

# Metallogenesis along the Indian Ocean Ridge System

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Twenty years after the discovery of the sea-floor hot springs, vast stretches of the global mid-ocean ridge system still remain unexplored for locating hydrothermal vents. In comparison to the mid-oceanic ridge systems of the Pacific and the Atlantic, so far the Indian Ocean Ridge system (IORS) drew less attention from the world researchers towards finding out hydrothermal deposits. But recently several investigations took place in this direction by investigators of about half a dozen countries including India. Among these studies majority were concentrated around the Central Indian Ridge and the Southwest Indian Ridge areas, while a few observations were made around the rest of the areas in the IORS. The findings of these studies are discussed here.

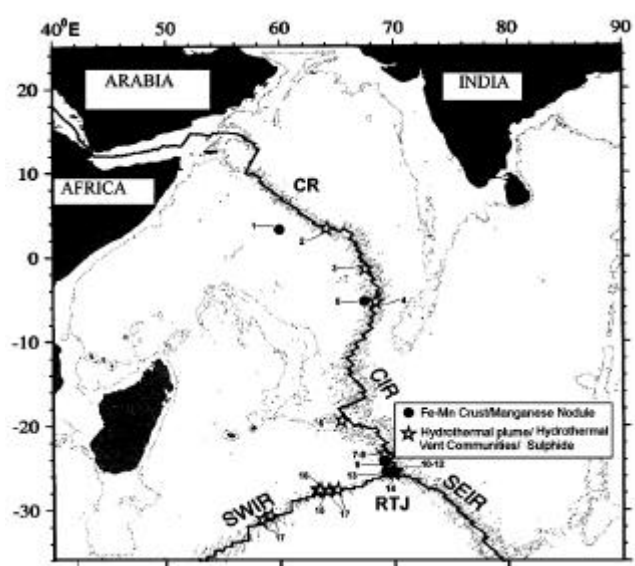
In this article we briefly synthesize the findings of all those studies pertaining to mineralization along the IORS, spanning just more than a decade, including the one which could locate the first active hydrothermal black smoker deposit along this ridge system (Figure 1). The observations summarized here comprise the results obtained from the Central Indian Ridge (CIR), Southwest Indian Ridge (SWIR), Southeast Indian Ridge (SEIR), Carlsberg Ridge (CR), and Andaman back arc basin, including both hydrothermal and hydrogenous deposits (Table 1).

## Central Indian Ridge

Magnetic anomalies along seven northeast-southwest profiles across the CIR segment (latitudes 18° and 22°S and longitudes 66° and 69°E) revealed the existence of a northwest-southeast trending median valley, associated with a broad and high-amplitude magnetic anomaly (the central anomaly) along the ridge crest<sup>1</sup>. In this study, a series of linear magnetic anomalies (2, 2A, 3, 3A and 4) parallel to the ridge were identified and a half spreading rate of 22 mm/yr was estimated for the last 10 Ma. This study further indicates a ridge jump between the anomalies 2–2A (approx. 2.5 Ma) and presence of a new left

lateral transform fault offsetting the ridge axis by about 50 km.

Herzig and Plüger<sup>2</sup>, and Plüger *et al.*<sup>3</sup> reported the existence of an inactive hydrothermal field and a hydrothermal plume site along the CIR, about 200 km northwest of the Rodriguez Triple Junction (RTJ). They termed it as SONNE Hydrothermal Field after the famous German research vessel *FS Sonne*. This field is located at lat. 23°23.6'S and consists of hydrothermally influenced basalts and sediments, layered ferromanganese precipitates, and blocks of massive sulphides. The deposit occurs at a depth of about 2800 m close to the crest of a central neo-volcanic ridge. The ridge occurs as an along-strike topographic high and appears to be in a tectonic stage of rift development. A hydrothermal plume with maximum concentration of 202 nM methane (CH<sub>4</sub>) and a temperature anomaly of +0.05°C was delineated at 24°03'S (hydrothermal plume site). Manganese concentrations were as high as 23.1 nmol/kg and showed a significant positive correlation



**Figure 1.** A comprehensive map (not to scale) showing various locations of Fe–Mn crust, manganese nodule, hydrothermal plume, hydrothermal vent communities and sulphides reported so far along the IORS. All 17 locations shown in this map are as per sl. no. in Table 1. CIR, Central Indian Ridge; SWIR, Southwest Indian Ridge; SEIR, Southeast Indian Ridge; RTJ, Rodriguez Triple Junction.

