A documentation on burrows in hard substrates of ferromanganese crusts and associated soft sediments from the Central Indian Basin

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Substrates of ferromanganese encrustations collected from the hummocky topography of the Central Indian Basin (CIB) (lat. 12°25′–12°45'S, water depth between 5150 and 5300 m) are largely composed of indurated claystone and altered pumice fragments, which are extensively bioturbated. Both the ferromanganese-coated and uncoated relict burrows have been collected from the same locality. Mobile epibenthic megafauna, e.g. molluscs, echinoderms, etc. seem to be the main bioturbating organisms. The adjacent sediments on the sea floor also show numerous records of recent bioturbation activity. Thus presence of the ancient and modern burrows from the same locality on the ocean floor indicates a prolonged bioturbation activity in this part of the CIB and this may have been a continuous process, pre- and post-dating the initiation of the formation of ferromanganese oxides at this place. The intense and prolonged bioturbation activity of the benthic fauna reported here indicates that they could have facilitated the occurrence of ferromanganese nodules at the sediment–water interface.

Among the deep-sea benthic community the mobile epibenthic megafuna are large (>ca 1 cm) and conspicuous members of this community[1]. They are ecologically important[2] and are significant contributers to bioturbation[1,3–7]. Megafauna burrows in soft sediments, as well as burrows preserved in rocky bottoms and hard indurated substrates at many low-sedimentation areas of the world oceans are well documented[3,8–10]. Urchin (Echinoidea) burrows are common in deep-sea sediments, and chemical changes associated with the burrows have been noted at some of the locations[1,11,12]. The role of bioturbation in deep-sea sediments as a means of cycling carbon in the deep ocean[13–15] and of supply and concentration of organic matter and metallic and radionuclide elements at the sediment–water interface has been well established in some places[16].

Associations of a rich benthic fauna and ferromanganese nodules were earlier reported from the North Pacific[17–18] and Indian Ocean[19]. The population density and biomass of benthic fauna at different depths in the Western and Central Indian Basin (CIB) were studied by Parulekar *et al.*[20,21]. They also observed that the fer-

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romanganese nodules in CIB are associated with a rich benthic fauna. At a depth of 5000 to 5499 m, 28.8% of the megafauna consists of Peracarid arthropods, which are voracious deposit feeders and can greatly contribute to the recycling and regeneration of bottom deposits and faecal matters[21]. The effects of bioturbation in recent sediments on organic carbon decomposition, and pore-water nutrient mobility in the CIB have been noted by Nath and Mudholkar[22]. Characterization of palaeoenvironments has also been attempted in the CIB from the studies of well-preserved relict bioturbation features[23,24]. Banerjee *et al.*[25] attributed the irregular distribution of radionuclides in one siliceous ooze core to recent bioturbation. From sea-floor photographic records, Sharma and Rao[26] have documented features of recent deep-sea bioturbation within and around the manganese nodule-rich regions of the CIB. Furthermore, Banerjee[27] and Gupta[24] recorded the ancient relict features of bioturbation in the oxide and nucleus parts of ferromanganese nodules and crusts from the CIB.

Although features of ancient and recent bioturbation are recorded from different areas of the CIB, no systematic documentation has been attempted to study the chronology of bioturbation in the CIB *vis-à-vis* the initiation of ferromanganese oxide precipitation. Here, an attempt is made to document both ancient and recent bioturbation that occur in deposits younger than Palaeogene, in the indurated substrates of ferromanganese encrustations, and in the underlying soft sediments of the CIB. The results suggest the occurrence of continuous bioturbation process in this basin which could keep the manganese nodules at the sediment–water interface for several million years.

The samples were collected from an area in the CIB, bounded by 12°25' and 12°45'S latitudes and 79° to 79°20'E longitudes (Figure 1). The bathymetry of the area was mapped by a hydrosweep system and also by a 3.5 kHz echosounder. The water depth varies between 5150 and 5300 m (Figure 1). The sea-floor topography is hummocky as observed from the echograms (Figure 2). Altogether there were 37 dredge operations and a total of 8042 kg of nodules and encrustations were collected. Numerous hard indurated fragments of claystones and partially altered pumice pieces with extensive features of ancient relict borings and burrows dominate the dredged collections. From these collections representative samples with prominent bioturbation features were selected for the present study (Figure 3 *a–g*). In addition, the photographic records of recent bioturbation (Figure 4 *a* and *b*) on soft sediments were taken using a deep-towed camera.

