

Mid-ocean ridges, InRidge and the future

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In this article, we chronicle the events that lead to the creation of a global scientific network for mid-oceanic ridge research, identify areas where Indian researchers could participate and built a case to support and gain momentum within the country for the young, emerging InRidge programme.

THE first ocean-wide bathymetric chart was of the North Atlantic¹ that depicted the existence of the Mid-Atlantic Ridge (MAR). The British government-funded HMS CHALLENGER expedition (between 1872 and 76) resulted in a large database and the findings were published in 50 volumes², dealt with the sounding data and geological and biological samples.

One of the major geological findings has been that of large continuous mid-ocean ridges (MOR) that are ~ 70,000 km long (Figure 1 a), with an average width of 300 km and elevated ~ 2000 m above the seafloor. In some cases, MOR either intrude into the continents (e.g. East Coast of Africa and the Gulf of California) or subduct below the continent (West Coast of Chile) or manifest as a landmass (e.g. Iceland). MOR are the constructive margins (divergent boundary) of the oceanic plates, where new oceanic lithosphere is continually generated due to rifting and are characterized by high heat flow and marked seismicity. The formation of MOR is generally ascribed to rapid upwelling of mantle material of peridotitic composition.

Simultaneous with the discovery of the MOR, the theory of 'Continental Drift' was proposed³. About 200 Ma ago there was a single supercontinent (Pangea) surrounded by a superocean (Panthalassa). When the Northern landmass (Laurasia) split from the Southern landmass (Gondwanaland) ~ 135 Ma ago, India drifted north towards Eurasia and a rift developed between South America and Africa. Large scale plate reorganization occurred ~ 65 Ma ago, during which time the North Atlantic and Indian Oceans were shaped, the South Atlantic widened and Australia was still attached to Antarctica. Gradually a number of events came about such as the separation of Australia

from Antarctica and of Laurasia into North America and Eurasia and the initiation of collision between India and Eurasia (> 65 Ma to ~ 33 Ma (ref. 4)). The driving mechanism to carry the floundered continents was unknown but in 1960s, Hess⁵ and Dietz⁶ independently proposed the concepts of 'Plate Tectonics' and 'Seafloor Spreading'.

Proponents of plate tectonic hypothesis conceive the earth's crust to be made up of seven major lithospheric plates: four of continental types (Eurasian, N. American, S. American and African), three of oceanic types (Pacific, Atlantic and Indian) and 14 minor ones (Arabian, China, Philippine, Cocos, Caribbean, Nazca, Fiji, Somali, Scotia, Antarctica, Anatolian, Sandwich, Juan de Fuca and Indo-Australian). The MOR are the best examples of divergent plate boundaries wherein, new oceanic crust is continuously generated at a variable speed (spreading rate) along a narrow axial rift valley. These areas typically have shallow focus earthquakes, high heat flow and are volcanically active. The oceanic plates move at variable rates: slow (< 40 mm/yr, full rate; Atlantic; Indian), intermediate (40–80 mm/yr, Juan de Fuca, East Pacific Rise 21°N, EPR; SouthEast Indian Ridge, SEIR) and fast to ultrafast (80–160 mm/yr; EPR 5–14°N)⁷.

The abrupt changes in seismic velocity imply the presence of different rock types at various depths. A typical section through the oceanic crust reveals four layers: an uppermost layer 1 (0.5 km thick) of ocean floor sediments, layer 2 (2.5 km thick) of basalts as lava flows and dykes, layer 3 (2.5 to ~ 7 km thick) of gabbros and the deep-seated layer 4 composed of peridotite. The existence of these layers has also been confirmed through sampling (dredging and drilling).

