistry of these basalts suggests that the volcanism that produced them was of a late-stage nature (Frey et al., this volume), and this interpretation is supported by the radiometric age determinations (Duncan, this volume), which suggest that the rocks are about 5 Ma younger than expected. The geochemistry, paleomagnetic data, and radiometric ages are all consistent with eruption of the basalts at Site 756 at about 5 Ma after the volcanic center passed over the hot spot.

Most of the ages from the DSDP sites are paleontological ages determined from basal sediments. Sites 253 and 254 are middle Eocene (44 Ma) and early Oligocene–late Eocene (38 Ma), respectively (Davies, Luyendyk, et al., 1974). Sites 214, 216, and 217 were given basal ages of middle Paleocene (59 Ma), late Maestrichtian (65 Ma), and Campanian (73 Ma), respectively (von der Borch, Schlater, et al., 1974). Isotopic $^{40}\text{Ar}/^{39}\text{Ar}$ determinations (Duncan, 1978) helped in refining these ages at Sites 254 (38 Ma), 214 (59 Ma), 215 (61 Ma), and 216 (65–81 Ma). Basal sediments at the three additional sites drilled during Leg 121 date the underlying basalts as older than 38 (Site 756), 58 (Site 757),

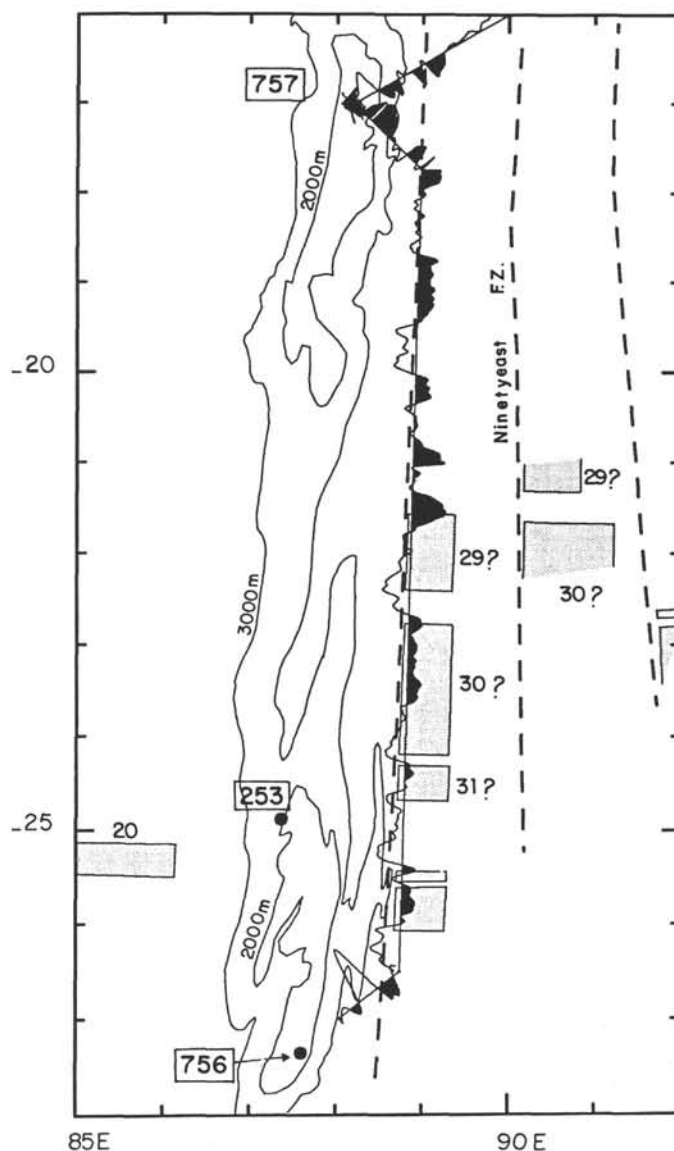


Figure 5. Detail of the tectonic chart from Figure 2 showing the interpretation of the residual magnetic anomaly profile recorded by *JOIDES Resolution* en route between Sites 756 and 757 (profile 1). The profile is severely disturbed by the proximity of the fracture zone bounding the eastern flank of Ninetyeast Ridge. Magnetic data are plotted at right angles to the ship track, positive values in black.

and 80 (Site 758) Ma. The corresponding radiometric ages are 43.2 ± 0.5 , 58 (poorly constrained), and 81.8 ± 2.6 Ma (Duncan, this volume). Although the ages along Ninetyeast Ridge decrease from 82 to 38 Ma from north to south as do the ages in the Central Indian Basin, the distribution of the samples is still too coarse to test whether or not the ages are decreasing monotonically.

HOT-SPOT MODEL

Based on their kinematic model for the Indian, Antarctic, and Australian plates, Royer and Sandwell (1989) showed that a single hot-spot model for Ninetyeast Ridge and Kerguelen/Broken Ridge fits all the paleomagnetic and dating constraints mentioned earlier (Fig. 7). This model assumes that the hot spot remained under the Kerguelen Plateau because the nearly constant paleolatitude found at the DSDP and ODP sites coincides with the present-day latitude of the plateau. We do not have a fully satis-

