Paleocene on-spreading-axis hotspot volcanism along the Ninetyeast Ridge: An interaction between the Kerguelen hotspot and the Wharton spreading center

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Investigations of three plausible tectonic settings of the Kerguelen hotspot relative to the Wharton spreading center evoke the on-spreading-axis hotspot volcanism of Paleocene (60–54 Ma) age along the Ninetyeast Ridge. The hypothesis is consistent with magnetic lineations and abandoned spreading centers of the eastern Indian Ocean and seismic structure and radiometric dates of the Ninetyeast Ridge. Furthermore, it is supported by the occurrence of oceanic andesites at Deep Sea Drilling Project (DSDP) Site 214, isotopically heterogeneous basalts at Ocean Drilling Program (ODP) Site 757 of approximately the same age (59–58 Ma) at both sites. Intermix basalts generated by plume-mid-ocean ridge (MOR) interaction, exist between 11° and 17°S along the Ninetyeast Ridge. A comparison of age profile along the Ninetyeast Ridge between ODP Sites 758 (82 Ma) and 756 (43 Ma) with similarly aged oceanic crust in the Central Indian Basin and Wharton Basin reveals the existence of extra oceanic crust spanning 11° latitude beneath the Ninetyeast Ridge. The extra crust is attributed to the transfer of lithospheric blocks from the Antarctic plate to the Indian plate through a series of southward ridge jumps at about 65, 54 and 42 Ma. Emplacement of volcanic rocks on the extra crust resulted from rapid northward motion (absolute) of the Indian plate. The Ninetyeast Ridge was originated when the spreading centers of the Wharton Ridge were absolutely moving northward with respect to a relatively stationary Kerguelen hotspot with multiple southward ridge jumps. In the process, the spreading center coincided with the Kerguelen hotspot and took place on-spreading-axis volcanism along the Ninetyeast Ridge.

1. Introduction

The hypotheses of plate tectonics and mantle plume are able to explain the formation of the Earth's major structural and tectonic features. Seafloor spreading records provide data of relative plate motion, whereas volcanic traces left by hotspots provide histories of relative plate motion (measured from spreading ridge), absolute plate motion (relative to the Earth's spin axis) and interhotspot motion. The traces of the Kerguelen and Reunion hotspots (Ninetyeast Ridge and Chagos-Laccadive Ridge, respectively) have recorded the Indian plate's combined (relative and absolute) motions and interhotspot motions (if at all they exist).

The Ninetyeast Ridge (figure 1) is a major tectonic feature in the eastern Indian Ocean that has prompted several geological investigations since its identification

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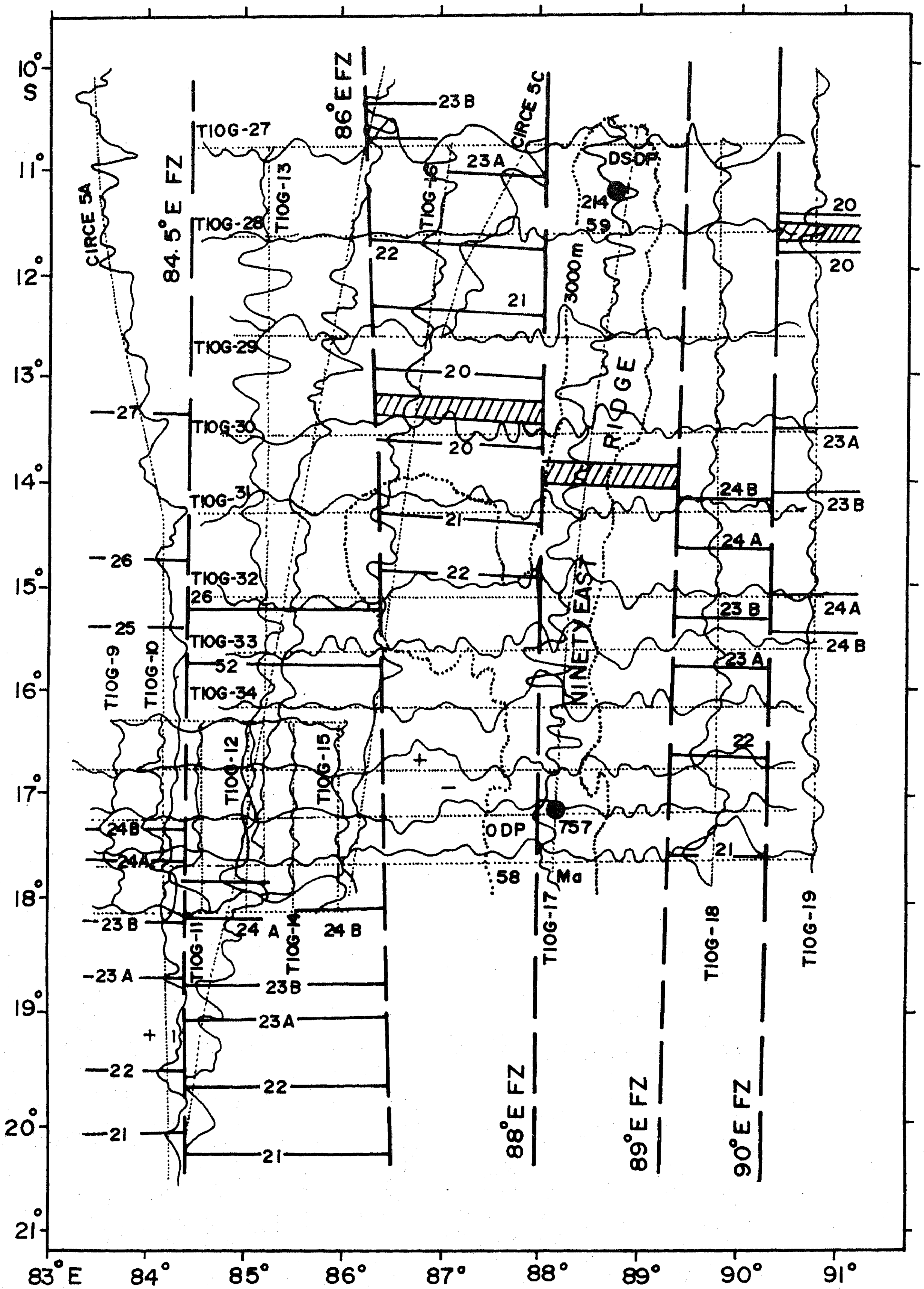

Figure 1. Magnetic anomaly profiles plotted at right angles to the ship tracks. The profiles other than TIOG are published by Sclater and Fisher (1974). Interpretations of magnetic anomalies, fracture zones and abandoned spreading centers are superimposed on the data. The 3000 m bathymetry contour of the Ninetyeast Ridge is shown. DSDP and ODP Sites are located with geochronological ages.