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with CH<sub>4</sub>. The plume site was located close to the eastern wall of the rift valley, which is dominated by closely spaced normal faults. The mode of occurrence of this plume suggests tectonic stage of rift evolution which creates channel-ways for such hydrothermal discharge. Neither the spaced extension and composition of the SONNE Hydrothermal Field nor the source of the methane/manganese plume could however be established.

Jean-Baptiste *et al.*<sup>4</sup> reported the presence of a hydrothermal <sup>3</sup>He plume north of the RTJ at 19°29'S, 65°54.4'E along the CIR during cruise onboard the *RV Marion-*

*Dufrense* in April 1988. The highest variation in *d*-<sup>3</sup>He recorded so far in the Indian Ocean, shows a spike of 33.8% at 2460 m water depth. They correlated the <sup>3</sup>He data with dissolved manganese and methane and deduced ratios of CH<sub>4</sub>/<sup>3</sup>He and Mn/<sup>3</sup>He. The Mn/<sup>3</sup>He (3.8 × 10<sup>4</sup> g/cm<sup>3</sup> STP) is comparable to that of East Pacific Rise (EPR) at 21°N (4.2 × 10<sup>4</sup> g/cm<sup>3</sup> STP) and that of Juan de Fuca Ridge (3.3 × 10<sup>4</sup> g/cm<sup>3</sup> STP) (refs 5, 6) while the CH<sub>4</sub>/Mn data are close to those of average value along EPR (9 × 10<sup>4</sup> g/cm<sup>3</sup> STP)<sup>7</sup>. On a regional scale, the <sup>3</sup>He distribution over the RTJ exhibits a notable increase in <sup>3</sup>He at the

**Table 1.** A compilation of reported metallogenesis along the IORS

Sl. no.	Location	Ridge/Back arc	Geologic setting and type of deposit
1.	3°N/60°E	CR	Manganese nodules from the southern part of Carlsberg Ridge. Water depth 3600–4500 m (ref. 32)
2.	3°35'N/64°07'E		Magmatic sulphide–oxide mineralization in Carlsberg Ridge rocks. Water depth 3750 m (ref. 30)
3.	1°40'S/67°46'E		Presence of hydrothermal sulphide globules in the rocks from Owen fracture zone, North Western Carlsberg Ridge <sup>31</sup>
4.	5°23.7'S/68°35.1'E	CIR	Magmatic sulphide–oxide mineralization near the Vityaz Fracture Zone. Water depth 3500 m (ref. 29)
5.	5°33.90'S/67°53.40'E		Presence of thick ferromanganese crust and nodules from Vityaz Fracture Zone. Water depth 3500 m (refs 16, 17)
6.	19°29'S/65°44'E		Presence of hydrothermal <sup>3</sup> He and manganese plume north of the RTJ. Water depth 2460 m (ref. 4)
7.	23°23.6'S/69°14.4'E		200 km NW of RTJ. Water depth 2800 m (SONNE Hydrothermal Field) Fossil Hydrothermal Field <sup>2,3</sup>
8.	23°23.63'S/69°14.43'E 23°23.38'S/69°14.48'E		3 km west of the rift axis of the fourth segment of the RTJ. Water depth 2870 m MESO Zone, Extinct Hydrothermal Field first report of massive sulphide from IORS (refs 8–12)
9.	24°05.30'S/69°32.03'E 24°06.25'S/69°32.79'E 24°14.30'S/69°40.92'E 24°05.20'S/69°41.65'E 24°00.03'S/69°37.7'E		North of RTJ Ferromanganese encrustation with distinct hydrothermal signature. Water depth 2466–3730 m (ref. 15)
10.	25°18'S/70°01.23'E		12 miles north of RTJ hydrothermal plumes. Water depth 2300 m (ref. 13)
11.	25°19'S/70°03'E		Dive of Shinkai 6500 submersible located heaps of dead shells (at CIR near RTJ). This is the first demonstration of <i>in situ</i> biological communities associated with hydrothermalism along the IORS <sup>21</sup>
12.	25°19.17'S/70°02.40'E		First hydrothermal vent communities discovered on a volcanic knoll at the eastern crest of an axial valley ~ 22 km north of RTJ. Water depth 2420–2450 m (ref. 19). The same site also locates the active black smoker chimney 'Kaarei field' <sup>14</sup>
13.	25°24'S/69°45.36'E and 25°16.30'S/70°08.63'E		Layered Fe–Mn crust from off axis region of the first segment of the CIR, mixed hydrogenetic–hydrothermal signature. Water depth 2700–2800 m (ref. 18)
14.	25°50'S/70°E	SEIR	Sediments of SEIR near RTJ show mixed hydrothermal and hydrogenous signature <sup>28</sup>
15.	27°50.97'S/63°56.15'E	SWIR	Segment of 11 of SWIR, signature of extinct hydrothermal activity along SWIR on the Mt Jourdanne. Water depth 2941 m (ref. 21)
16.	27°51'S/63°56'E		Relict hydrothermal field, east of Melville fracture zone. Water depth 2940 m (ref. 25)
17.	27°46'S/65°08'E 27°55'S/64°27'E 27°58'S/63°33'E 30°51'S/59°23'S 31°04'S/58°58'E 31°11'S/58°30'E		Signatures of fossil, as well as active hydrothermal deposits, at six locations from SWIR a 200 km long section within. Water depth 3100–4100 m (ref. 20)
18.	10°N to 11°40'N	Andaman Back arc	Evidence of hydrothermal activity in the Andaman Back arc Basin comprising broken parts of chimney structures and rocks with disseminated and vein type metal sulphides. Water depth 2000–4100 m (ref. 33)