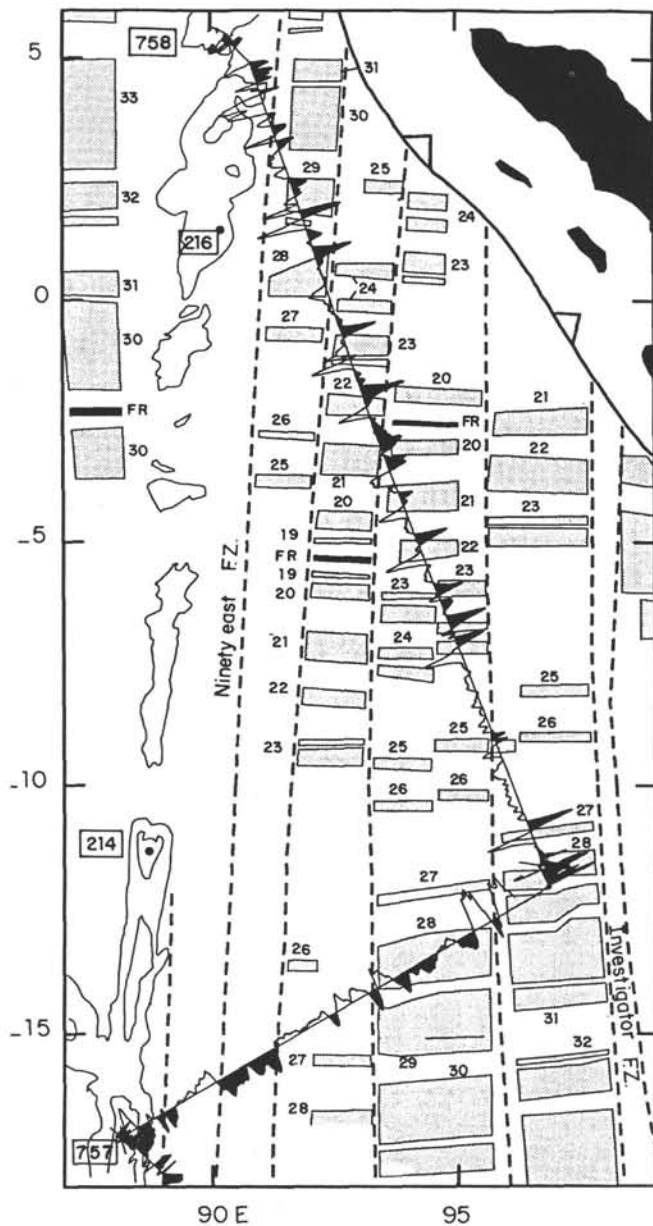


Figure 6. Detail of the tectonic chart from Figure 2 showing the interpretation of residual magnetic anomaly profiles recorded by *JOIDES Resolution* en route between Sites 757 and 758 (profiles 2 and 3). Magnetic data are plotted at right angles to the ship tracks, positive values in black.

factory explanation for the anomalous paleolatitude at Site 757. It can be partially explained by the possibility that the spreading center migrated well north of the hot-spot locus, but this effect should have been more dramatic at Site 214 than at Site 757. One can also hypothesize various local tectonic and/or thermal effects that may have affected the site, but these are unsatisfying ad hoc arguments to explain data that do not seem to fit. We believe that these anomalous results are an indication of a second-order complexity in the development of this portion of Ninetyeast Ridge which we do not understand.

This model also assumes that the ridge axis immediately west of Ninetyeast Ridge remained in the vicinity of the hot-spot location from the Late Cretaceous to the late Eocene. The latitudinal location of the hot spot is constrained by the ages at the drilled sites. Its longitudinal location is determined on the as-

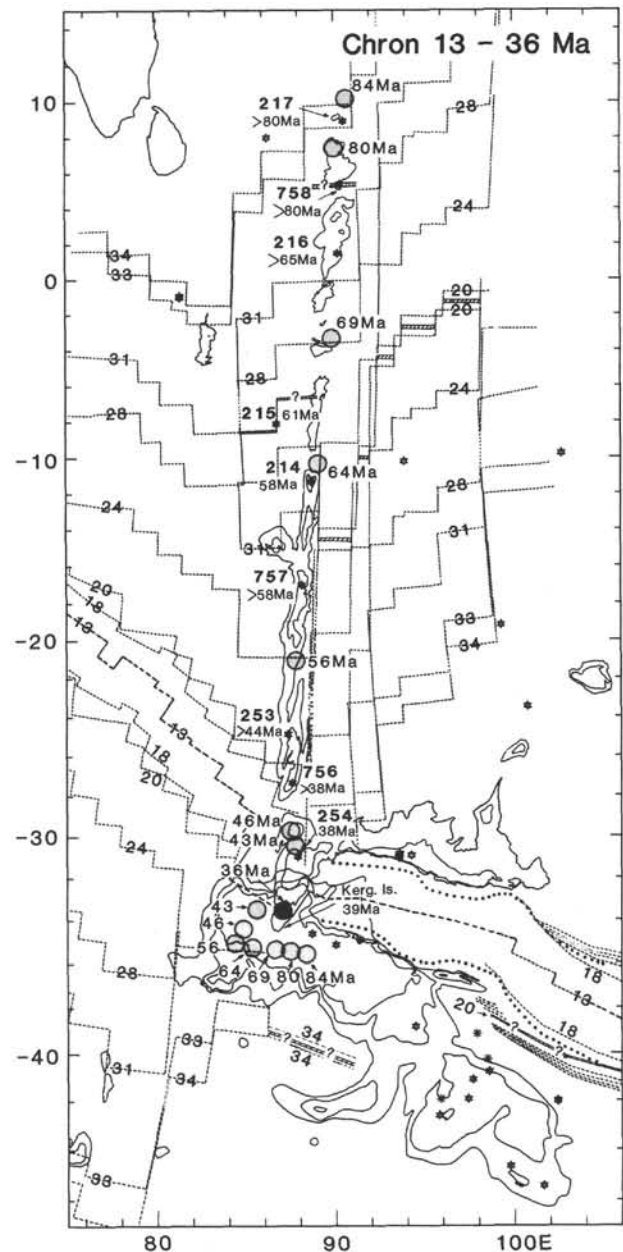


Figure 7. Reconstruction at 36 Ma (Chron 13) from Royer and Sandwell (1989) showing the location of hot spots (circles) from the Late Cretaceous to the early Oligocene, as suggested by the ages along Ninetyeast Ridge and the kinematic and geometric constraints (see text). Australia is fixed relative to its present-day coordinates. Note that the linearity of Ninetyeast Ridge requires the hot spot to migrate westward relative to the northern Kerguelen Plateau.