The wealth of information collected during the International Indian Ocean Expedition in 1962 and later by the Russians, resulted in remarkable maps of the Indian Ocean^{8,9}. Marine geologists were keen to drill at the MOR and into the oceanic crust to better understand the various geophysical and geochemical characters. Although drilling the ocean floor is not so easy or economical as on land, but a beginning was made by Lamont Geological Observatory, Scripps Institution of Oceanography and leading universities. In the 1960s, the specialized drilling vessel, DV GLOMAR CHALLENGER, was used under the auspices of the Deep Sea Drilling Project (DSDP). In

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1985, the Ocean Drilling Project (ODP) used the more sophisticated JOIDES RESOLUTION to drill into the oceanic crust. So far, drilling of the oceans' floor has yielded kilometres of samples in the form of drill hole cores. The deepest of these holes, measuring over 2100 m, penetrated under 200 m of sediment cover and sampled 1900 m of oceanic crust near the EPR¹⁰.

One major fall-out from investigating the MOR is that of hydrothermal activity. At places where seawater percolates down through the cracks and fissures in the oceanic crust, it encounters hot rocks, leaches the elements and concentrates these into hydrothermal deposits. These deposits laden hot water rises to the sub-seafloor to form

hydrothermal vents and chimneys. This fact gained acceptance when hydrothermal vents were discovered in the Atlantic and Pacific Oceans¹¹. The water temperature could be $< 30^{\circ}\text{C}$ to $> 350^{\circ}\text{C}$ and under such conditions, minerals like galena, pyrite, chalcopyrite, gypsum, silica, baryte and many others precipitate. The fastest forming chimneys reported from the EPR, grow at a rate of 8 cm in height and 2 cm in diameter everyday¹².

Hydrothermal sites have unusual ecosystems in which the primary production that forms the local food cycle depends on chemosynthetic bacteria that exist at elevated temperatures and derive their energy by oxidizing sulphide from the vents. A vent community may comprise of tube-worms, crabs, seaworms, clams and mussels. These organisms due to their enhanced metabolism mature and reproduce quickly; qualities that are advantageous because activities at some vents may cease to exist while newer ones may appear¹³. The influence of hydrothermal vents on the chemical, thermal and ecological balances in the world oceans needs to be understood through detailed and continuous water column measurements and sampling along the entire MOR. These could help to establish the primary vent field locations, the geochemical characteristic of the plume and their distribution and dispersal patterns.

