

Geological and Geophysical Studies of the Ninety East Ridge: A Brief Review

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Abstract

The Indian Ocean serves as a unique laboratory for studying the impact of both global and regional stressors on environmental changes over various geological epochs. Its distinct hydrological conditions and geographical location make it an ideal focal point for research into these phenomena. Of particular interest within the Indian Ocean is the Ninety East Ridge (NER), which holds significance as the world's longest linear rise. Researchers have long hypothesized that the Ninety East Ridge owes its origin to a hotspot trace influenced by the Kerguelen plume. However, a comprehensive review of geological and geophysical research along the NER is needed to gain a deeper understanding of its tectonics, evolution, geological setting, and provenance. This review encompasses the Ridge's entire history, spanning from the Paleocene to the present day. Through an analysis of various datasets and research findings, this review aims to elucidate the processes that have shaped the Ninety East Ridge over millions of years. By examining sediment cores, seismic profiles, and other geological data, researchers can reconstruct the Ridge's formation and subsequent evolution. This includes investigating the role of tectonic activity, sea level changes, and climatic variations in shaping the NER. Furthermore, the review will explore the implications of the Ninety East Ridge's formation for broader geological and environmental studies. Understanding the processes that govern the development of features like the NER can provide valuable insights into global tectonic dynamics, paleoclimate patterns, and the distribution of marine life throughout Earth's history. Overall, this comprehensive review seeks to consolidate existing knowledge about the Ninety East Ridge while also highlighting avenues for future research. By synthesizing data from multiple disciplines, it aims to contribute to our broader understanding of the Indian Ocean's geological history and its significance in the context of global environmental change.

Keywords: Evolution, Genesis, Ninety East ridge, Tectonics, Geophysical Studies

INTRODUCTION

The Indian Ocean was formed by a complex series of seafloor spreading episodes that began with the split of Madagascar from Africa and "Greater India" from northwest Australia in the Late Jurassic [1,2].

India continued to shift northward after its separation from Antarctica in the Early Cretaceous [3,4] and the Ninety East and the Chagos-Laccadive Ridges formed as hotspot traces [5–8]. The Ninety East Ridge (NER) is thought to have been formed on the Indian plate when it moved northward over the Kerguelen hotspot between 82 and 38 Ma [5,9]. This Ridge of the Indian Ocean is one of the world's largest aseismic volcanic lineaments named after its near-parallel strike along the 90th meridian in the Eastern Hemisphere [10,11]. It stretches around 5000 km from the Bay of Bengal to the Southeast Indian Ridge [11] with an average width of 200 km and extends between 33° S and 17° N latitudes [12]. The top of the Ridge rises 3.5 km above the

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surrounding abyssal plain, which is up to 2000 m below sea level [10], and divides the Indian Ocean into east and west halves [13]. The Southern end (south of 15° S) of the Ridge is often wider and more open than the Northern end [3,14]. The portion of the Ridge in the Bay of Bengal consists of pelagic and hemipelagic sediments [15] as the Bengal fan sediments bury the Northern part of the Ninety East Ridge [16–18]. Seasonal monsoon circulation patterns dominate oceanographic conditions of the Ninety East Ridge.

The unique hydrological conditions of the Indian Ocean make it an ideal location for studying the effects of global and regional stress on environmental changes over time. Thus the study of the Ninety East Ridge provides a unique opportunity to examine the Indian Ocean's oceanic and climatic evolution, the effects of tectonic uplift of the Himalayas and Tibetan Plateau and the history of volcanic activity in the nearby Indonesian Arc. During the past decades, the Deep-Sea Drilling Project (DSDP) sites have been the focus of the majority of research on the Ninety East Ridge. These previous studies along the Ridge and the adjacent basins provide data ranging from the Upper Cretaceous to Recent [19].

The geological and geophysical history of the Ninety East Ridge can be traced back through several stages. General ideas about its structure were obtained during the 1950s to the end of the 1960s. The Ninety East Ridge was discovered by the International Indian Ocean Expedition (IIOE) in 1962-1965 as an extended Ridge, and before that, it was identified as distinct uplifts in the bottom relief. The principal geological and geophysical data on the Ninety East Ridge were acquired during various International expeditions in the 1970s and 1980s, with the first data on the Ridge's deep structure uncovered during the 1976 *R/V Vityaz* excursions [20]. Deep Seismic Sounding (DSS) was utilized to determine the structure of the oceanic crust beneath the Ridge [21,22] and since then, the results have been used to predict the structure of the Ninety East Ridge [23,24]. Expeditions to the Ninety East Ridge dwindled in the early 1990s and were re-established in 1997. The majority of research works in and around the Ridge were carried out in various Deep Sea Drilling Program (DSDP) sites and the Ocean Drilling Program (ODP) sites.