Extensive fossil burrows are seen in the claystone and altered pumice substrates of many ferromanganese encrustations and nodules (Figure 3 *a–g*). Among the observed relict burrow features, at least in one of the semiconsolidated claystone substrates, which appears to
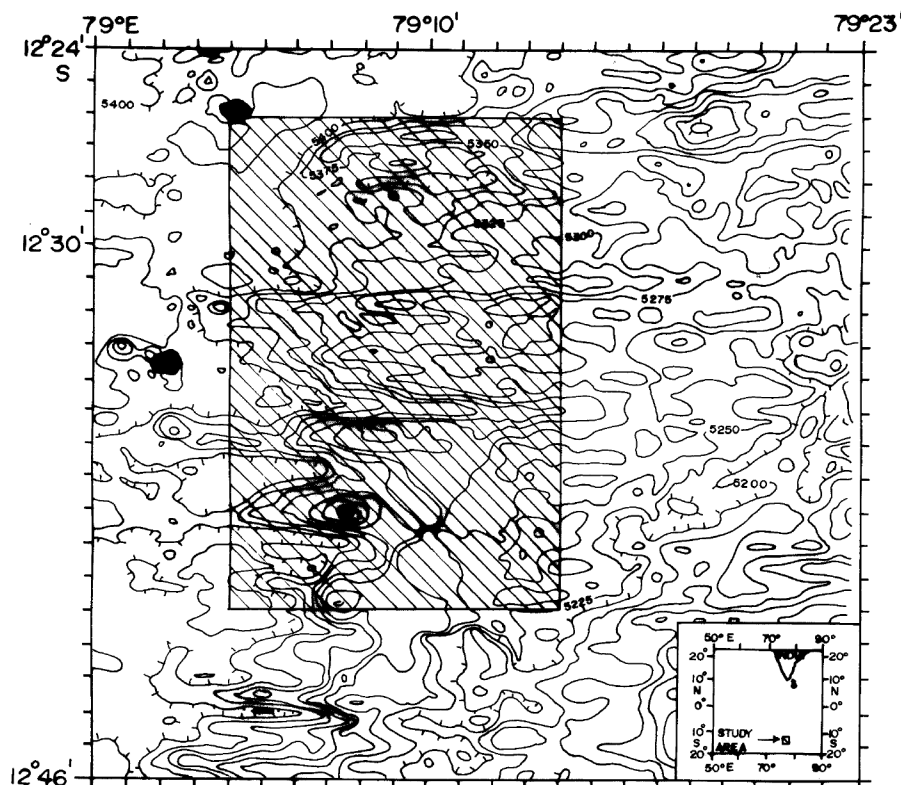
Figure 1. Detailed bathymetry (contour interval 25 m) of the study area. The dark black patches in the north-western and western parts of the area are sea-mounts. The hatched portion indicates the dredged area.
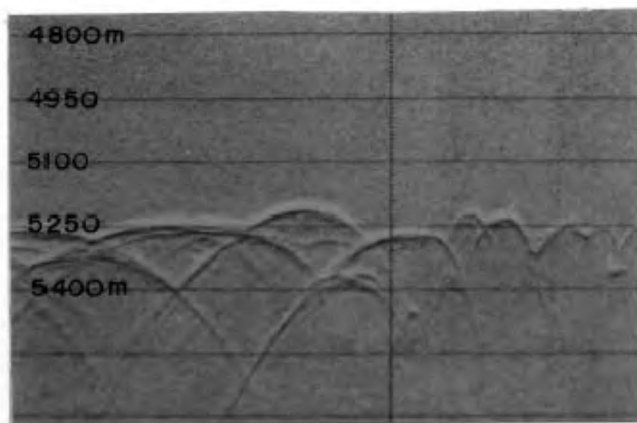

Figure 2. 3.5 kHz echogram of the sea-floor showing undulated topography and hummocky structure. The numbers indicate the water depth of the area.

be of recent origin, very clear cross-hatched marks were observed on the burrow walls (Figure 3 h). One of the associated organisms collected with these samples is Echinodermata (Figure 3 i).