sumption that the hot spot was at the intersection of Ninetyeast Ridge and the Kerguelen Plateau. Because Ninetyeast Ridge is oblique relative to the flowlines, this simple geometric constraint requires a slow (1.4 cm/yr) westward migration of the Kerguelen/Ninetyeast hot spot relative to the Antarctic plate. The hot spot at Chrons 33 and 34 (80 and 84 Ma) is positioned relative to a sedimentary basin, due east of Kerguelen Island, estimated to be of Late Cretaceous age (Munschy and Schlich, 1987). Similar hot-spot models have been previously proposed (e.g., Duncan, 1978; Curray et al., 1982), but they do not make allowance for the occurrence of a middle Eocene fossil spreading ridge in the Wharton Basin, the initiation of spreading between Australia and

Antarctica in the Late Cretaceous (Cande and Mutter, 1982), and the fact that the Kerguelen Plateau and Broken Ridge cannot overlap prior to their breakup at 43 Ma.

We examine the compatibility of Royer and Sandwell's (1989) model with some of the recent hot-spot models from Duncan (1981), Morgan (1983), and Fleitout et al. (1989). These three hot-spot models describe the absolute motion of the African plate relative to the Atlantic and western Indian Ocean hot spots. To test these models, we link the African plate to the Indian, Antarctic, and Australian plates, using the relative motion models from Royer et al. (1988) and Royer and Chang (in press) (Africa/Antarctica) and Royer and Sandwell (1989) (Antarctica/India/Australia). Before applying these models to the Kerguelen/Ninetyeast hot spot, we examine the trail of the Réunion hot spot on the Indian and African plates as an independent check. This hot spot progressively built the Deccan Traps, Laccadive Ridge, Chagos Bank, Nazareth Bank (i.e., southern Mascarene Plateau), Mauritius Island, and La Réunion Island, where a volcano is still active. ODP Leg 115 sampled and dated the Réunion hot-spot track (Backman, Duncan, et al., 1988). Figures 8 through 10 compare the predicted hot-spot tracks with the observed trails on the Indian Ocean plates for each hot-spot model. The predicted trails originate from La Réunion Island for the Réunion hot spot and from two points on the Kerguelen Plateau for the Kerguelen/Ninetyeast hot spot. One of the latter points is located on McDonald Island, a present-day active volcano in the vicinity of Heard Island (Fig. 1); the other is located at the western extremity of a small spur of the Kerguelen Plateau, west of Kerguelen Island.

Réunion Hot Spot

In each model, the Mascarene Plateau and the Chagos-Laccadive Ridge lie in the predicted wake of the Réunion hot spot. Fleitout et al.'s (1989) model (Fig. 10) fits the volcanic ridges best, but predicts ages slightly too old, whereas Duncan's (1981) model is better in predicting the ages (Fig. 8). On the Mascarene Plateau, the predicted ages are 45 and 40 Ma, respectively, at Site 706, where the basement is older than 35 Ma as determined from the basal sediments (Backman, Duncan, et al., 1988). On the Chagos Bank and Laccadive Ridge, the agreement is satisfactory in both models. The oldest recovered sediments are 47 Ma old at Site 713 and 55 to 60 Ma old at Site 715 (Backman, Duncan, et al., 1988). The predicted ages are 46 and 56 Ma, respectively, in Duncan's model and 48 and 57 Ma in Fleitout et al.'s model. Radiometric determinations from the Deccan Traps suggest age limits of 65–69 Ma (Duncan and Pyle, 1988; Courtillot et al., 1988). The predicted location of the hot spot at 65 Ma is better centered on the Traps in Duncan's model than in that of Fleitout et al. Morgan's (1983) model gives similar ages to that of Duncan; however, the predicted trail falls farther off the Laccadive Ridge (Fig. 9). Our kinematic model neglects any relative motion across the East African Rift between the Somalian plate and the African plate. In Duncan's model, such motion would account for the slight offset between the predicted track and the Mascarene Plateau, which actually belongs to the Somalian plate. Conversely, Fleitout et al.'s model may then be considered somewhat in disagreement with the observed trail. These discrepancies are within the uncertainties both in the absolute motions and the relative motions.

Recent relative motions between the Indian and the Australian plates resulted in important intraplate deformation of the Central Indian Basin (Weissel et al., 1980; Cochran, Stowe, et al., 1989). These motions correspond to a clockwise rotation of the Indian plate relative to the Australian plate about a pole located at about 5°S, 78°E (Gordon et al., 1990; Royer and Chang, in press). Consequently, the shape of the Chagos-Laccadive Ridge has been modified, since the Laccadive Ridge (Indian plate) rotated clock-

wise relative to the Chagos Bank (Australian plate). Figures 8 through 10 display both the corrected (solid line) and uncorrected (dotted line) paths. The effect of this correction is to better center the hot spot on the Deccan Traps at 65 Ma, while the predicted track falls slightly off the Laccadive Ridge. Although the uncertainties on the India/Australian motions are known (Royer and Chang, in press), we still lack the uncertainties on the absolute motion of the African plate relative to the hot spots to test the significance of this result (has the Réunion hot spot moved relative to the Atlantic hot spot?). It is also not known whether the Laccadive Ridge has been used to constrain the absolute motions of the African plate in Fleitout et al.'s (1989) model. Except for these intraplate motions, we emphasize that our model for the Central Indian Ocean (India/Africa/Antarctica) is similar to that by Patriat and Ségoufin (1988) or Molnar et al. (1988).