(Stocks 1960). While its morphological characteristics have been well-studied (Sclater and Fisher 1974), its origin remained elusive. Considering geochemical (Frey *et al* 1977; Weis and Frey 1991; Weis *et al* 1991), isotopic composition (Class *et al* 1993), paleomagnetic (Peirce 1978; Klootwijk *et al* 1992), geochronological (Duncan 1978; Duncan 1991), and subsidence (Bowin 1973) results, the formation of the Ninetyeast Ridge is currently accredited to the eruption of the Kerguelen hotspot. The ridge was emplaced as the Indian plate moved northward over the Kerguelen hotspot during the period 82–38 Ma following formation of the Rajmahal traps on the Indian subcontinent, the Bunbary basalts on the Australian continent, the Broken Ridge, and the southern portion of the Kerguelen Plateau. Several investigators (Von der Borch *et al* 1974; Davies *et al* 1974; Weis and Frey 1991) have suggested that the hotspot was located on or near active spreading center during the formation of the Ninetyeast Ridge. Subsequently, Royer *et al* (1991) proposed a three-phase tectonic model for emplacement of the ridge. Geochemical and geochronological results of the DSDP and ODP Sites on the Ninetyeast Ridge reveal anomalous basalt compositions and symmetrical age distribution around 15°S latitude. The southward ridge jumps off spreading center beneath the Ninetyeast Ridge (Krishna *et al* 1995) and its interactions with the Kerguelen hotspot add a more complicated tectonic history for the Ninetyeast Ridge. These aspects are very important to study in detail to understand the plate motions with respect to the hotspot and to reconstruct the Indian Ocean.

The main objectives of this work are:

- to study various tectonic settings of the Kerguelen hotspot relative to the Wharton spreading center in space and time, and
- to compare ages of the crest of the Ninetyeast Ridge with the ages of the oceanic crust of the adjacent basins in order to have a better understanding of the evolution of the eastern Indian Ocean.

The present study proposes a new tectonic model of on-spreading-axis hotspot volcanism for a part of the Ninetyeast Ridge, which fits the radiometric and geochemical data of the DSDP and ODP Sites of the Ninetyeast Ridge better than those previously proposed.

The recent tectonic model of the northeastern Indian Ocean (Krishna *et al* 1995) shows several abandoned spreading centers (ASCs) of ≈ 42 Ma age between the 96°E Fracture Zone (FZ) and the 86°E FZ and interpreted them as the defunct Wharton spreading ridge (India-Australia spreading system). The present study investigates the three proposed locations of the Kerguelen hotspot with respect to the Wharton spreading center at the time of creation of the Ninetyeast Ridge. The discussion is based upon magnetic lineations and abandoned spreading centers of the area surrounding the Ninetyeast Ridge (figures 1, 2 and 3) and two seismic sections across and along the ridge (figure 4).

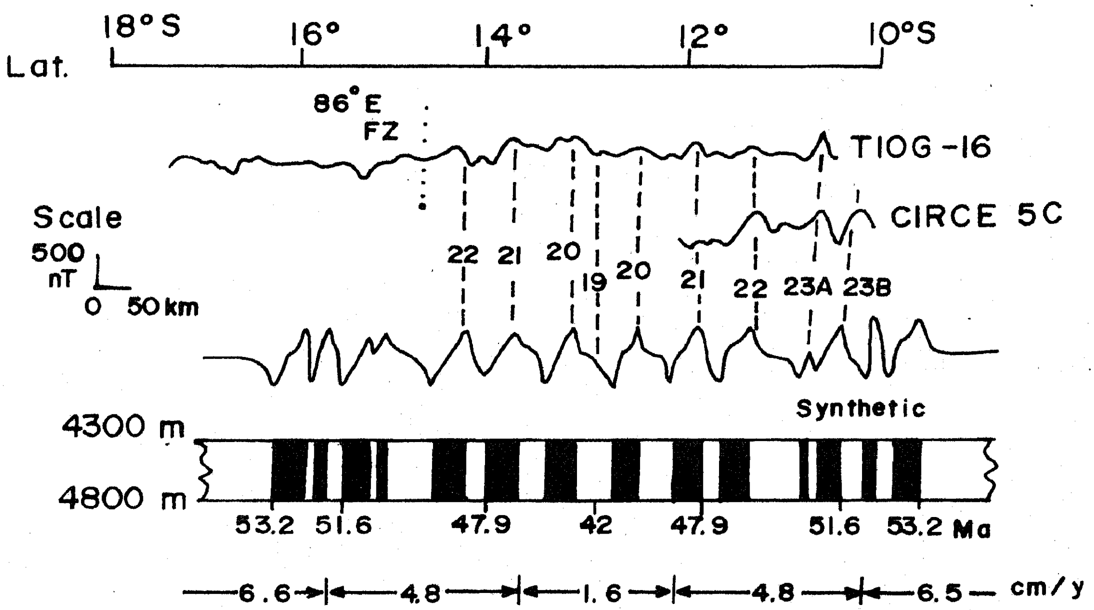

Figure 2. Correlations between observed and synthetic magnetic anomalies east of the 86°E FZ are shown. Synthetic profile with anomaly numbers generated following the magnetic reversal time scale suggested by the Cande and Kent (1992). For generating synthetic magnetic anomaly profile, the seafloor at an average depth of 4300 m is divided into 500 m thick normally (solid) and reversely (open) magnetized blocks with a magnetization of 0.01 A/m. The synthetic profile is generated normal to the ridge striking east-west and with a paleolatitude of 30°S. Half spreading rates (in centimeters per year) are shown below the synthetic profile.