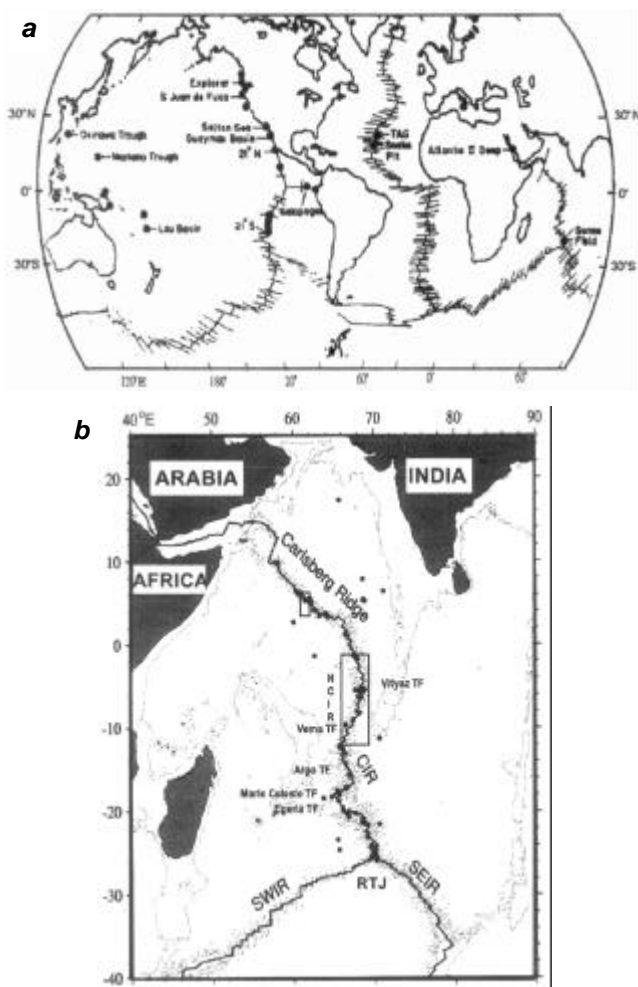


Figure 1. *a.* The meandering mid-oceanic ridges in the three oceans together with the sites of active hydrothermal activities. The 'Sonne Field' in the Indian ridge system encompasses the sites discovered by German, Japanese and American researchers. *b.* Map showing the Indian Ocean Ridge System (IORS) and 125 dredge locations along the Carlsberg–Central Indian Ridge. The data have been compiled from 30 different references. (Data bank is available with the authors.) Presently our areas of investigations are marked on the Carlsberg Ridge (CR $\sim 3^{\circ}\text{N}$ to 5°N) and the Northern Central Indian Ridge (NCIR $\sim 2^{\circ}$ – 12°S). The areas between 10° – 6°N , 4° – 1°N , 2° – 5°S , 6° – 9°S and 10° – 14°S need to be thoroughly studied. Base map has been taken from ETOPO5 map⁴⁷. NCIR, Northern Central Indian Ridge; CIR, Central Indian Ridge; SEIR, SouthEast Indian Ridge; SWIR, SouthWest Indian Ridge; RTJ, Rodriguez Triple Junction; TF, Transform Fault.

International efforts and developments in MOR investigations

Although a study of the MOR is useful from academic and possibly from economic viewpoints however, such investigations are extremely arduous and expensive in terms of logistics, resources, manpower and rapidly developing technology. Therefore, it was essential to synergize the efforts of many Institutions and Universities to ensure optimum input to obtain appreciable achievements. With these yardsticks, the RIDGE (Ridge Inter-Disciplinary Global Experiments) was conceived and formalized in 1987 at a Workshop sponsored by the Ocean Studies Board of the National Academy of Sciences, USA. RIDGE (now RIDGE 2000) provides ample opportunities for innovative science and integrate exploration and experiment and theorise to understand the earth's evolution. Resources are pooled in by the participating institutions and by NASA (National Aeronautic and Space Agency of the USA), USGS (US Geological Survey) and NSF (National Science Funding). RIDGE identified six major research components: global structure and fluxes, crustal accretion variables, mantle flow and melt generation, event detection and response, temporal variability of ridge crest phenomena and biological studies. Based on a number of critically considered criteria such as a good background knowledge of current circulation, presence of diverse and abundant deep-sea communities, evidence for recent volcanic and hydrothermal activities, in 1991 RIDGE first explored the Cleft Segment on Juan de Fuca, near Iceland¹⁴.

Besides the USA, simultaneously other countries began an interactive and interdisciplinary initiative (www.inridge.org) of MOR research to form the InterRidge (IR). Under the IR, the capabilities and motivations of nations grew rapidly and in the process, a stronger international networking and excellent scientific and logistic coordination has been agreed. To achieve the objectives of the IR, Australia, Canada, France, Germany, Iceland, Italy, Japan, Korea, Mexico, Norway, Portugal, Russia, Spain, UK and US pooled in their expertise. Some of the national ridge research programmes of various countries are: Bridge (Britain, this programme is now over), CanRIDGE (Canada), R-RIDGE (Russia), DORSALES (France, the programme ended in 2001 and is under transition) and DeRIDGE (Germany, presently the programme has been extended for another six years). The IR has a Steering Committee (STCOM) to oversee the development and implementation of its various programmes. This committee consists of a cross-section of the global ridge researchers. A central office (presently in Japan) is involved to plan activities, hold special conferences, conduct workshops, disseminate information and sponsor post-doctoral candidates. As the IR programmes moved from the planning to operation stage, sub-committees were formed, with the mandate to manage the individual programmes and present recommendations and reports to the STCOM.