Kerguelen/Ninetyeast Hot Spot

Regarding the evolution of the eastern Indian Ocean, our kinematic model is based on the assumption that the northern Kerguelen Plateau and Broken Ridge remained attached and essentially fixed relative to the Australian plate since the time of their formation (middle Cretaceous) until they broke apart in the middle Eocene (43 Ma, Chron 18) (Peirce, Weissel, et al., 1989; Schlich, Wise, et al., 1989; Munsch et al., in press). Accordingly, several hot-spot tracks are shown on Figures 8 through 10. One section corresponds to the trail left on the Antarctic plate from the present day back to 43 Ma. Another section corresponds to the trail left on the Australian plate from 43 to 84 Ma (this section is shown both on the northern Kerguelen Plateau and Broken Ridge, because the two features formed a single ridge at these times). The third section corresponds to the trail left on the Indian plate by the Kerguelen/Ninetyeast hot spot. A single hot-spot model not only requires the hot spot to progressively build Ninetyeast Ridge linearly, but also to produce excess volcanism on the Kerguelen Plateau and/or Broken Ridge as the mirror image of Ninetyeast Ridge. These requirements can be tested by comparing the two latter sections of the hot-spot tracks with the shape of the three ridges.

Back to the Late Cretaceous, each tested model is consistent with the idea of a single hot-spot origin for Ninetyeast Ridge and for parts of the Kerguelen Plateau and Broken Ridge. However, comparisons of the computed and observed hot-spot trails on the Indian, Antarctic, and Australian plates show that none of them is fully satisfactory. The age progressions along Ninetyeast Ridge are consistent with the drilling results. Except for the northern part of Ninetyeast Ridge, there is a mismatch between the hot-spot trail and Ninetyeast Ridge; this mismatch is smaller in Fleitout et al.'s (1989) model (Fig. 10) than in Duncan's (1981) (Fig. 8) and Morgan's (1983) models (Fig. 9). Uncertainties in the reconstructions may also partly account for these discrepancies. The mirror images of Ninetyeast Ridge on the Kerguelen Plateau and Broken Ridge are also plausible, except in Duncan's model, where most of the predicted tracks run outside both ridges (Fig. 8). These general observations raise two questions: Where is the present-day location of the Kerguelen/Ninetyeast hot spot? and Did the Kerguelen/Ninetyeast hot spot remain fixed with respect to the Atlantic and western Indian hot spots?

In order to follow Ninetyeast Ridge approximately on the Indian plate, the three models must assume that the Kerguelen/Ninetyeast hot spot is presently located at the westernmost extremity of the Kerguelen Plateau. No recent volcanic or seismic activity has yet been reported from this (still unsurveyed) submarine spur of the plateau. Only Duncan's (1981) model predicts that this volcanic spur is the youngest part of the hot-spot trail. If one assumes as in Luyendyk and Rennick's (1977) model or Duncan's (1978) original model that the Kerguelen/Ninetyeast hot spot is