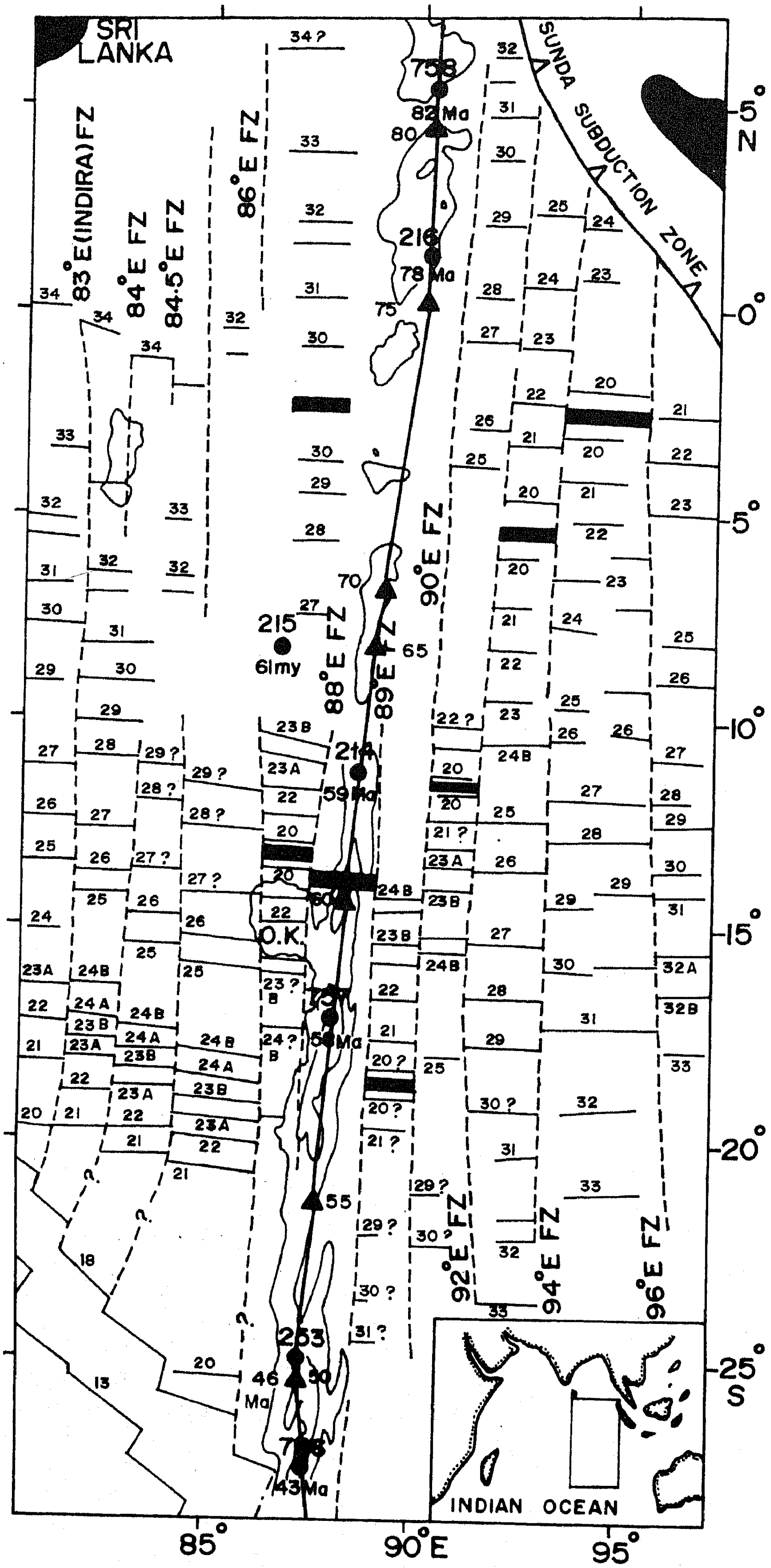

Figure 3. Tectonic map of the area surrounding the Ninetyeast Ridge in the northeastern Indian Ocean (Krishna *et al* 1995). Solid boxes indicate the locations of the abandoned spreading centers (ASC) of the Wharton Ridge. OK represents the Osborne Knoll. Solid circles on the Ninetyeast Ridge represent the DSDP and ODP Sites with ages (Duncan 1978; Duncan 1991). Solid triangles with ages and connecting thick line show the computed path of the Indian plate relative to the Kerguelen hotspot (Müller *et al* 1993). The box in the insert map indicates the study area.

2. Marine geophysical data

Trans Indian Ocean Geotraverse (TIOG) project under the Indo-Russian bilateral program has provided the opportunity to acquire marine geophysical data between latitudes 10°S and 18°S from the Argo Abyssal Plain, northwestern continental margin of Australia to the Mascarene Plateau. The area was surveyed in 1988–1989 by the Russian research vessels Issledovatel, XVII Syezo Profsoyuzov and Discoverer. A Satellite Navigation System Magnavox 1107 was used for obtaining positions during the surveys. The data were processed and basic maps of bathymetry and magnetic anomalies were prepared. The magnetic anomalies were computed by subtracting the International Geomagnetic Reference Field (IAGA Division, Working Group 1, 1986). Bathymetry, magnetic and seismic reflection (two small profiles) data acquired in the vicinity of the Ninetyeast Ridge are used in the present study with a view to understand the tectonic history of the ridge. Magnetic anomaly data are plotted along ship tracks and shown in figure 1.

3. Magnetic lineations and abandoned spreading centers

Magnetic lineations 19 through 32B, fracture zones, and abandoned spreading centers identified by Krishna *et al* (1995) are superimposed on the magnetic anomaly data (figure 1). The magnetic profiles on the crest of the Ninetyeast Ridge (TIOG-17) and on the oceanic crust to the west (TIOG-16) show the presence of abandoned spreading centers and similar shaped anomalies on either side. Although the central portions of both the profiles appear somewhat similar, we could identify anomaly numbers only on profile TIOG-16. A comparison of observed profiles TIOG-16 and CIRCE 5C with synthetic profile (figure 2) reveal pairs of anomalies 20 to 22 on either side of the central anomaly 19. Anomalies 23A and 23B on profiles CIRCE 5B and 5C identified by Peirce (1978) are well correlatable with the same anomalies on TIOG-16 (figure 1). The spreading center east of the 86°E FZ ceased after formation of anomaly 19 and jumped southward leaving ASC on the Indian plate. On profile TIOG-17, we were unable to identify the anomaly numbers as the previously formed oceanic crust was remagnetised with the emplacement of volcanic rocks of the Ninetyeast Ridge. The results of this study are coupled with those of Royer *et al* (1991) and shown in figure 3. The magnetic lineation offsets west of the 86°E FZ are mostly right lateral with oceanic crust increasing in age to the north, whereas the magnetic lineation offsets east of the 90°E FZ are consistently left lateral with oceanic crust increasing in age to the south. In contrast, the crust between the 86°E FZ and the 90°E FZ increases in age to both the north and south about ASCs.

Although the ages of the magnetic anomalies that bound the ASC beneath the Ninetyeast Ridge can not be determined, it is generally thought that activity along this spreading center ceased during the formation of magnetic anomaly 19 (≈ 42 Ma) (Krishna *et al* 1995; Liu *et al* 1983). On the other hand, Royer *et al* (1991) and Krishna *et al* (1995) postulated that the spreading centers between the 86°E FZ and the 90°E FZ underwent a series of southerly ridge jumps at anomalies 30, 26 and 19. If this is the case, the spreading center beneath the Ninetyeast Ridge might not have ceased simultaneously along the other ridge segments. To resolve this enigma, three plausible tectonic settings of the Kerguelen hotspot relative to the Wharton spreading center have been investigated: (**a**) hotspot north of the spreading center, (**b**) hotspot south of the spreading center and (**c**) hotspot on the spreading center.