The diameter of the fossil burrows varies from 3 to 10 mm. Their length ranges between 1 and 10 cm in different substrates (Figure 3 a–g). Some burrows are

straight, while others are multichannelled. The channels are interconnected, tube-shaped, and in places filled with mud (Figure 3 e). In some places these burrow channels are empty, and at times they are coated with thin veneer of ferromanganese oxide (up to 2 mm thickness). Following Bromley[28], the fossil burrows are classified as Thalassinoides (Figure 3 a, b, d and e) and Planolites (Figure 3 c). Trypanite borings (Figure 3 f) are also seen. Burrows filled with sediments are grouped as Planolites. Thalassinoide burrows show a horizontal network of more or less 'Y-shaped' cylindrical tubes.

Presence of tracks, trails, burrows, etc. on the sea floor of the CIB was recorded using a deep-towed camera (Figure 4 a and b). These features indicate recent extensive activity of the mobile epibenthic megafauna[26]. Unlike the relict burrow features on hard substrates described earlier, these recent bioturbation features on soft sediments include faecal coils – which begin and end abruptly on the sea-floor (Figure 4 a) and also burrow mark on soft sediment (Figure 4 b).

From the relict bioturbation features (Figure 3 a–g) it is interpreted that the claystone and altered pumice substrate materials were subjected to extensive burrowing activity by benthic organisms at different times pre and post-dating the initiation of deposition of ferromanga-
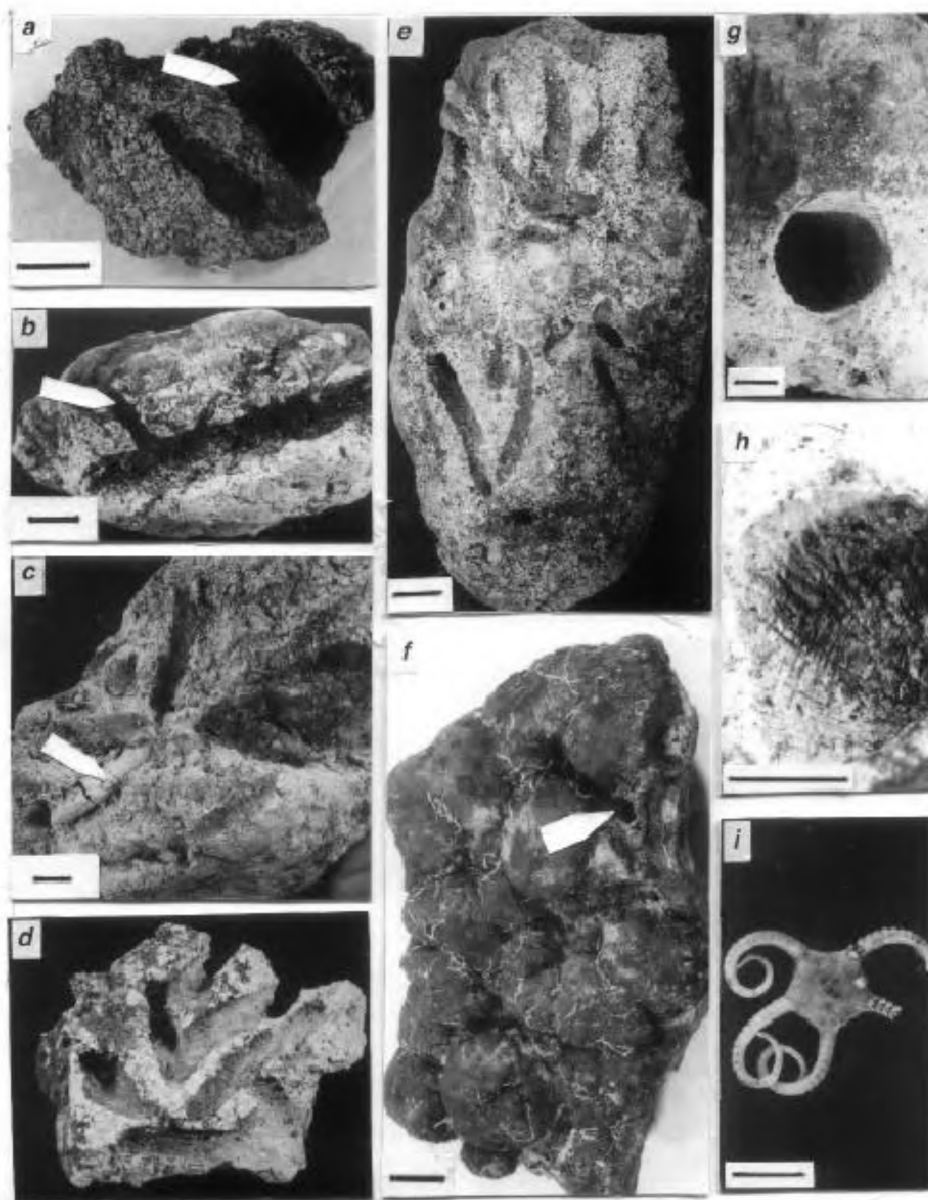
Figure 3. Photographs of different ancient relict burrows and borings from the CIB (scale bar = 1 cm); *a*, *b*, 'Y-shaped' Thalassionide burrows with cylindrical tube nature and with a thin film of ferromanganese coating on some of the burrow walls (see arrow); *c*, Cylindrical-shaped planolite burrow, partly filled with sediments (see arrow); *d*, *e*, Horizontal network of thalassionide burrows on hard indurated clay (*d*) and pumice (*e*) substrates; *f*, Ferromanganese encrustation with a (trypanite) boring mark (see arrow) on the surface. The fine white thread-like features on the surface are the benthic foraminiferal tubes living on the encrustation; *g*, Indurated clay fragment with a large burrow feature; *h*, Enlarged view of the burrow wall of Figure 2 *g*, with distinct cross-hatched marks on its surface; *i*, Echinodermata, recovered from a depth of 5200 m with the studied samples expected to be among chief bioturbating agents. Class: Ophiuroidea, Genus: Ophiothrix, Popular name: Brittle star.