In essence, the main issues concerning ridge studies are to: acquire a balanced set of global data of the entire MOR system and understand the mantle dynamics and the process of metal deposition; observe, measure and monitor active processes at individual ridge sites in order to quantify the magma fluxes and heat emitted by the mantle that conceivably influence the chemistry of the ocean; to decipher the evolution, reproduction strategies and dispersion paths of organisms existing near hydrothermal vents and the interplay between geological processes and biological activities.

The Indian perspective

The MOR in the Indian Ocean manifest itself as the Central Indian Ridge (CIR) that bifurcates to form the SouthEast Indian Ridge (SEIR) and SouthWest Indian Ridge (SWIR) (Figure 1). These three ridges meet at the Rodriguez Triple Junction (RTJ, 25°S/70°E). In the north, the CIR forms the Carlsberg Ridge (CR) truncating against the Owen fracture zone and extending north-westward as Sheba Ridge into the Red Sea. In addition to these features, there exists the Andaman Back-Arc Basin (ABAB) in the Andaman Sea.

Ridge research in India was mostly individual-driven but it set the pace for subsequent activities¹⁵⁻¹⁸. It was realized that a coordinated effort at a national level is necessary and hence in 1997 the InRidge was conceived with affiliation to the IR. Initially, India was a corresponding member of the IR but in the year 2000 she

became an associate member. This was to help India have a firm say to her advantage during the STCOM's formulation of research plans. In 2001, India's proposal for a Carlsberg-Central Indian Ridge (CR-CIR) working group¹⁹ was enthusiastically received at the June 2001 STCOM and at the Next Decade Working Group in December 2001.

InRidge is a national umbrella body of ridge research that aims to integrate, plan and foster collaboration amongst various individuals and institutes. InRidge would seek to avoid repetition and make effective use of the available expertise and resources of the country. Furthermore, it would facilitate cooperation between Indian ridge researchers and nominate them on International expeditions, working groups and research programmes.

Under the InRidge programme, currently four research projects (three at the National Institute of Oceanography (NIO)) and one at National Geophysical Research Institute (NGRI) are in progress. Two projects are investigating parts of the CIR, the one at the NIO is funded by the Office of Naval Research (USA) and the other at the NGRI is funded by the Department of Science and Technology (DST, India). The CR project is funded by the Department of Ocean Development, New Delhi while the DST is funding the ABAB project.

So far, seven expeditions (> 250 cruise days) have been undertaken, two each along the CR-CIR and three in the ABAB. The results of India's expeditions appear promising and it is expected that these investigations (a gist of these follows) would lead to unravel the secrets held by the Indian Ocean.

Central Indian Ridge

The InRidge plans detailed geophysical and geological studies at four major intersections between the CIR and the transform faults: Vityaz (5°44'S), Vema (8°45'S), Argo (13°45'S) and Marie Celeste (16°37'S), and the ridge segments between them (Figure 1 b). We envisaged documenting the regional tectonic fabric, with special reference to growth and evolution of transform faults and near-axis seamounts, petrological studies especially of mantle-derived rocks and searching for possible hydrothermal sites.

The new data collected from the CIR have so far revealed its complex nature that could probably be the result of short ridge segments, influence of the fracture zones and interaction between the CIR and the Wide Boundary Zone that separates the Indo-Australian plate^{20,21}. Basalts (pillowed and columnar) have been recovered which together with the seafloor magnetic data probably indicate overprint magnetization in parts of the ridge²². Initial observations of the manganese nodules indicate a possible mixed hydrothermal-hydrogenous source for the metals. On the basis of the calcareous nannoplankton assemblages recovered from the substrate of a ferromanganese crust from the Vityaz fracture zone, an early Pliocene

age has been assigned for a change in the depositional environment. This coincided with the hiatuses that resulted from the incidence of intermediate Somali or the Western Boundary subsurface currents²³.