4. Morphology of the Ninetyeast Ridge

The Ninetyeast Ridge stretches for about 5000 km in a north-south direction between 18°N and 34°S with an average width of 200 km. North of 10°N, the ridge is almost entirely buried by the thick sediments of the Bengal Fan (Curray *et al* 1982; Gopala Rao *et al* 1997). The ridge flanks have uniform gradient, while the seafloor adjacent to the eastern flank is ~1 km deeper than the western flank (figure 4). Towards north of 15°S (figure 3), the Ninetyeast Ridge is 170 km wide and rises 3.4 km above the seafloor, whereas towards south, it is significantly wider and shallower (Sclater and Fisher 1974; Krishna *et al* 1995). The seafloor topography of the Ninetyeast Ridge between latitudes 10°S and 18°S differs from that of the oceanic crust to the west (Krishna *et al* 1995; Krishna 1996). The ridge rises to 2600 m from the surrounding 5000 m water depth. An array of isolated elongated highs with troughs in between occurs on top of the rise. Immediately to the west of the Ninetyeast Ridge, the seafloor topography is smooth (average depth 4800 m) except Osborne Knoll and fewer small abyssal rises. Osborne Knoll is a circular topographic rise adjoining the Ninetyeast Ridge on its west.

An along-ridge seismic section (figure 4) reveals a gradual southerly rise in the level of both seafloor and basement topography with the latter comprising a number of blocks. Investigations at DSDP Site 214 (Veevers 1974) and ODP Site 757 (Peirce, Weissel *et al* 1989) on the Ninetyeast Ridge (figure 3) indicate that Paleocene volcanic rocks are overlain by three sedimentary sequences with a total thickness of about 0.6 km. Bases of sequences are considered to represent the Eocene, Oligocene and Quaternary boundaries.

5. Wharton spreading center-Kerguelen hotspot interaction

The hotspots in the Atlantic and Indian Oceans, in general, at sometime or other during their active life tend to occur near to a spreading center. Some hotspots such as Trista Da Cunha in South Atlantic Ocean, Iceland in North Atlantic Ocean and Afar in the Red Sea, intermingled with spreading centers in various ways to create symmetrical features such as continental flood basalts and volcanic ridges. Some hotspots change location with respect to a spreading center due to absolute plate motion, ridge jumps and plate reorganizations. Müller *et al* (1993) believe that the Crozet hotspot changed location from north of the spreading center to the south due to northward ridge jump between magnetic anomalies 31 and 25. Similarly it has been proposed that the Reunion hotspot changed its location to the African plate from the Indian plate at about 30 Ma (Lytwyn and Burke 1995). The close proximity of the Kerguelen hotspot and the Wharton spreading center in the northeastern Indian Ocean is another clear example for such an explanation.

The cessation of spreading along the ASC located beneath the Ninetyeast Ridge is considered to have occurred at 42 Ma (figure 5a). The paired anomalies older than anomaly 19 and ASCs shown in figure 2 support this interpretation. If the Kerguelen hotspot was located north of the Wharton spreading center, volcanic rocks which comprise the Ninetyeast Ridge to the north of this ASC should be older than 42 Ma minus the time taken to move the ASC over the hotspot, while the rocks to the south of the ASC should be younger (figure 5b). However, ages of basement rocks at DSDP Sites 214 (59 Ma) and 253 (46 Ma) and ODP Sites 757 (58 Ma) and 756 (43 Ma) are not consistent with this scenario of active spreading until 42 Ma (figure 2). On the other hand, if the hotspot was located south of the spreading center, there should be a gap in the continuity of the Ninetyeast Ridge (figure 5c), similar to the gaps between the Chagos Bank and the Mascarene Plateau which were created by the Central Indian Ridge, and between the Broken Ridge and the Kerguelen Plateau which were created by the central part of the Southeast Indian Ridge. The continuity of the Ninetyeast Ridge in this region rules out the possibility of hotspot location south of the Wharton Ridge.

Alternatively, if the location of the hotspot coincides with the spreading axis, the age of the Ninetyeast Ridge should increase on both sides of the ASC (figure 5d) until spreading activity ceased (up to 42 Ma), as is currently true for the Icelandic plume located on the Reykjanes Ridge and as occurred with the Walvis Ridge-Rio Grande Rise system prior to 70 Ma. The ages of rocks at DSDP Site 214 and ODP Site 757 (figure 3) are almost equivalent (59–58 Ma) which supports the above tectonic setting. Their distances to the ASC (DSDP 214-ASC-ODP 757) are only about 300 km, which is very short against the 750 km relative motion of Indian plate during the period of 60–42 Ma (Liu *et al* 1983; Patrtiat and Segoufin 1988; Krishna *et al* 1995). Therefore, we suggest the tectonic setting of on-spreading-axis hotspot volcanism of the Paleocene (60–54 Ma) age for a part of the Ninetyeast Ridge with immediate southward ridge jump. The setting, a product of plume-MOR interaction, was subsequently moved to north and is presently lying between 11° and 17°S along the Ninetyeast Ridge.

The hypothesis that the hotspot was located on the spreading axis appears to be supported by geochemistry and morphology of both the seafloor and the underlying basement of this section of the Ninetyeast Ridge. Oceanic andesites at DSDP Site 214 and much more isotopically heterogeneous basalts at ODP Site 757 show the mix of two different source components, namely plume and mid-ocean ridge basalts (MORB) (Thompson *et al* 1974; Weis and Frey 1991; Weis *et al* 1991). These rocks are different from an intermix of depleted upper mantle and plume-derived magmas found at other sites on the Ninetyeast Ridge. The increased width and rise of both seafloor and basement of the Ninetyeast Ridge (figure 4) toward south of the ASC may indicate the slow motion of the Indian plate over the Kerguelen hotspot after 54 Ma.