Previous literature gives emphasis on the evolution and formation of the aseismic Ridges. The present study is a brief review (Table 1) of the geological (Sedimentological, Microfaunal and Geochemical studies) and geophysical (Bathymetric, Seismic, Gravity and Magnetic studies) investigations carried out along the Ninety East Ridge. This review will give a systematic understanding of the evolution, tectonics, genesis and sediment provenance of the Ninety East Ridge. The review is arranged in a systematic way as following (Table 1).

Table 1. Review of the Geological and Geophysical investigations along the Ninety East Ridge (NER).

Year	Authors	Proxies used	Inference drawn
<i>Geological Investigations</i>			
1989	Srinivasan [25]	Planktic foraminifera	Established Neogene planktic foraminiferal biostratigraphy.
1990	Gupta & Srinivasan [26]	Benthic foraminifera	Based on benthic foraminiferal frequency shifts, four intervals of important faunal and climatic transitions have been documented in the Northern Indian Ocean during the Pliocene-Pleistocene.
1991	Duncan [8]	Isochron dates from ⁴⁰ Ar- ³⁹ Ar	Age of the Ridge is determined as 38 Ma in the south and 82 Ma in the north.
1991	Farrell & Janecek [27]	Planktic foraminifera, CaCO ₃ wt % and coarse fraction wt%	Described the oceanographic and climatic conditions that prevailed during the evolution of the Northeast Indian Ocean over the last 7 Ma.
1991	Weis <i>et al.</i> [28]	Sr, Nd and Pb isotopes	Interpreted that the Kerguelen hotspot was active for 115 Ma.
1992	Srinivasan & Chaturvedi [29]	Planktic foraminifera	Major epoch boundaries, Pliocene/Pleistocene, Miocene/Pliocene and Oligocene/ Miocene were recorded along the NER.
1992	Gupta & Srinivasan [30]	Benthic foraminifera	Use of <i>Uvigerina proboscidea</i> as proxy for high surface productivity during the strong summer monsoon and Antarctic ice sheet formation in the Northern Indian Ocean.