CR, Carlsberg Ridge; CIR, Central Indian Ridge; SWIR, Southwest Indian Ridge; SEIR, Southeast Indian Ridge.

ridge crest and appears to spread eastwards through the deep Indian Ocean<sup>4</sup>.

The massive sulphide from the Indian Ocean was first described during the *Sonne 92* cruise (1993), and later during *Meteor 33/2* cruise (1995). During these cruises three individual sulphide fields were discovered and sampled at about 3 km west of the rift axis of the fourth segment of the RTJ, at about 23°S, and the area was named as MESO Zone<sup>8</sup>. This zone represents an extinct hydrothermal field with a size of 0.6 km<sup>2</sup> in the Central Indian Ocean and occurs at a water depth of about 2870 m. The genesis of these sulphide deposits was described later indicating the difference in their mineral compositions, age of formation and states of weathering<sup>9–12</sup>.

Subsequently, Gamo *et al.*<sup>13</sup> studied the light transmission anomalies in the water column in different parts of the IORS. During this study, Mn, Fe, Al, and CH<sub>4</sub> concentrations were searched in different segments of the central, southeastern and southwestern parts of the IORS centered on the RTJ (~ 25°32'S, ~ 70°02'E), for the purpose of locating hydrothermally active areas. They located a new hydrothermally active site in the CIR segment (25°18'S), approximately 22 km north of the RTJ, where significant hydrothermal plumes were observed at 2200–2400 m water depth. During this survey, intensive *tow-yo* observations using a CTD rosette multi-sampling system equipped with a transmissometer, revealed that the plumes have temporal and spatial variations. Discrete water samples within the plumes were enriched in Mn, Fe, and CH<sub>4</sub>, with maximum concentrations of 9.8 nM, 40.2 nM and 3.3 nM respectively. Judging from the spatial and chemical characteristics of the plumes, especially from transmission anomalies and CH<sub>4</sub>/Mn ratios, they speculated that the hydrothermal venting site might not be in the rift valley but on the eastern off-axis zone, several kilometers away from the rift valley. During a recent survey<sup>14</sup>, the first active black smoker chimney was discovered nearly at 24 km north of the RTJ, on the southwestern flank at an off-axis knoll, named as 'Kairei field'.