6. Southward ridge jumps beneath the Ninetyeast Ridge

Similar to the southward ridge jumps at anomalies 30 (65 Ma), 26 (58 Ma) and 19 (42 Ma) (Royer *et al* 1991; Krishna *et al* 1995) between the 86°E FZ and the Ninetyeast Ridge, the spreading center beneath the Ninetyeast Ridge possibly also jumped towards south at about 65 Ma, 54 Ma and 42 Ma. The Kerguelen hotspot remained north of the spreading center, even after the first ridge jump, until 60 Ma (figure 6, left). At that time it coincided with the spreading center and remained so until the occurrence of a second ridge jump to south at about 54 Ma (figure 6, middle). During the period from 60 to 54 Ma, interaction between hotspot and spreading center generated an intermixed magma of MOR and plume. These rocks occur on both sides of spreading center between 11°S and 17°S along the Ninetyeast Ridge. After the second ridge jump, spreading continued until 42 Ma then ceased along with other spreading centers (Wharton Ridge), during the second major plate reorganization (figure 6, right). Multiple southward ridge jumps beneath the Ninetyeast Ridge allowed the Kerguelen hotspot to remain on the Indian plate until 38 Ma. The process involved the repeated southward jumps of the spreading center relative to the Kerguelen hotspot, unique case on the Earth, and rapid northward motion of the Indian plate created

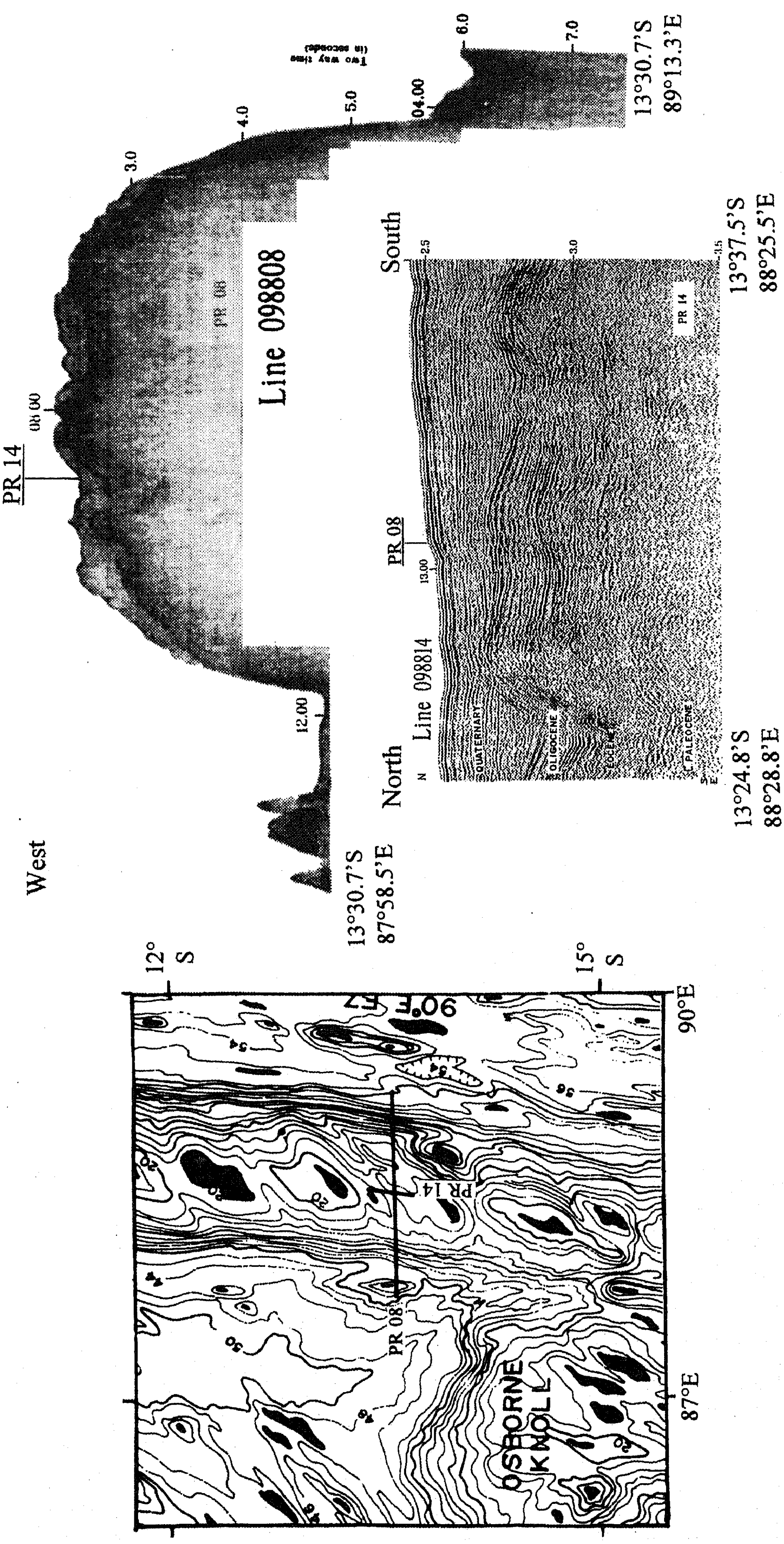

Figure 4. Seismic reflection record across and along the Ninetyeast Ridge. The locations of the profiles are shown on the insert map.

