Two decades of Indian research on Ninetyeast Ridge reveal how seafloor spreading and mantle plume activities have shaped the eastern Indian Ocean

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The Ninetyeast Ridge, one of the longest, linear, age-progressive seamount chains on the Earth extends ~5600 km in the N–S direction from the Bay of Bengal to almost near the Southeast Indian Ridge (Figure 1). It is widely accepted that the ridge is a product of volcanic trace of the Kerguelen mantle plume (hot spot) on the northward-drifting Indian plate between ~85 and 42 Ma. The ridge is also unique because the feature is located within a diffuse deformation zone between three sub-plates, Indian, Australian and Capricorn and is associated with seismicity.

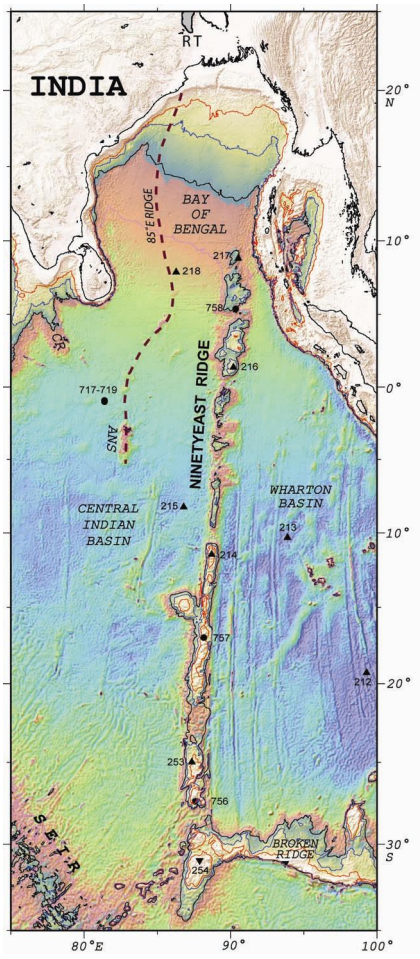

Figure 1. General bathymetry map of the eastern Indian Ocean showing location of the Ninetyeast Ridge between 34°S and 10°N latitudes. The region also includes aseismic ridges of 85°E, Broken and Comorin ridges and mid-oceanic ridge system of Southeast Indian Ridge. Numbered solid triangles and circles show Deep Sea Drilling Project and Ocean Drilling Program sites drilled during Legs 22, 26 and 121.

The presence of the Ninetyeast Ridge in the Indian Ocean was first reported by Th. Stocks in 1960. Subsequently a comprehensive picture of the ocean floor emerged from the compilation of depth soundings made during the International Indian Ocean Expedition (1960–65), which emphasized the presence of this long, linear, aseismic ridge in the Indian Ocean.

Emergence of plate tectonics and mantle plume hypotheses in the early 1960s led the way to mount rigorous experiments on the Ninetyeast Ridge for understanding its origin. The results of Legs 22 and 26 of the Deep Sea Drilling Project (DSDP) (1974), Leg 121 of the Ocean Drilling Program (ODP) (1989) and the geophysical surveys have helped establish that the Ninetyeast Ridge originated from the Kerguelen hot spot, when the volcanic source was located beneath the northward-moving Indian plate from the Late Cretaceous to the Early Cenozoic period.

In the early 1990s, two bilateral programmes, viz. Trans Indian Ocean Geotraverse (TIOG) and Integrated Long-Term Programme (ILTP), aimed to understand better the evolution of the Indian Ocean lithosphere, were initiated with the support of the Indian and Russian governments. Subsequently in 2007, India participated in an International Expedition on the Ninetyeast Ridge for collection of bathymetry, magnetic and seismic reflection data together with basement samples from 33 sites along the ridge to investigate the behaviour of the Kerguelen hot spot during the formation of the ridge. From the Indian side, CSIR-National Institute of Oceanography (CSIR-NIO), Goa took a lead position in understanding the evolution, internal structure and several fundamental processes of the Ninetyeast Ridge. Besides, institutes like NGRI, IIT Bombay and IISc as part of their own programmes also carried out research on some selected aspects of the Ninetyeast Ridge.

Studies carried out from the early 1990s to 2013 have brought out greater details on spreading centre – hot spot interactions, mid-ocean ridge migrations, ridge jumps, evolution of triple diffuse–plate boundary between the sub-plates, etc. Major inferences drawn from the research work carried out so far are listed below.