Nath *et al.*<sup>15</sup> described the mineralogy and the geochemistry of the ferromanganese crusts recovered from five locations (at a water depth 2466 m–3730 m) from the spreading CIR (between 24°00.03'S and 24°14.30'S) north of the RTJ. The crusts are highly porous, have maximum oxide thickness of 2 cm, and occur on basaltic substrates. The composition of the crusts resembles that of hydrothermal ferromanganese crusts from other oceanic-spreading centers. Compared to hydrogenous ferromanganese crusts and nodules, the hydrothermal crusts exhibit very low Mn/Fe ratios, lower transitional metal contents, low  $\Sigma$ REE contents and negative Ce anomalies. Geochemical signatures of these crusts show similarities with metalliferous sediments and hydrothermal deposits recovered from other areas. Shale-normalized REE patterns indicate that the hydrothermal contribution to these crusts is between 60 and 92%. Crusts studied by Nath *et al.*<sup>15</sup>

are consistent with the earlier findings on water column temperature and chemical anomalies around this area, indicating presence of hydrothermal activity in the region. It was suggested that some aspects of these crusts, such as *d*-MnO<sub>2</sub> mineralogy and middle REE enrichment, are not typical of hydrothermal Fe–Mn oxides<sup>15</sup>. Microprobe studies show that some layers within these crusts have Mn/Fe ratios close to unity, indicating a significant input from normal seawater. Growth rates, estimated from an algorithm based on Mn, Fe and Co contents, are orders of magnitude faster than rates determined for hydrogenous Fe–Mn oxides. The outer layers and some internal layers of the crusts had relatively faster growth rates, indicating that the crusts precipitated from distinct hydrothermal episodes. Similar ferromanganese crusts of about 25–32 mm thickness have also been reported from a western off axis segment at northern part of the CIR on Vityaz Fracture Zone (5°33.9'S, water depth 3500 m). From initial geochemical signatures these crusts appear to be of mixed hydrothermal–hydrogenous origin<sup>16</sup>. These crusts have been formed on basaltic and carbonate substrates. On the basis of calcareous nannoplankton assemblages, the age of formation of these crusts was estimated as late Pliocene<sup>17</sup>.

In continuation of the search for active hydrothermal sites in the Indian Ocean, Halbach *et al.*<sup>10</sup> reported the geological setting, mineral zonation of different sulphide types, and described the different stages of formation of the 'Sonne Sulfide Field', which is part of a larger mineralized zone identified initially by Plüger *et al.*<sup>3</sup>. During a cruise in the Central Indian Ocean in December 1993, Halbach *et al.*<sup>10</sup> recovered the first massive sulphides from the Indian Ocean floor, north of RTJ, in the fourth CIR segment, close to the rift axis and it is hydrothermally inactive. This deposit appears to be of typical mid-ocean ridge massive sulphide type but is in a phase of disintegration and about to be buried by sediment. The chimney structures were formed by multiple hydrothermal events and are now degraded by mass wasting showing various stages of weathering. Later-stage, low-temperature hydrothermal mineralization processes led to copper and gold enrichment in this deposit.

Kuhn *et al.*<sup>18</sup> studied the geochemistry and mineralogy of the layered Fe–Mn crusts recovered from the off-axis region of the first segment of the CIR north of the RTJ. Vernadite (*d*-MnO<sub>2</sub>) is the main mineral oxide phase in these crusts. <sup>230</sup>Th<sub>xs</sub> and Co concentrations suggest high growth rates of up to 29 mm/Myr and a maximum age of the basal crust layer of 1 Ma. Most of the major and minor elements show concentrations typical of hydrogenetic formation, including strikingly lower concentrations of Co, Pb, Ni and Ti. Concentration and distribution of the strictly trivalent rare-earths and yttrium (REY) are typical of hydrogenetic ferromanganese oxide precipitates, but in marked contrast, the crusts are characterized by negative Ce<sub>SN</sub> (shale normalized) anomalies and

(Ce/Pr)<sub>SN</sub> ratios less than unity. Profiles through the crust reveal only minor variations of the REY distribution, and (Ce/Pr)<sub>SN</sub> ratios range from 0.45 to 0.68 (compared to ratios of up to 2 for typical hydrogenetic crusts from the Central Indian Basin). The apparent bulk partition coefficients between the crusts and seawater suggest that for the strictly trivalent REY the adsorption–desorption equilibrium has been reached. Positive Ce anomalies in the partition coefficient patterns reveal preferential uptake of Ce, but to a lesser extent than in normal hydrogenetic crusts. A new parameter (excess Ce) to quantify the degree of decoupling of Ce from REY(III) is established on the basis of partition coefficients. Ce<sub>XS</sub>/Ce<sub>bulk</sub> ratios suggest that the CIR crusts formed by precipitation of Fe–Mn oxides from a hydrothermal plume and that in hydrothermal plumes and normal seawater the enrichment of Ce results from the same oxidative sorption process. The growth rates, calculated with <sup>230</sup>Th<sub>XS</sub> data and with the Co formula, appear inversely related to Ce<sub>XS</sub>.