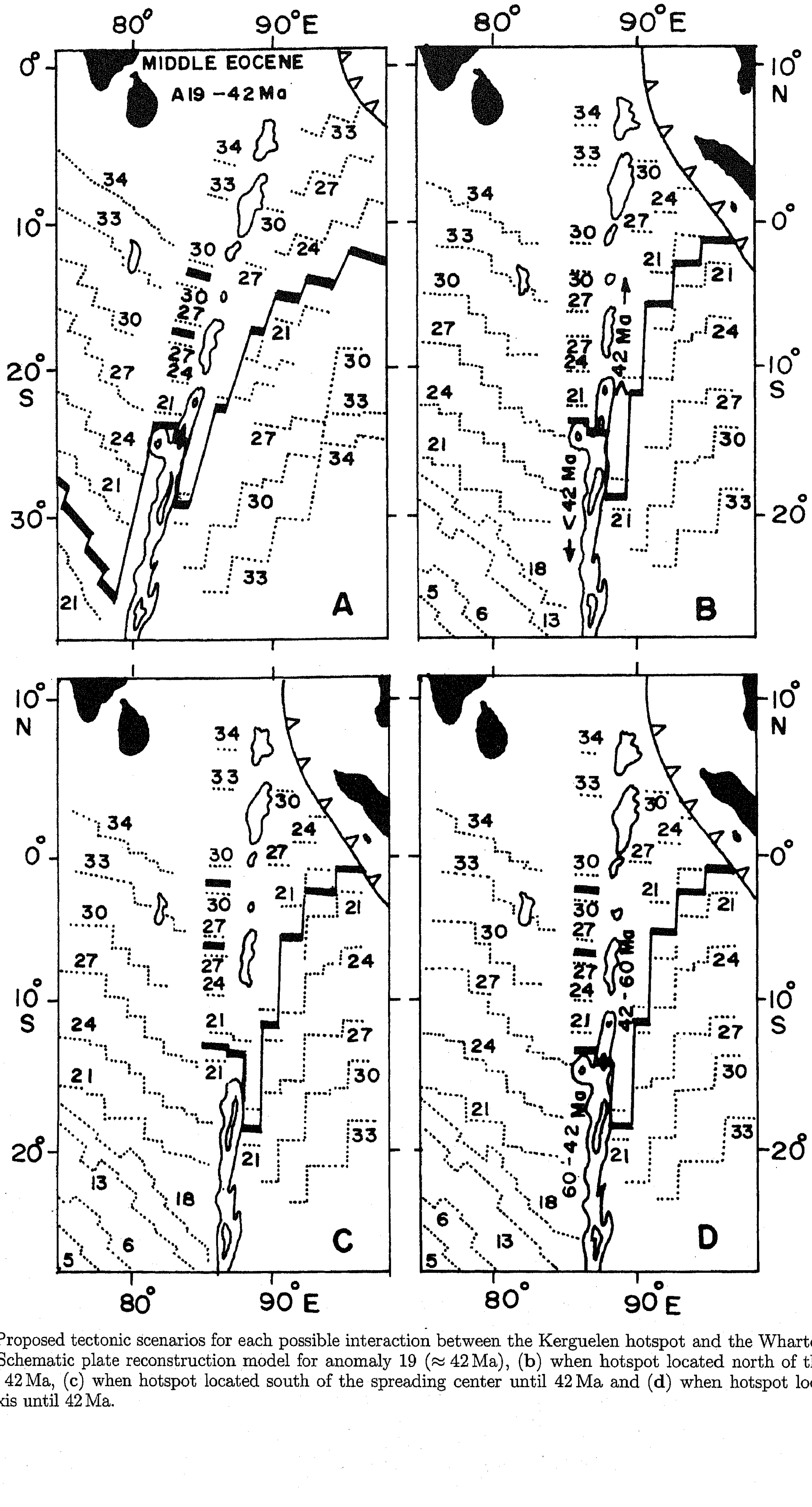

Figure 5. Proposed tectonic scenarios for each possible interaction between the Kerguelen hotspot and the Wharton spreading center. (**a**) Schematic plate reconstruction model for anomaly 19 ($\approx$ 42 Ma), (**b**) when hotspot located north of the spreading center until 42 Ma, (**c**) when hotspot located south of the spreading center until 42 Ma and (**d**) when hotspot located on the spreading axis until 42 Ma.

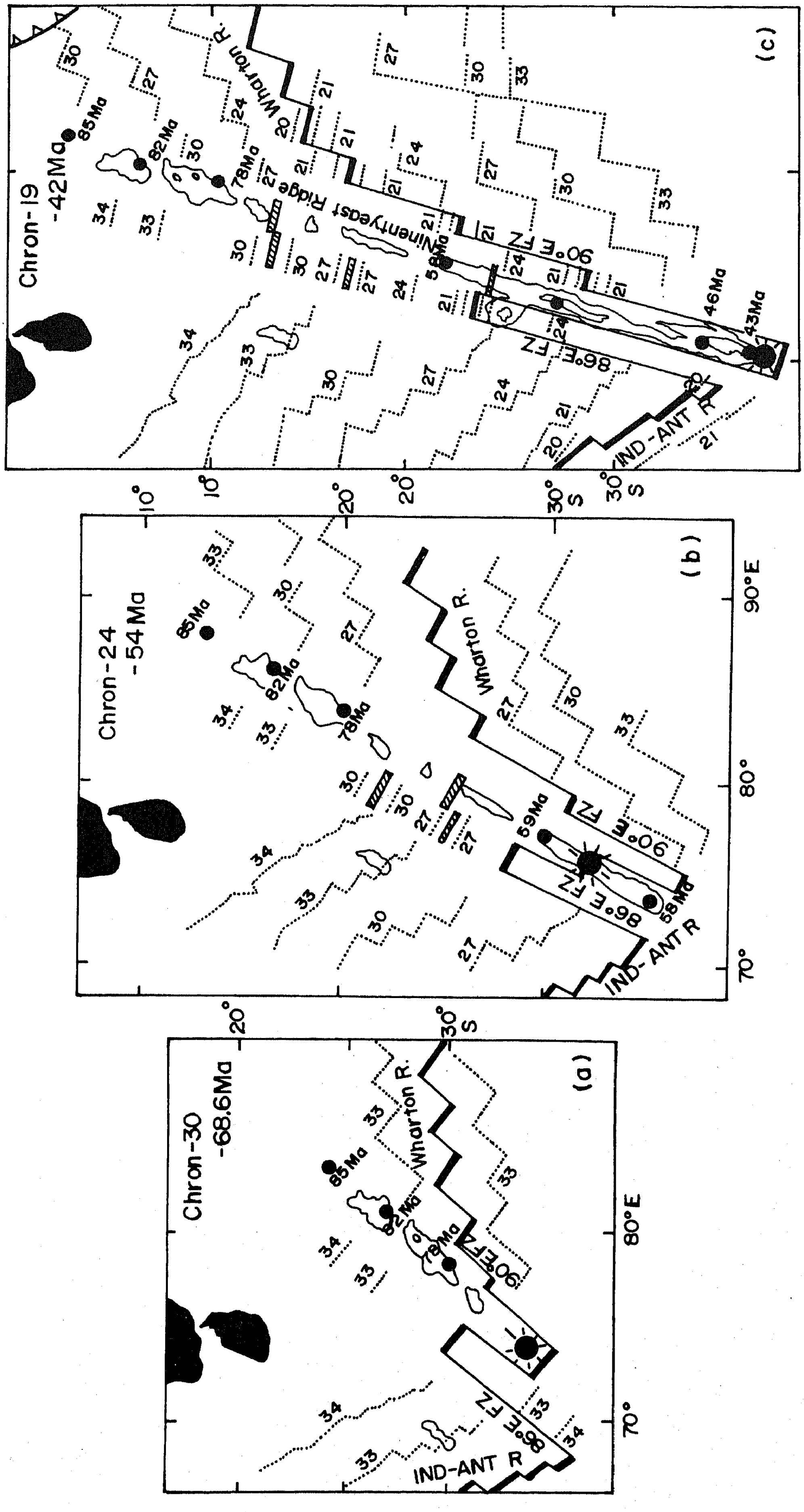

Figure 6. Schematic reconstruction models illustrating the location of the Kerguelen hotspot with respect to the active spreading center at times (68.6, 54, and 42 Ma) when ridge jumps occurred.