- The marine magnetic data (measures the Earth's past magnetic fields hidden in basaltic rocks) of both Central Indian and Wharton basins, including the Ninetyeast Ridge revealed significant tectonic elements such as (a) seafloor spreading anomalies 34 through 19, (b) middle Eocene extinct spreading ridge system and (c) ~N5°E striking fracture zones. Identification of an extinct spreading ridge and its continuity across the Ninetyeast Ridge up to the 86°E FZ and associated tectonic fabrics clearly brought out the geometry of the Indian and Australian plates which existed from Late Cretaceous to Early Eocene period and then formation of a single Indo-Australian plate[1–3].
- The Ninetyeast Ridge includes ~22 km thick crust, which is on the whole much greater than the average thickness (7 km) of oceanic crust estimated in the Central Indian and Wharton basins. The excessive crustal thickness of the ridge is isostatically compensated by (a) flexure of layers 2 and 3A to the extent of ~2 km and (b) a 12 km thick deep crustal body (layer 3B) of underplated material[4,5].
- A series of E–W trending horst and graben structures with average spacing of ~45 km on the Ninetyeast Ridge and their extensional nature

revealed that these faulted structures were formed near the spreading ridge which separated the Indian and Antarctic plates[6].

- New Ar/Ar dates of volcanic rocks from the Ninetyeast Ridge revealed that the ridge track was emplaced at a rate of ~118 km/Myr, twice that of the ~48–58 km/Myr accretion rate of adjacent oceanic crust. The reasons for such significant difference in emplacement rates were explained in terms of northward migration of mid-ocean ridge system and southward jumps of spreading centres toward the Kerguelen hot spot, which transferred portions of the crust from the Antarctic plate to the Indian plate, lengthening the Ninetyeast Ridge[7,8].
- Elastic Plate Thickness (*Te*) determined from flexural modelling of the Ninetyeast Ridge is a new proxy for detailing the interactions between hot spot and migrating spreading ridge system. Spatial variation of *Te* values (range from 4 to 35 km) along the entire length of the Ninetyeast Ridge clearly shows that the ridge possesses a highly segmented isostatic pattern due to either the inclusion of sub-crustal underplated material or subsurface loading. These varied isostatic compensation mechanisms are attributed to the occurrence of a series of ridge jumps caused by interaction of Kerguelen hot spot with rapid northward migration of Wharton Spreading Ridge. The ages of the ridge rocks, magnetic lineations and *Te* values together suggested that the Kerguelen hot spot emplaced the volcanoes on the Indian plate initially at a distance from the Wharton Spreading Ridge, but as the northward-drifting spreading ridge approached the hot spot, the two have interacted, keeping the subsequent volcanism near the spreading ridge crest by spreading centre jumps[9–13].
- Several fault planes are found to be active on most part of the Ninetyeast Ridge and they are controlled by the reactivation of original, spreading centre-formed, normal faults, implying that diffuse deformation is widespread and often complex. The style of strike–slip faulting observed over the northern part of the Ninetyeast Ridge is a clear manifestation of India–Australia deformation and it differs from the style of extensional faulting in the southern part of the ridge which was ascribed due to Capricorn–Australia deformation. The findings further indicate that structural style of deformations varies on either side of the Ninetyeast Ridge, implying that the ridge structure is currently acting as a tectonic boundary[14–16].

The research carried out in the last two decades on the Ninetyeast Ridge has clearly revealed the geometry of the Indian and Australian plates from the Late Cretaceous to the Early Cenozoic period. The research further led to the conclusion that within the Indian Ocean region, the spreading ridge migrations were much more dominant than the hot spot drifts. This is contrary to the behaviour of the Pacific Ocean hot spots.

The research on the Ninetyeast Ridge was mainly led by the CSIR-NIO in collaboration with the following national and international research institutes: Yuzhmorgeologia, Galendzhik, Russia; Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia; Department of Oceanography, Texas A&M University, College Station, Texas, USA; Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA and Geosciences Division, MPSG/EPSA, ISRO-Space Applications Centre, Ahmedabad.

The results and proposed models have been published in top geophysical journals and also in doctoral theses submitted to universities. Thus India will remain in the forefront in the area of Ninetyeast Ridge research.

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