Finally, Hashimoto *et al.*<sup>19</sup> reported the occurrence of active black smokers at the CIR and also located the presence of thriving chemosynthetic communities associated with these active chimney deposits at a depth between 2420 and 2450 m, on a volcanic knoll at the eastern crest of an axial valley, approximately 22 km north of the RTJ. The biological communities were distributed in a 40 m by 80 m field around the knoll. At least seven active vent sites, including black smoker complexes that were emitting superheated water at 360°C, were observed at the field. From these findings, they concluded that the faunal composition of the Indian Ocean hydrothermal vent communities has similarities with that of both the Pacific and the Atlantic oceans. This would support the postulation that there exists a significant communication between vent faunas of the Pacific and the Atlantic Oceans via active ridges of the Indian Ocean.

### Southwest Indian Ridge

German *et al.*<sup>20</sup> discussed the findings of the hydrothermal activities along the SWIR. This ridge represents a particularly intriguing region, as it is not only the slowest-spreading among the main ridges but also the sole modern migration pathway between the diverse vent fauna of the Atlantic and the Pacific Oceans. A recent model<sup>20</sup> postulates that a linear relation exists between the vent frequency and the rate of spreading, and predicts vent fields to be scarcest along the slowest-spreading ridge sections, thus impeding migration and enhancing faunal diversity. The presence of hydrothermal plumes at six locations within two 200-km-long sections of the SWIR indicates a higher frequency of venting than expected<sup>20</sup>. These results suggest that fluxes of heat and discharged chemicals from slow-spreading ridges may be greater than that previously thought of and that faunal migration

along the SWIR may serve to identify an important corridor between the Pacific and the Atlantic hydrothermal fields.

Fujimoto *et al.*<sup>21</sup> described in detail the first submersible investigation on mid-ocean ridges of the Indian Ocean, which was carried out in September–October 1998 during the INDOYO cruise, with the submersible Shinkai 6500 onboard R/V *Yokosuka*. The objectives of this investigation were to obtain detailed information about accretionary processes along the SWIR, and to locate new hydrothermal vent sites in the Indian Ocean.

The SWIR, which separates the African and the Antarctic plates at ultra-slow half rate of 0.77 to 0.8 mm/yr, represents an end-member of the global ridge system in terms of spreading rate. The SWIR has been selected by the InterRidge program as an important target of global ridge studies. Although many active hydrothermal vent fields with specific biological communities have been found and sampled on the Mid-Atlantic Ridge (MAR) and on the EPR, no active sites have been located in the Indian Ocean until 2000. The vent fauna of the MAR are different from that of the EPR<sup>22,23</sup>. Considering the importance of the Indian Ocean Ridges as the main propagation pathway between the Atlantic and the Pacific vent fauna, another site in the first segment of the CIR north of the RTJ, where geochemical anomalies were observed earlier<sup>13</sup>, was also examined<sup>21</sup> but without any major success.

To characterize the accretionary processes in the ultra-slow spreading environment, Fujimoto *et al.*<sup>21</sup> attempted seven dives on Segment 11 (~ 64°E)—two on the axial volcanic ridge (AVR), three on a ‘megamullion’ and two in the non-transform discontinuity (NTD). Some of the larger fissures on the eastern AVR of Mt Jourdanne show a strong spatial relationship to the location of extinct hydrothermal sites. Favoured by both volcanic (heat source) and tectonic activity (pathways for fluid convection) several extinct hydrothermal sites were found lying within an area of approx. 0.5 km<sup>2</sup> at a water depth of about 2941 m (27°50.97’S, 63°56.15’E) and these were related spatially either to the graben or to the smaller fissures. These are the first known records of sulphide mineralization along the ultra-slow spreading SWIR21.