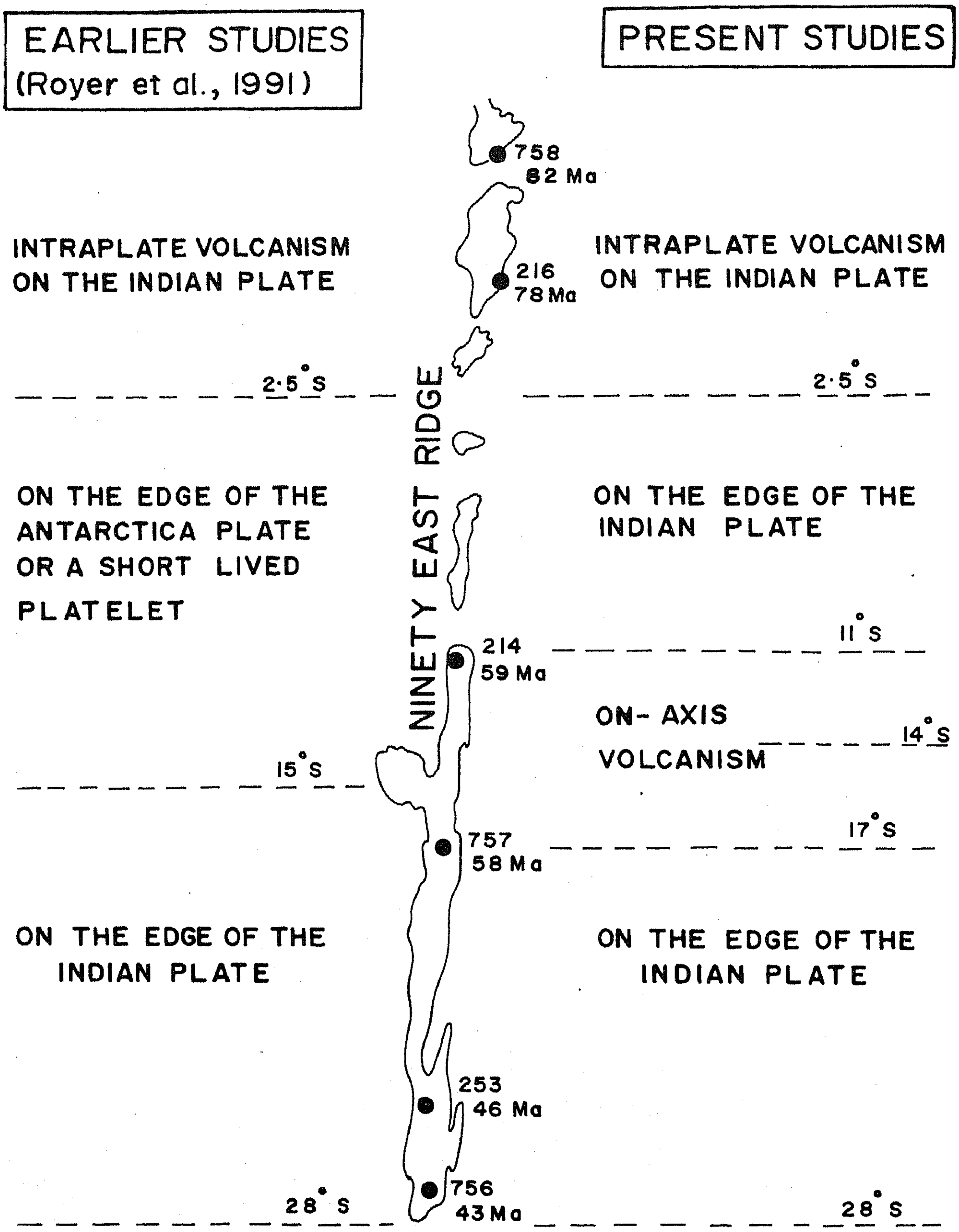

Figure 7. Tectonic history of the Ninetyeast Ridge.

the world's longest structural feature, the Ninetyeast Ridge.

7. Tectonic setting of the Ninetyeast Ridge

Formation of the Ninetyeast Ridge by the Kerguelen hotspot is the preferred model. Previous studies have focused on understanding the interaction of spreading centers with hotspot. According to Royer *et al* (1991), the Ninetyeast Ridge north of 2.5°S is a product of intraplate volcanism on the Indian plate, the portion between 2.5°S and 15°S formed at the edge of either the Antarctica plate or a short lived platelet, and the ridge south of 15°S erupted on the edge of the Indian plate. The present study suggests that the ridge north of 2.5°S was created in intraplate volcanism on Indian plate, the portion between 2.5°S and 11°S was most likely emplaced on the edge of the Indian plate, the portion between 11°S and 17°S resulted from hotspot volcanism on-axis, and the ridge south of 14°S was formed on the edge of the Indian plate (figure 7). Emplacement of the Ninetyeast Ridge between 14°S and 17°S was accomplished in two consecutive phases. During the period 60–54 Ma, the Kerguelen hotspot was located directly beneath the Wharton spreading