Indications of active hydrothermal discharge, vent biota, or shimmering water were absent at the Sonne site²⁴ (Figure 1). The area has, therefore, been considered to represent an extinct, inactive (fossil) zone. The occurrence of small cracks (< 0.5 m) and fissures (1–4 m wide), low angle normal faults (up to 15 m displacement) at the slopes of the central ridge indicate a tectonic rather than a volcanic stage of ridge development, where hydrothermal activity is weak. The recent discoveries of an active hydrothermal site on the CIR include an area north (25°18'–20°S) of the Rodriguez triple junction²⁵ and massive sulphide deposit²⁶. On 19 April 2001, American researchers discovered an active hydrothermal site and a seamount at 23° 52.7'S (www.divediscover.who.edu). To the north occurs sulphide-impregnated and pure silica precipitates of hydrothermal origin²⁷.

Carlsberg Ridge

The CR was one of the earliest ridges to be studied for its petrology^{28,29} and was followed by discovery of magnetic stripes³⁰. During the maiden voyage of *ORV Sagar Kanya* in 1983, a segment of the CR was dredge and detailed petrology of the basalts^{31,32} and the geophysical aspects were reported³³. A 120-km-long section of the ridge was mapped and besides basalts, upper mantle rocks were recovered³⁴.

Indications of weak hydrothermal activity were detected in the CR³⁵. However, the occurrence of sulphide specks in amphibolites and granulites seems to be from the uplifted materials from the mantle. Basal sediments from the DSDP Site 236 (1°40'S, 57°38'E) with enrichment in iron (28%) were reported to be the products of low intensity hydrothermal activity³⁶.

Andaman Back-Arc Basin

Under the ABAB project, the NIO has mapped an area of 30,000 km², using multibeam bathymetric system. Furthermore, gravimeter, magnetometer and single channel seismic data and rocks and sediments were also collected. The ABAB is an area of subduction with complex morpho-tectonic fabrics, a spreading center, seamounts and faults. Evidence of hydrothermal activity is borne out by the occurrence of disseminated and vein type pyrite mineralization in the rocks³⁷ and by the presence of hydrocarbons in the sediments³⁸. The irregular pyrite lumps and rods (3–4 cm) in the sediments, from the intersection of west Andaman fault and the spreading center, suggest widespread hydrothermal activity in the region.

In addition to the above planned projects, significant work has been done at the CR by the Geological Survey of India on the magnetic lineations³⁹ and micropalaeon-

tology^{39–42} and by the National Geophysical Research Institute on the gravity and isostasy⁴³ and effect of fluid circulation on the thermal structure⁴⁴. Furthermore, individual researchers have studied parts of the CIR with respect to the gravity⁴⁵ and near-ridge intraplate seismicity⁴⁶.

The future

Only ~ 25% of the 4200 km long intricate CR–CIR system is known and in addition very few studies have been made in the ABAB. Hence, a vast tract of the ridges and the basin await discovery. Some key issues that need to be addressed by the InRidge are: tectonic architecture, ridge–transform interaction, incipient triple junction formation and relation of spreading kinematics of CR–CIR with the seismicity of the Indian sub-continent. The location of active hydrothermal sites and their characteristics and ridge–crest biological communities are also of priority. These efforts could result to develop a model for ridge–crest processes and hydrothermal events.

The response to InRidge has been overwhelming. Already more than 50 scientists working in varied fields of geology, geophysics, water chemistry and biology, and affiliated to several universities, Indian Institutes of Technology and national laboratories have evinced interest by enlisting with InRidge. The Indian scientific community having interest in the fascinating world of MOR should come together under InRidge to set goals, give directions, coordinate and monitor high-quality multidisciplinary integrated scientific research. Incidentally, the first decade of IR has been completed and at the STCOM meet in September 2002 at Italy, the science plans (especially for the Indian Ocean) for the next decade were discussed. Furthermore, at this moment, the Council of Scientific and Industrial Research, New Delhi, has earmarked ridge studies as a thrust programme for the X 5-year plan. Presently, science plans and proposal are afoot to turn this 'dream' into a reality.

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