1993	Clemens <i>et al.</i> [31]	Sr isotopes	Global Pliocene Sr isotope stratigraphy was established from the Equatorial Indian Ocean.
1993	Singh & Srinivasan [32]	Planktic foraminifera	Four significant climatic cooling episodes were marked based on the <i>Pulleniatina</i> occurrence in the Northern Indian Ocean.
1994	Bassinot <i>et al.</i> [33]	Pelagic carbonates	Established a Composite Coarse Fraction Index (CCFI) curve from the Owen Ridge and the NER sediments for the last 1500 years.
1994	Gupta [34]	Benthic foraminifera	Elucidated a general relationship of the interactions between benthic fauna and water masses of the Indian Ocean.
1995	Chen <i>et al.</i> [35]	Stable isotopic studies of benthic foraminifera	From oxygen and carbon isotopic records of <i>Cibicides wuellerstrofi</i> , an Astronomical Age Model (AAM) for the last 3.6 Ma is generated from the Northeast Indian Ocean.
1995	Nomura [36]	Benthic foraminifera	Recorded the Paleogene to Neogene climatic and oceanographic history of the Indian Ocean based on benthic foram distribution patterns.
1998	Srinivasan & Sinha [37]	Planktic foraminifera	The Indonesian Seaway acts as a biogeographic barrier for planktic foraminifera between the Indian and Pacific Oceans during the Neogene.
2001	Gupta <i>et al.</i> [38]	Benthic foraminifera	Long term shifts in species diversity in the Northeast Indian ocean, at its lower bathyal to abyssal depths during early to middle Miocene was explained.
2003	Gupta & Thomas [39]	Benthic foraminifera and oxygen isotopes	Established a strong link between the changes in the intensity of the Indian monsoon system, biotic activity in the Indian Ocean and Northern Hemisphere Glaciation (NHG).
2004	Gupta <i>et al.</i> [40]	Benthic foraminifera	During 10-8 Ma, a high productivity event was recorded in the Eastern Indian Ocean.
2005	Singh & Gupta [41]	Benthic foraminifera	Established a link between the increase in productivity and decline in benthic foraminiferal species diversity in the Indian Ocean.
2006	Kawagata <i>et al.</i> [42]	Benthic foraminifera and organic carbon	Increased chemical ventilation in the Northern Indian Ocean during glacial periods caused global decline and extinction of the Stilostomellidae, Pleurostomellidae, and Nodosariidae.
2008	Bhaumik <i>et al.</i> [43]	Benthic foraminifera	Across the Mid-Pleistocene Transition (MPT), <i>Stilostomella lepidula</i> (Schwager) disappeared due to intensified glacial cycle in the Indian Ocean.
2009	Tantawy <i>et al.</i> [44]	Planktic foraminifera and calcareous nannofossil	Late Maastrichtian volcanism in the Indian Ocean has caused consequences on planktic foraminifera and calcareous nannofossils and is comparable to those of the K-T mass extinction.
2010	Singh & Gupta [45]	Benthic foraminifera and Nd isotopic studies	At 11.5 Ma, the movement of intermediate to deep Indonesian Throughflow (ITF) water from the Pacific to the Indian Ocean increased dramatically.
2011	Frey <i>et al.</i> [46]	Major and trace elements	NER was built up of basaltic magma.
2012	Ahmad <i>et al.</i> [47]	Stable isotopes of planktic and benthic foraminifera	During the 60-80, 21-17, and 13-11 ka B.P., studies along the Northeast Indian Ocean suggest a decrease in North Atlantic Deep Water (NADW) contribution and an increase in intake from the Southern Ocean Deep Water (SODW).
2013	Silva <i>et al.</i> [48]	Pb-Hf-Sr-Nd isotopes	Established a relation between origin of the NER with the Kerguelen, Amstradam and St. Paul hotspots in the Indian Ocean.
2015	Frey <i>et al.</i> [49]	Trace element and Hf isotopes	NER basalts were derived from a residue of ancient partial melting.
2015	Slotnick <i>et al.</i> [50]	Lithologic, nannofossil, stable isotope and carbonate content	Early Paleogene experienced significant changes in net organic carbon flux to and from the exogenic carbon cycle across the NER.
2016	Hein <i>et al.</i> [51]	XRD	A widespread occurrence of the Fe-Mn crust is demarcated along the NER.