nese oxides. The presence of ferromanganese coated (up to 2 mm thickness, Figure 3 *a* and *b*) and uncoated (Figure 3 *d*, *e* and *g*) burrow channels could indicate that at the time of formation of those burrows, some of the burrow walls may have had some coating of organic matter, excreted by the active biota, or due to some bacterial activity. Thus burrow walls became a favourable site for the initiation of organo-metallic complexation or chelation at suitable Eh, pH and redox conditions. Possibly the formation of ferromanganese coatings was initiated on some of these relict burrow walls, while the uncoated empty channels could be of more recent origin. The maximum oxide thickness of a ferromanganese crust that has been observed in the CIB[29] is about

4.4 cm. Based on $^{232}Th_{ex}$, the maximum growth rate of this crust was calculated to be 3.4 ± 0.4 mm/Ma (ref. 29). Using their growth rate, the substrate materials with ferromanganese coating (of 2 mm thickness) would be older than 2.2 to 2.8 Ma, while the exact time of the initiation of the formation of Fe–Mn coating remains unknown. Earlier, at four other locations in the CIB, similar substrates of sixteen ferromanganese nodules and crusts, with fossil burrow and borings, were dated as Palaeogene based on icthyolith studies[23,24].

In the course of searching for the patchily-distributed food resources on the ocean floor, the mud in-filling could have been excreted by the deposit-feeding epibenthic megafauna as back-fill in the case of Planolite burrows (Figure 3 c). In one of the semi-consolidated claystone substrates, which appears to be of recent origin, the very clear cross-hatched marks observed on the burrow walls (Figure 3 g and h) could have been developed by Echinodermata (Figure 3 i), which is one of the organisms recovered with these samples. The photographic records of the recent activities of the mobile epibenthic megafauna (Figure 4 a and b) reported here, show different conspicuous traces, including tracks, trails, burrows, etc. These features show similarity to those reported by other workers from deep-sea photographs taken at different locations in the world oceans[4,9,30–34]. The feature of faecal coil reported here (Figure 4 a) is similar to that reported by Heezen and Hollister[35] from the deep-sea floor. They concluded that acon worms are responsible for their formation. The observed burrow marks (Figure 4 b) on soft sediments are comparable with those created by a deep-sea crab[35]. The recent faecal coils are excretion of mud by the benthic organisms after their consumption of available organic matter in these sediments. Recently from the Indian Ocean sector of the Southern Ocean, Rabouille et al.[36] observed that the relatively labile fractions of organic matter can be present at a greater depth, packaged in faecal pellets or in rapidly sinking cell aggregates. In comparison to the soft sediments, the indurated sediment substrates of the ferromanganese oxides contain lower concentration of organic matter[27] and the recent burrowing epibenthic megafauna may not have preferred to feed on them, hence we see no formation of coiled features among the ancient burrows or they may have been destroyed given the long duration of time involved since they are fragile. The recent biota may be using some of these ancient burrows as their shelter, while they feed on the present-day sediments.