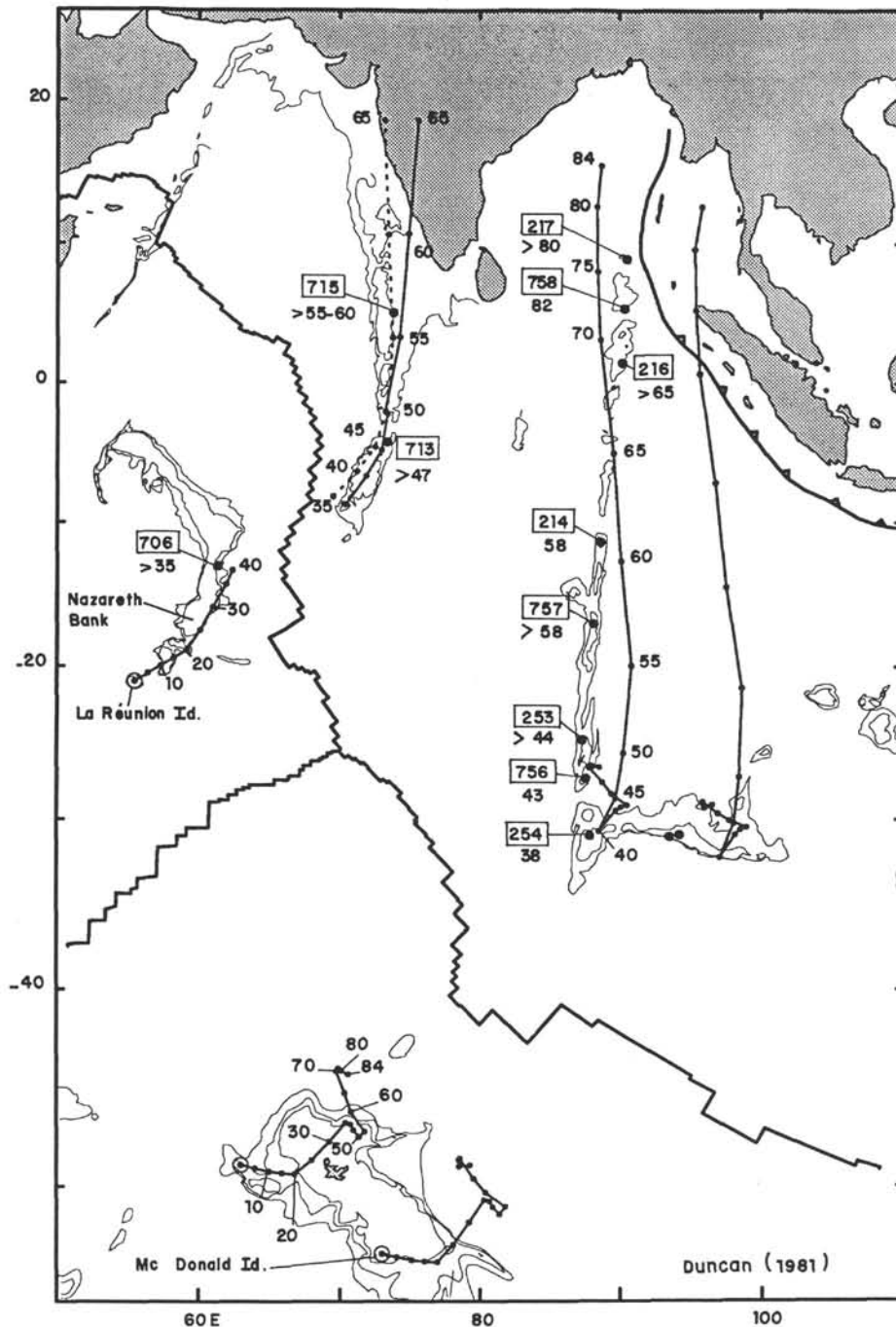


Figure 8. Synthetic hot-spot tracks derived from Duncan's (1981) model for the absolute motion of the African plate relative to the Atlantic and western Indian Ocean hot-spot frame (see text). Predicted track lines are calculated with a 5-Ma time step (small dots); ages in Ma. Presumed present-day locations for the hot spots are circled. DSDP and ODP sites are represented by large dots; age limits determined from the basal sediments or basalts are below the site labels. The Réunion hot-spot path (solid line) over the Laccadive Ridge (Fig. 1) takes into account relative motion between the Indian and Australian plates, whereas the path indicated by the dotted line is not corrected (see text).

beneath volcanically active Heard Island, then the logical implication is that the hot spot has migrated. In the three models we tested here, the track originating from volcanically active McDonald Island is consistently and definitely off Ninetyeast Ridge. One can also argue either that the volcanic activity in McDonald Island is simply evidence for a diffuse activity of the hot spot or that the

hot spot just recently migrated from the volcanic spur to McDonald Island.

From simple geometric considerations, we suggested earlier that the Kerguelen/Ninetyeast hot spot migrated westward relative to the Australian and Antarctic plates from Chrons 34 (84 Ma) to 24 (56 Ma) at a rate of 1.4 cm/yr (Table 1). We combined these