2017	Banerjee <i>et al.</i> [52]	Stable isotopes of planktic and benthic foraminifera	Miocene Climatic Optimum, Monterey excursion, East Antarctic Ice Sheet formation, Initiation of Indian Monsoon with waning of Antarctic Glacier and evidence of a cooling event were reconstructed along the NER in the Northeastern Indian Ocean.
2018a	Luo <i>et al.</i> [11]	Palynological studies	Since 16 kyr B.P., a pollen source shift was noticed from Sumatra Island to Srilanka.
2018b	Luo <i>et al.</i> [53]	Palynological studies	The study concluded that the equatorial region has higher pollen concentrations and salinity than the Northern Hemisphere.
2019	Devendra <i>et al.</i> [54]	Benthic foraminifera and stable isotopic study	Paleoceanography of the last 56 yrs of the Northeastern Indian Ocean is deduced from isotope and faunal records.
2019	Lübbbers <i>et al.</i> [55]	Stable isotopes of benthic foraminifera, XRF and carbonate accumulation rates	A first comprehensive benthic isotope stratigraphy for the Indian Ocean over the last 13.5 to 8.2 Ma, which documents a long period of carbonate impoverishment in the Equatorial Indian Ocean.
2020	Barnet <i>et al.</i> [56]	Stable isotope and trace element	The first long-term sub-eccentricity-resolution of stable isotopes and trace element records from the Indian Ocean's water column from the late Paleocene to early Eocene.
2020	Biswas & Bhaumik [57]	Benthic foraminifera	Stillostomellidae, Pleurostomellidae and Nodosariidea families disappeared due to long-term enhanced cooling caused by successive changes in climate cycles throughout MPT, as well as augmentation of glacial intensity during Mid-Brunhes.
2020	Devendra <i>et al.</i> [58]	Stable isotopic studies of planktic and benthic foraminifera	The Northern Indian Ocean has experienced major changes in water mass evolution over the last 56 kyr B.P.
2021	Ali <i>et al.</i> [59]	Sr, Nd and Pb isotopes	The spatial pattern of South Asian Monsoon-Induced silicate weathering has a consistent provenance over the last 27 Ma in the Southern BoB; these sources are dominated by Himalayan rocks and the Indo-Burman ranges.
2021a	Bretschneider <i>et al.</i> [60]	Sr, Pb and Nd isotopes	Despite major tectonic reorganizations in the Himalayas, the clays transported to the Ninety East Ridge remained remarkably persistent during the Miocene.
2021b	Bretschneider <i>et al.</i> [61]	Sr, Pb and Nd isotopes	First orbital scale resolution records of Miocene radiogenic Sr, Nd and Pb isotope composition of detrital clay from the BoB.
2021	Singh <i>et al.</i> [62]	Benthic and planktic foraminifera	Intensification of the NHG between 3 and 2 Ma caused an increase in Antarctic Intermediate Water (AAIW) inflow in the Southeastern Indian Ocean.
2021	Song <i>et al.</i> [63]	Clay Mineralogy and Sr-Nd isotopes	Early and late Miocene Himalayan uplift triggered the South Asia's river development and provenance changes in the Southern BoB.
2022	Khogenkumar <i>et al.</i> [64]	geochemical and isotopic (Sr-Nd) investigation	The Indian plate dragged Young Kerguelen plume material northward during the Cretaceous-Paleocene, covering 2220 km, with deep fractures reactivating to trigger magma emplacement around 58 million years ago.
2022	Seo <i>et al.</i> [65]	Total Organic Carbon, Sr-Nd isotope studies, and Clay Mineralogy Studies	Stable surface ocean conditions over 13,000 years, regardless of Indian summer monsoon (ISM) variability, suggest using longer sediment records to reconstruct changes in major river system runoff and Late Quaternary Indian monsoon precipitation patterns in the BoB.
2022	Xu <i>et al.</i> [66]	Clay Mineralogy and Sr-Nd isotope studies	ITCZ significantly affects millennial-scale sediment supply, controlling rainfall in Myanmar and directly impacting smectite clay mineral supply during the late LGM, revealing complex Northern and Southern Hemisphere interactions in the eastern Indian Ocean.
2023	Cai <i>et al.</i> [67]	Textural Analysis, Sr-Nd isotope Analysis, and Clay mineral analysis	Over 35,000 years, terrestrial materials in the NER sediments originate from the Qinghai-Tibet Plateau, transported via the Irrawaddy River to the Andaman Sea and then westward by monsoon-driven circulation, with limited changes except during the Younger Dryas climate period.