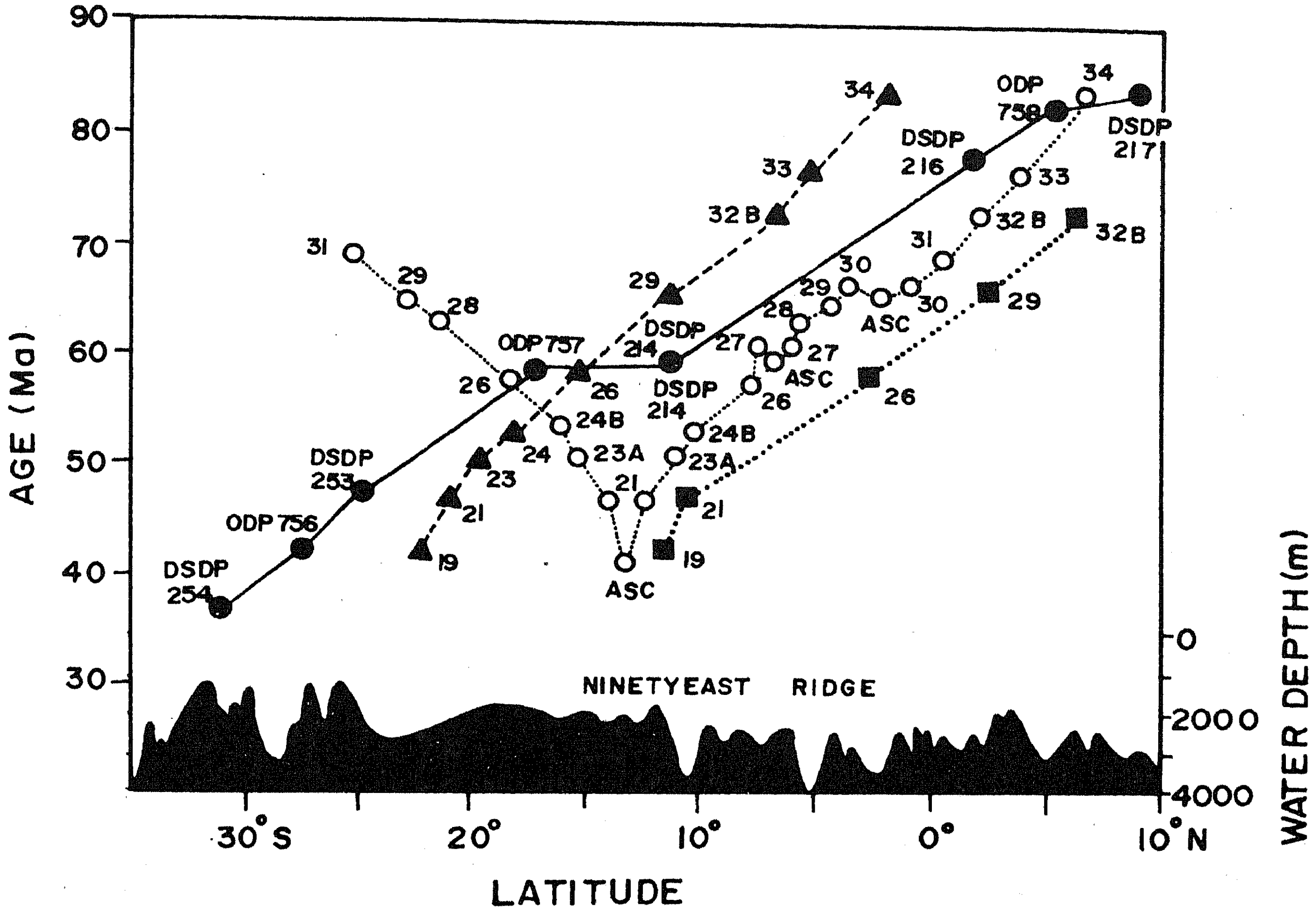

Figure 8. Age versus latitude plot for basaltic basement along the Ninetyeast Ridge (solid circles), between the Ninetyeast Ridge and the 86°E FZ (open circles), in the Central Indian Basin, west of the 86°E FZ (solid triangles) and in the Wharton Basin, east of the 90°E FZ (solid squares). Depth profile of the Ninetyeast Ridge is after Fisher *et al* (1982).

center. After a southward ridge jump at 54 Ma, the hotspot was once again located north of the spreading center.

8. Extra crust beneath the Ninetyeast Ridge – absolute motion of the Indian plate

Sclater and Fisher (1974), Sclater *et al* (1974), Peirce (1978), Royer *et al* (1991) and Krishna *et al* (1995) have identified the existence of the extra portion of oceanic crust spanned 11° in latitude between the 86°E FZ and the Ninetyeast Ridge. Evidence for existence of such extra oceanic crust beneath the Ninetyeast Ridge, can be provided by comparing the distance between ODP Sites 758 (82 Ma) and 756 (43 Ma) on the Ninetyeast Ridge with the distances covered for similar ages of oceanic crust in the Central Indian and Wharton Basins (figure 3). The sites 758 and 756 on the Ninetyeast Ridge are separated by about 32° distance, whereas the anomalies 34 (84 Ma) and 19 (42 Ma) in the Central Indian Basin, west of the 86°E FZ and in the Wharton Basin, east of the 90°E FZ are separated by a distance of only 21° (figure 8). This clearly indicates the existence of extra oceanic crust spanning 11° latitude between ODP Sites 758 and 756 similar to that between the 86°E FZ and the Ninetyeast Ridge. The transfer of lithospheric blocks can account for this extra portion of oceanic crust from the Antarctica plate to the Indian plate through a process of repeated southward ridge jumps.

The existence of such extra oceanic crust makes it difficult to explain how the stationary Kerguelen hotspot erupted on top of it. To account for this extra crust, Sclater *et al* (1974) suggested that there might be a leak in the transform fault between 10°S and 21°S when the ridge jumped toward south at anomaly 27. They predicted that the rocks of the Ninetyeast Ridge between 10°S and 21°S should be the same age, ≈ 60 Ma. However, the proposed hotspot formation of the Ninetyeast Ridge does not allow for such a localized phenomenon.

Volcanism on extra oceanic crust beneath the Ninetyeast Ridge may be explained in terms of either interhotspot movement towards south, rapid northward motion of the spreading center (absolute motion of the Indian plate) or combination of both activities.

Continuous southward migration of the Kerguelen hotspot at a rate of about 3 cm/yr. may be proposed to account for the volcanism on the extra oceanic crust. Duncan and Richards (1991) have examined the Atlantic and Indian Ocean hotspots and concluded that there is no perceptible interhotspot motion over periods as long as 120 Ma. On the other hand Molnar and Stock (1987) suggest that these hotspots allow maximum relative motion of about 2 – 5 mm/yr. The paleolatitudes measured at DSDP and ODP Sites along the Ninetyeast Ridge (Peirce 1978; Klootwijk *et al* 1991) show approximately the same value of about $-50°$ except at DSDP Site 217 and ODP Site 756. Considering these facts, we rule out the possibility of significant interhotspot motion for the Kerguelen hotspot.

Alternatively, we consider the process of absolute motion of the Indian plate to explain the volcanism on the extra oceanic crust during 82–43 Ma. The absolute motions of plates do have temporal variations. The absolute motion of the Indian plate was significantly increased from about 1.4 cm/yr. to 8.0 cm/yr. after 54 Ma. The stretches of the volcanic traces left by the Kerguelen hotspot and the Reunion hotspot during 54–43 Ma are approximately the same ($\approx$ 1400 km) and are much greater than that of similar aged oceanic crust ($\approx$ 500 km) in the Central Indian Basin. During the period 84–54 Ma when India's northward motion was high the absolute motion of Indian plate was very low. Whereas between 54 and 43 Ma, the absolute motion was high than the relative plate motion. As a whole combined motions of the Indian plate for time 82–43 Ma were in comparable range and in agreement with the closing rates of Teethys Sea (10.0-18.4 cm/yr.) between India and Eurasia (Molnar and Tapponnier 1975). However, this explanation still needs supporting evidence of further investigations. The Ninetyeast Ridge was formed when the spreading centers of the Wharton Ridge were absolutely moving northward with respect to a relatively stationary Kerguelen hotspot with a series of southward ridge jumps in order to keep the hotspot north of the spreading center. Further detailing of the emplacement mechanism to account for the volcanism on the extra crust of the Ninetyeast Ridge will greatly help the geoscientists in postulation of detailed plate kinematic and geochemical models in the area.

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