Hydrothermal precipitates consist of sulphide impregnated basalts, and massive sulphides dominated by pyrite, sulphates and oxides. Hydrothermal products occur on the ocean floor as mounds with an average size of about 5 m<sup>3</sup>; the mounds are usually cracked and highly weathered at the surface. Besides mound-like structures, small chimneys were also observed on the ocean floor. During the INDOYO cruise it was possible to sample sulphide chimneys from the SWIR. These chimneys are tube-shaped and consist of sphalerite, chalcocopyrite, pyrite and minor amounts of sulphates. Silica seems to be more or less absent in chimney samples, which might explain the fra-

gility of chimney edifices. The chimneys are fully covered by manganese encrustations.

During this study, Fujimoto *et al.*<sup>21</sup> could not find indication of any hydrothermal activity along the SWIR other than presence of extinct sites on the Mt Jourdanne, and later they sampled the CIR near the RTJ. Two dives were undertaken on a spur extending to the NW from the crestal ridge at 25°19'S, 70°03'E, where earlier very fresh hydrothermal plumes were observed<sup>31</sup> in 1993, and which had been expected to converge, as suggested by the CH<sub>4</sub>/Mn ratio values of the water column. Heaps of dead shells were found on the ocean floor just on the landing site of the first dive. Shells of two species of Calyptogena were sampled, and the shell heaps were regarded to represent *in situ* biological communities, related to the former or possibly to recent hydrothermal activity<sup>21</sup>. The characterization of the hydrothermal vent communities has been highly expected by most marine biologists to depict the global distribution map of chemosynthetic communities to understand their propagation mechanisms and evolution. This is the first recognition of *in situ* biological communities associated with hydrothermalism along the Indian Ridge system. In addition, the CTD attached to Shinkai 6500 detected bottom temperature anomalies of about 0.05°C at a location close to that of the observed transmission anomalies. These findings further support the existence of recent hydrothermal activity around the survey area.

Using the submersible Shinkai 6500, Sohrin and Gamo<sup>24</sup> reported hydrothermal activity at 31°05'S, 59°00'E and 27°54'S, 64°29'E on the SWIR, and at 25°19'S, 70°02'E in the off-axis area of the CIR, just north of the RTJ. Although seven dives failed in locating the active venting site, strong anomalies of light transmission (up to 0.5%) were found at 2200–2450 m depth during the dives in the off-axis area of the CIR, suggesting that hydrothermalism was active in this area. In addition, temperature anomalies were observed on the bottom of the off-axis area of the CIR and the SWIR. The strongest temperature anomalies of ~0.1°C were observed around Mt Jourdanne (27°50.97'S, 63°56.15'E) area located at the axial volcanic ridge in the SWIR, where the first extinct chimneys were found in the Indian Ocean. Munch *et al.*<sup>25</sup> described the mineralogy, chemistry and chronology of the sulphide samples collected from the relict hydrothermal field along the SWIR near 63°56'E. The findings of the *Shinkai* 6500 submersible proved that high-temperature massive sulphide chimneys can also develop at a ultra-slow spreading ridge system, and the chronology of these deposits indicates that they might have formed between 70,000 and 13,000 years ago<sup>25</sup>.

### Southeast Indian Ridge

Evidence for the existence of hydrothermal plumes overlying the medium-fast-spreading SEIR has been obtained