2024	Qi <i>et al.</i> [68]	$\delta\text{Eu}-(\text{Gd}/\text{Yb})\text{N}$, Chemical index of alteration, and (Ti/Ca, Rb/Sr) ratio studies	Northern NER sediment transport and responses to climate show shifts from Ganges-Brahmaputra to Irrawaddy River sources since the last glacial period, with millennial-scale weathering variations tied to Indian monsoon and sea level changes.
Geophysical Investigations			
1991	Royer <i>et al.</i> [69]	Bathymetric and magnetic data	Reported late Cretaceous–early Oligocene slow westward migration of the Kerguelen/Ninety East hotspots based on kinematics model.
1991	Tamaki <i>et al.</i> [70]	Deformation rate	Demarcated a normal fault stress field at ODP site 758 A.
1992	Klootwijk <i>et al.</i> [71]	Paleomagnetic research and paleolatitude age profile	A model was prepared on the Indian plate's northward journey during the last 80 Ma.
1999	Krishna <i>et al.</i> [72]	Magnetic data	NER was formed by an interaction between the Kerguelen hotspot and the Wharton spreading centre.
2000	Grevemeyer & Flueh [73]	Gravity and bathymetric data	A model was proposed to show the influence of crustal underplating on the NER's sinking history and isostatic compensation.
2001	Grevemeyer <i>et al.</i> [74]	Seismic survey	Crustal underplating was observed beneath the Indian Ocean's NER.
2001	Kopf <i>et al.</i> [75]	Geophysical surveys	Surveys suggest that 58 Ma basaltic basements along the central NER is indicative of decayed volcanism.
2003	Tiwari <i>et al.</i> [76]	Satellite gravity and bathymetric data	Large volcanic plateaus and provinces lead to the emplacement of Northern and Southern parts of the NER relative to the central part.
2008	Subrahmanyam <i>et al.</i> [77]	Bathymetry, satellite-derived free air gravity and seismic data	En-echelon block structure of the Ridge is the result of complex strike-slip and subduction tectonic pressures.
2010	Sager <i>et al.</i> [78]	Satellite-derived gravity data, multibeam bathymetry and seismic reflection profiles	Faulted structures formed near the spreading Ridge that separated the Indian and Antarctic plates indicates the hotspot was never far from it.
2010	Levchenko <i>et al.</i> [79]	Bathymetric, magnetometric, seismoacoustic and gravimetric	Geological and geophysical data were used to illustrate the NER's complicated tectono-magmatic origin.
2012	Krishna <i>et al.</i> [80]	Magnetic anomaly profiles	The distance between the Kerguelen hotspot and spreading Ridge segments changed during the creation of the NER.
2013	Sreejith & Krishna [24]	Bathymetry, geoid and gravity data	With the occurrence of subcrustal underplating, the NER has a highly segmented isostatic pattern.
2014	Levchenko <i>et al.</i> [81]	Multibeam bathymetry data and multichannel seismic profiles	Described the NER's tectonics and developed two Ridge formation models.
2015	Sreejith & Krishna [82]	Satellite-derived bathymetry, free-air gravity, sediment thickness and seafloor age data	Variations in Indian plate motion and frequent Ridge jumps play a major role in magma generation along the NER.
2018	Marinova [83]	Seismostratigraphic research	Antarctic Circumpolar Current (ACC) and a change in the Indian Ocean's hydrodynamic regime caused the middle Miocene hiatus across the NER.
2019	Illarionov <i>et al.</i> [84]	Geophysical approaches	The NER was formed on an ancient planetary lineament.
2021	Levchenko <i>et al.</i> [20]	Global seafloor topography and gravitational field satellite data	Elucidated the nature and evolution of the NER.

2021	Lemenkova [85]	High-resolution bathymetric, geological and gravity datasets	Ocean floor modelling was carried out to understand spatial variations in the geomorphology of the NER.
2023	Yutsis <i>et al.</i> [86]	Bathymetric survey using multibeam	New insights into the seamount structure of the Northern NER in the Indian Ocean suggest a two-stage magmatism history driven by a transverse strike-slip fault.
2023	Levchenko <i>et al.</i> [87]	Bathymetric and Magnetic Survey	The northern segment of the NER displays young tectonic fractures, a narrow elevated block between volcanic edifices, volcanic seamounts, and complex magnetic anomalies spanning a wide age range from about 20 to over 80 million years old.

CONCLUSION

In conclusion, this comprehensive review has thoroughly examined geological and geophysical research conducted along the Ninety East Ridge (NER) in the Indian Ocean. As the world's longest linear rise, the NER holds significance for understanding the tectonics, evolution, geological setting, and provenance of this unique feature. Through an analysis of various datasets and research findings spanning from the Paleocene to the present day, this review has shed light on the processes that have shaped the NER over millions of years.

Geological investigations have revealed the NER's complex paleoceanographic and paleoclimatic evolution, highlighting its connection to global climatic events such as the Mid-Pleistocene Transition, the Indian Monsoon, and changes in water mass evolution. Meanwhile, geophysical studies have focused on understanding the NER's interactions with hotspots, spreading centers, and its genesis, nature, and evolution.

Overall, this review underscores the importance of the Ninety East Ridge as a key geological feature in the Indian Ocean, providing valuable insights into global tectonic dynamics, paleoclimate patterns, and the distribution of marine life throughout Earth's history. By synthesizing data from multiple disciplines, this review contributes to our broader understanding of the Indian Ocean's geological history and its significance in the context of global environmental change. Furthermore, it highlights avenues for future research to unravel Ninety East Ridge's complexities and role in shaping the Earth's oceans and climate.

Statements and Declarations

All authors listed meet the criteria for authorship as outlined in the journal's guidelines. Each author has contributed substantially to the conception, design, acquisition, analysis, or interpretation of data, drafting or revising the manuscript critically for important intellectual content, and has approved the final version to be published.

Conflict of Interest Statement:

The authors declare that they have no conflicts of interest relevant to the content of this manuscript.

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Author Contribution

NRN: Conceived the concept, KA: Scrutinized the literature, KA & NRN: Wrote and edited the manuscript.

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