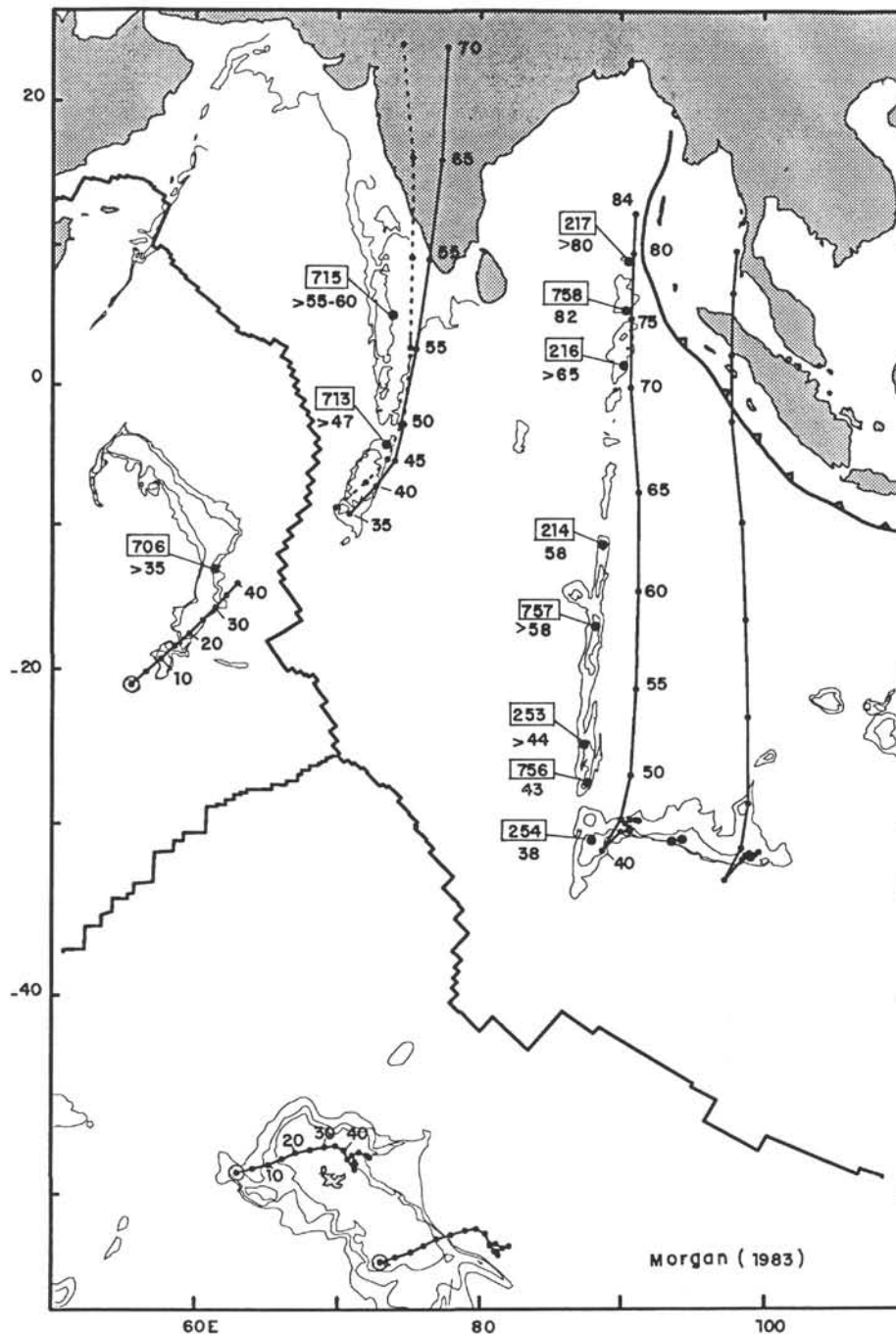


Figure 9. Model derived from Morgan's (1983) reference frame. The presentation is the same as for Figure 8.

relative motions with Fleitout et al.'s (1989) model for the absolute motion of the African plate in Figure 11. By assuming a slow migration of the Kerguelen/Ninetyeast hot spot and assuming that McDonald Island is the present-day location of the hot spot, we reach a better match of Ninetyeast Ridge with the hot-spot trace. The hot-spot path over the Kerguelen Plateau looks similar to that in Luyendyk and Rennick's (1977) model, although only one source of volcanism is invoked here. Such a model is still consistent with the paleomagnetic constraints (i.e., constant paleolatitude) because the hot-spot migration is mainly longitudinal. According to this model, most of the western Kerguelen Plateau would have been created between the Late Cretaceous and the Oligocene, and some trace of recent volcanism should be ob-

served between Kerguelen and Heard islands. Satellite altimeter data (Coffin et al., 1986; Haxby, 1987) clearly outline a chain of basement highs between the two islands, bordering the southwestern flank of the Kerguelen Plateau.

We cannot provide any definitive answer about the younger path of the hot spot and its present-day location. We note that the volcanic activity in Kerguelen Island spans from 1 to 39 Ma (e.g., Nougier et al., 1983; Giret and Lameyre, 1983). Figure 11 could have as well displayed a drift curve starting from Kerguelen Island or from the tip of the volcanic spur at 49°S, 6°E. Fleitout et al.'s (1989) model (Fig. 10) demonstrates that alternative models can be built with this latter point as the hot-spot location and, furthermore, without requiring any migration of the hot spot. Their