The features of extensive bioturbation activity reported here are created due to the activity of the benthic organisms in search of their food material. High biological productivity is reported earlier from the equatorial Indian Ocean[19,21,27,37,38]. Parulekar et al.[21] and Qasim[39] inferred that in comparison to Pacific and Atlantic Oceans the organic production in the Indian
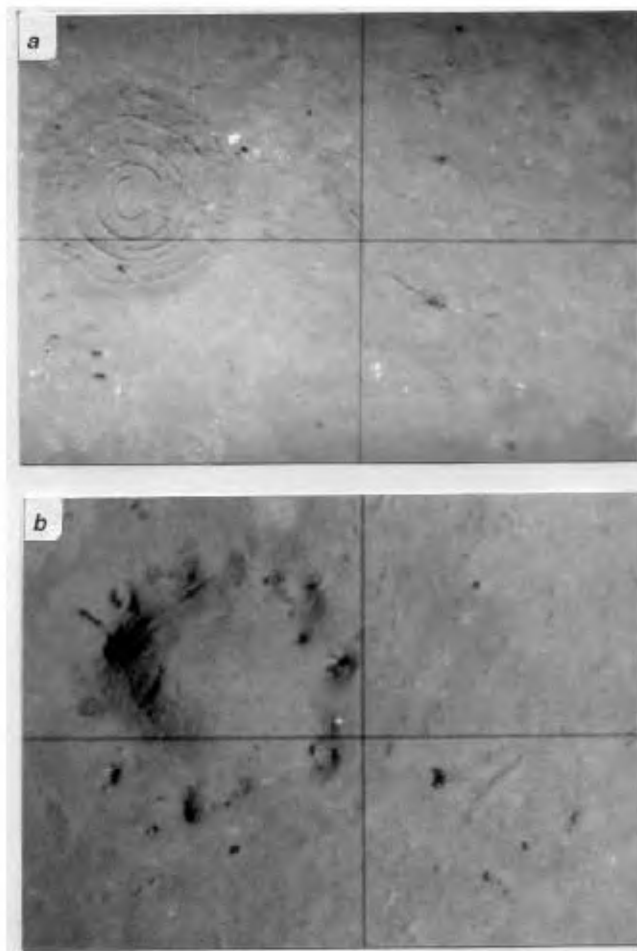

Figure 4. Photographic records of extensive recent bioturbation activity on the floor of the CIB. *a*, Coiled feature on the sediment surface. These faecal coils begin and end abruptly. Water depth, 5250 m; camera height, 4 m above ocean floor; *b*, Burrow mark on the sediment surface probably dug by a deep-sea crab. Water depth, 5230 m; camera height, 3.5 m above ocean floor.

Ocean is almost 75% and 17% higher, respectively. In the surface waters of the Central Indian Ocean biological productivity in the order of 100 to 150 mg $C/m^2/day$ was reported by Parsons et al.[40]. A large proportion of this surface-water productivity is exported to the deep ocean and produces high abyssal biomass in the bottom sediments and the benthic community living here feed on them.

On the basis of a study on pore water chemistry, nutrient pattern and their relation to the organic matter on a number of sediment cores collected from different locations in the CIB, Nath and Mudholkar[22] have shown the records of intense bioturbation extending up to about 45 cm below the sediment–water interface. The presently documented records of prolonged and extensive burrowing in this part of the CIB, may also have contributed to the regeneration of micronodules deeply buried in the sediments of the CIB and thus provided better seed for the formation of ferromanganese nodules

in this basin. Detailed petrographic observation of the ferromanganese nodules from this area supports this idea[27].

From the evidences on ancient and recent bioturbation documented here, in both hard nuclei substrates and adjacent soft sediments respectively, it is suggested that bioturbation has been a continuous process on the floor of the CIB, both pre and post-dating the formation of ferromanganese deposits in this basin. The extensive and prolonged signatures of benthic activity reported in this paper also support the hypothesis of 'biological pumping'[41–43] as one of the important processes to keep nodules at the sediment–water interface. These findings also support the presence of a rich community of deep-sea epibenthic megafauna on the floor of the CIB, much away from the actively spreading ridges. Future deep-ocean mining for the extraction of sea-floor ferromanganese deposits should take enough care to protect and preserve such extensive deep-sea benthic life.

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