recently by Scheirer *et al.*<sup>26</sup>. However, the full spreading rates reported for SEIR (65 mm/yr)<sup>27</sup> indicate that a higher abundance of hydrothermal venting was expected there in comparison to SWIR (14 mm/yr), while observations indicate somewhat reverse case. German *et al.*<sup>20</sup> indicated that tectonic processes can lead to the higher abundance of hydrothermal venting along slow-spreading ridges which would be predicted from the spreading rate alone. In order to relate the accumulation rates of sediment components to the volcanic and hydrothermal activities of the respective ridge segments, Kuhn *et al.*<sup>28</sup> further investigated the sediments from the CIR and SEIR near the RTJ. Their findings show that the sediments contain 50–90% biogenic carbonates and have been deposited over a period of the last 2.5 million years without large hiatuses. In addition, there has been no evidence of early diagenetic element mobilization and the main primary geochemical signals are preserved in the sediments. A three-step multivariate analysis of carbonate-free geochemical data showed that the sediments consist of two main end members with respect to Si, Ti, Al, Fe, Mg, K, Mn, Cu, Ni and Zn, which are mixed in different ratios in the sediments<sup>25</sup>. The first end member comprises volcanic detrital components, mainly basalt fragments, basaltic glass and their weathering products (smectites). The second end member is made up of hydrothermal Fe–Mn oxides. The volcanic detritus in these sediments are distributed via bottom currents, and the Fe–Mn oxides are formed as particle fallout from hydrothermal plumes. The first component dominates in the rift valley and the second on the ridge flanks. Along the SEIR, varying accumulation rates were found to reflect the cyclic magmatic–volcanic activity of the intermediate-spreading rift axis. In cores from the CIR, the accumulation of both end members reflects the evolution of a non-transform fault separating the first and the second CIR segments rather than the spreading axis history.

### Carlsberg Ridge

Magmatic sulphide–oxide mineralization in CR at 5°23'N was reported first by Baturin and Rozanova<sup>29</sup> in amphibolites and granulites and these rocks appear to have been uplifted from a deeper crust. Basal sediments from the Deep Sea Drilling Project (DSDP) site 236 (1°40'S, 57°38'E) also show higher content of Fe-oxide (28%) of hydrothermal origin. Later, Banerjee and Iyer<sup>30</sup> also reported magmatic sulphide–oxide mineralization in the basalts at 3°35'N of the CR. They observed the presence of chalcopyrite, pyrite and magnetite in these basalts and confirmed their findings by petrographic and subsequent studies using an electron microprobe. However, Rona *et al.*<sup>31</sup> indicated the presence of hydrothermal sulphidic globules in the rocks from the Owen Fracture Zone, at northwestern part of the CR.

Petrographic study of ferromanganese nodules collected from the southern part of the CR indicates that the nuclei of nodules are generally composed of clay, volcanic glass, basalt fragments, and broken parts of older nodules<sup>32</sup>. Polished sections of ferromanganese nodules reveal typical collomorphic globular segregations and partly crystalline oxides (todorokite). Scanning electron micrographs indicate that the segregations are made up of small and large botryoids, and also occasional presence of todorokite platelets were observed within cavities formed by the process of post-depositional recrystallization. X-ray diffraction patterns do not show any peaks of todorokite due to their poor crystallinity, while *d*-MnO<sub>2</sub> is seen in all the nodules studied. The nodules analysed contain: Mn 15.01–21.40%, Fe 10.07–20.10%, Cu 0.07–0.32%, Ni 0.32–0.57% and Co 0.07–0.21%, with a Mn/Fe ratio less than 2, indicating their hydrogenetic origin. A recent study on the geochemical sedimentation processes active in the CR and adjacent areas also indicated that the hydrogenetic sedimentation process in this region<sup>16</sup> is most predominant in comparison to other processes such as, hydrothermal and diagenetic.

### Andaman back arc basin

Evidence for hydrothermal activity in the Andaman back arc basin, at the southern part of the Bay of Bengal between 9° and 11°S, was initially reported by Rao *et al.*<sup>33</sup>. After a detailed survey of the Andaman basin, the Central Andaman Trough area was mapped by a multibeam bathymetric system during the Cruise 89 (1994) of the Indian research vessel *Sagar Kanya*. Later, during 1995, using the Russian research vessel, *AA Sidorenko*, chartered by Govt of India, magnetic, gravity and seismic surveys of this area were also completed. Sampling was carried out at water depths between 2000 m and 4100 m to locate, for the first time, a fossil chimney with disseminated and vein type sulphide mineralization indicating its relationship to back arc spreading and associated volcanism.

The above cited evidences of metallogenesis along the IORS would definitely encourage future ridge research to locate new mineral deposits along this ridge system. Keeping in mind this objective, an international project on ridge-related research activities was initiated at the National Institute of Oceanography, Goa since 1997 with necessary funding support from ONR, USA. Presently under the newly introduced CSIR NETWORK project scheme, a multi-institutional project (involving other CSIR laboratories and academic institutions) on similar objective has been just launched at NIO, Goa which is expected to fulfil the dreams of the Indian ridge researchers.

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