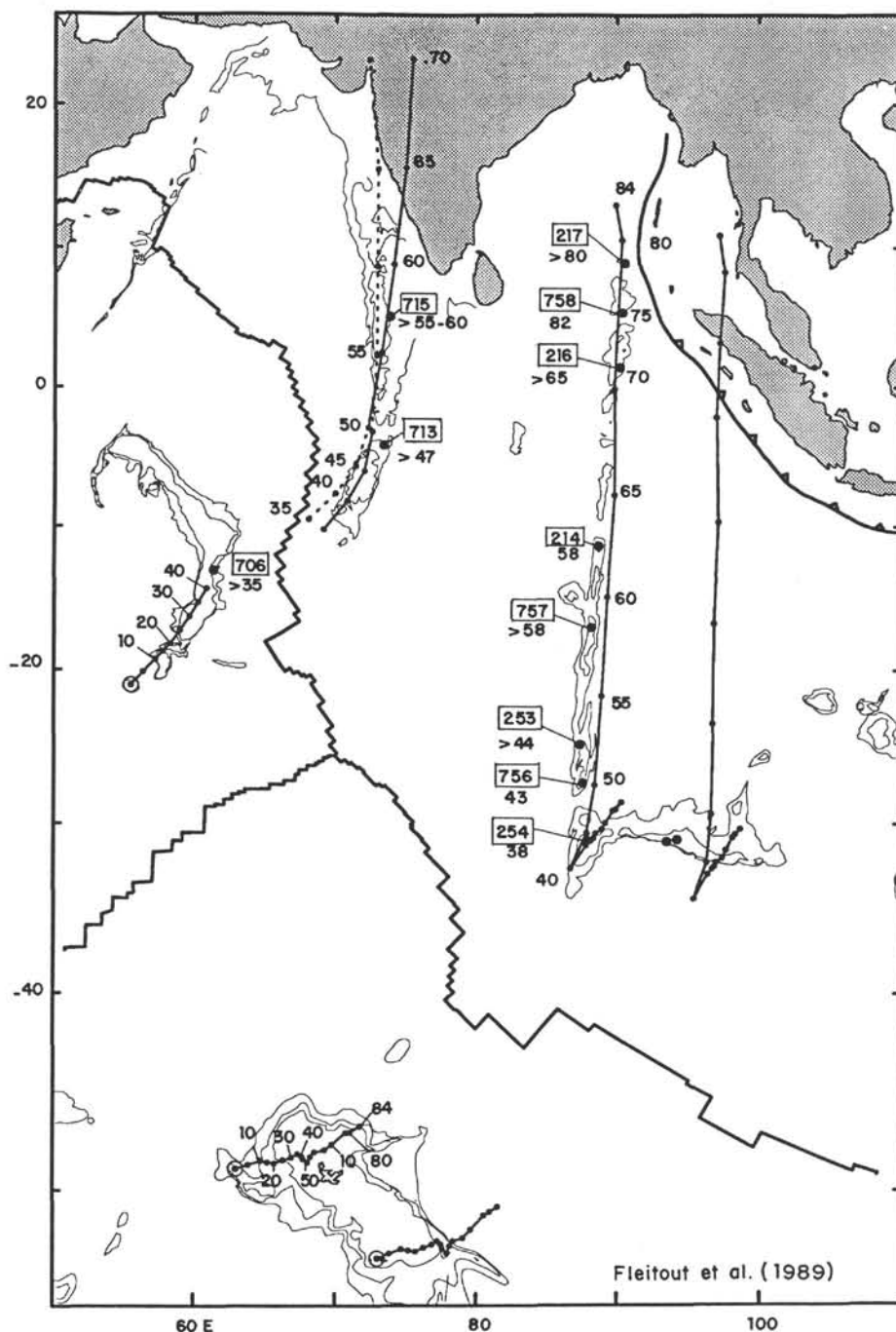


Figure 10. Model derived from Fleitout et al.'s (1989) reference frame. Little is known about how this model was derived. The presentation is the same as for Figure 8.

model nonetheless requires some modifications in order to improve the fit of the Kerguelen/Ninetyeast hot spot track with Ninetyeast Ridge, to adjust the youngest part of the path (0–20 Ma) to the topography of the volcanic spur, and to correct the oldest part (50–84 Ma), as it predicts either old volcanism overlying younger oceanic crust (30 to 43 Ma old, Royer and Sandwell, 1989; Munschy et al., in press) on the Kerguelen side or volcanism (70–84 Ma) where there is no topography on the Broken Ridge side. It may not be possible to meet all these requirements at once, while preserving the consistency with the Atlantic and western Indian Ocean hot spots. A detailed survey and sampling of the Kerguelen Plateau west of Kerguelen Island

is necessary to investigate further the question of the present-day location of the hot spot.

SUMMARY

A compilation of magnetic and bathymetric data in the Central Indian Basin and the Wharton Basin provides additional perspective on the tectonic setting of Ninetyeast Ridge. The northern part of Ninetyeast Ridge (north of 2.5°S) was emplaced as intraplate volcanism on the Indian plate; the middle portion (2.5°S to 15°S) formed at the edge of either the Antarctic plate or a short-lived platelet; and the southern part of the ridge (south of 15°S) erupted on the edge of the Indian plate. Magnetic data analysis as well as

Table 1. Motion of the Kerguelen/Ninetyeast hot spot.

Chron	Age (Ma)	Latitude (+°N)	Longitude (+°E)	Angle (°)
<i>Relative to the northern Kerguelen Plateau^b</i>				
13	35.5	12.1	146.5	5.33
18	42.7	17.1	138.9	6.17
20	46.2	22.6	129.5	6.06
24	56.1	26.1	122.6	6.02
28	64.3	25.0	124.8	5.24
31	68.5	22.1	130.4	4.31
33	80.2	19.5	135.0	3.72
34	84.0	15.7	141.2	3.10
<i>Relative to the Antarctic Plate^c</i>				
13	35.5	-12.1	-33.5	5.33
18	42.7	-17.1	-41.1	6.17
20	46.2	-22.6	-50.5	6.06
24	56.1	-17.1	-66.4	5.65
28	64.3	-1.4	-71.6	5.00
31	68.5	13.4	-73.1	4.42
33	80.2	30.3	-78.6	5.21
34	84.0	40.7	-84.4	5.59
<i>Relative to the African Plate^d</i>				
13	35.5	0.4	-40.5	10.46
18	42.7	-1.7	-42.3	12.79
20	46.2	-3.6	-45.6	13.25
24	56.1	-2.7	-48.9	14.95
28	64.3	-1.0	-48.9	15.77
31	68.5	3.7	-50.2	15.72
33	80.2	2.6	-49.1	19.73
34	84.0	6.8	-48.9	21.25
<i>Relative to the spin axis^e</i>				
13	35.5	-48.4	-41.0	6.91
18	42.7	-50.9	-44.5	8.52
20	46.2	-55.8	-52.5	9.01
24	56.1	-59.8	-62.2	9.54
28	64.3	-64.5	-64.3	9.39
31	68.5	-66.6	-71.8	8.15
33	80.2	-69.7	-92.0	9.01
34	84.0	-65.5	-92.1	7.40

^a Assuming a present-day location for the Kerguelen/Ninetyeast hot spot at 53°S, 73°E (~McDonald Island), as in Figure 11. Angles are positive counterclockwise. Ages after Kent and Gradstein's (1986) magnetic reversal time scale.

^b Derived from the hot-spot path shown in Figures 7 and 11.

^c Combination of the rotation relative to the northern Kerguelen Plateau with Royer and Sandwell's (1989) kinematic model (Antarctica/northern Kerguelen Plateau).

^d Combination of the rotation relative to the Antarctic plate with Royer et al.'s (1988) and Royer and Chang's (in press) kinematic models (Africa/Antarctica).

^e Combination of the rotation relative to the African plate with Fleitout et al.'s (1989) model (Africa/spin axis).

plate tectonic reconstructions suggest that several southward ridge jumps of the Southeast Indian Ridge occurred west of Ninetyeast Ridge, which tended to keep the spreading center in the vicinity of the plume. This is consistent with the MORB component found in the Ninetyeast Ridge basalts. Consequently, parts of the mirror-image ridge on the Antarctic plate have been trapped on the Indian plate and form portions of the present-day Ninetyeast Ridge. Nevertheless, the western Kerguelen Plateau remains pro parte the mirror image of Ninetyeast Ridge on the

Antarctic plate. Despite all the information available in the Central Indian Basin and Wharton Basin, still little is known about the age of the crust in the immediate vicinity of Ninetyeast Ridge.

A single hot-spot origin for Ninetyeast Ridge, Kerguelen Plateau, and Broken Ridge is consistent with a constant paleolatitude of formation and the age progression of the basalts recovered from Ninetyeast Ridge, as has already been shown (e.g., Peirce, 1978; Duncan, 1978). Furthermore, we have shown that this simple model is consistent with the kinematics of the surrounding plates based on the new interpretation of the magnetic anomaly pattern in the Wharton Basin (Liu et al., 1983; Geller et al., 1983) as well as in the Australian-Antarctic Basin (Cande and Mutter, 1982). Two hot spots (Luyendyk and Rennick, 1977) are no longer required to build the mirror image of Ninetyeast Ridge. We emphasize that a leaky transform-spreading center junction (Sclater and Fisher, 1974) would produce the same excess volcanism as the single hot-spot model, because this leaky junction remained in the vicinity of the plume responsible for the massive Kerguelen Plateau. However, intraplate volcanism must also be involved for the northern portion of the ridge.

Based on tectonic data, paleomagnetic results, and the basement ages of Ninetyeast Ridge, we suggest that the Kerguelen/Ninetyeast hot spot slowly migrated relative to the surrounding plates. We find by comparing different absolute hot-spot reference frames that the Kerguelen/Ninetyeast hot spot has also migrated with respect to the Atlantic and western Indian Ocean hot-spot frame. Because Ninetyeast Ridge formed between the Late Cretaceous and the early Oligocene, the migration of the Kerguelen/Ninetyeast hot spot can be inferred only from 36 (Chron 13) to 84 Ma (Chron 34).

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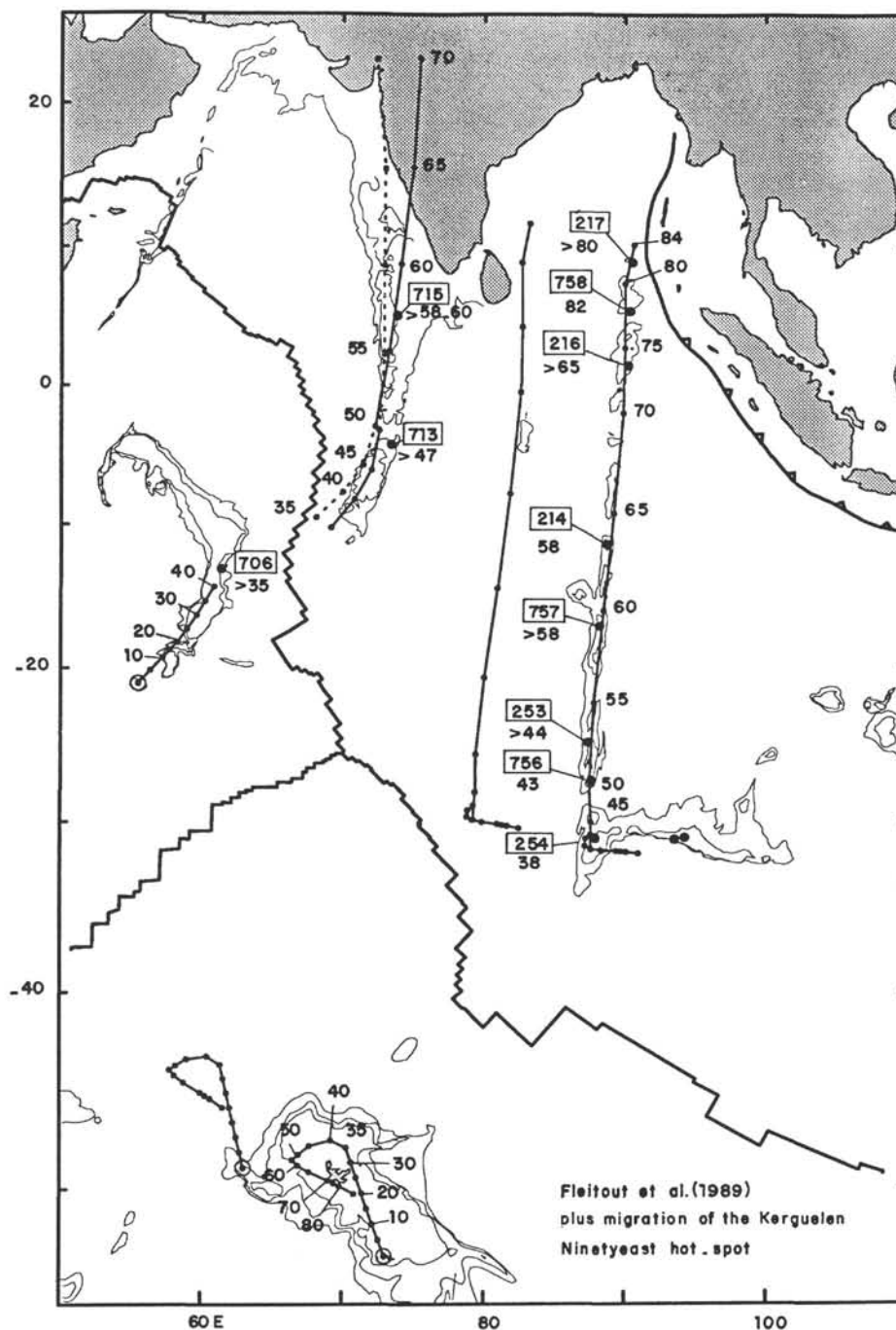


Figure 11. Migration of the Kerguelen/Ninetyeast hot spot with respect to the Atlantic and western Indian hot spots (derived from Fig. 7) shown on the plot of Fleitout et al.'s (1989) model (Fig. 10).