Extensive occurrence of Fe–Mn crusts and nodules on seamounts in the southern Andaman Sea, India

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A reconnaissance survey for Fe–Mn crusts and nodules from West Sewell Ridge (WSR) and Sewell Rise (SR) in the Andaman Sea revealed their widespread occurrence along the summit of the ridge and on the slopes. Remotely operated vehicle (ROV) dive observations illustrate that the crusts are more concentrated on massive exposures at water depth of 800–900 m and nodules swamped in foraminiferal ooze at water depth from 600 to 1100 m. During the ROV dives, massive, smooth, macro-botryoidal, flat, granular, gritty, coarse and knobby nature of Fe–Mn crusts and nodules have been observed. Nodules and crusts collected onboard were mostly black, brownish-black and pitch black in colour. Nodules show rough, botryoidal and granular/sacchoroidal texture. The diameter of the nodules increased up to 13 cm. They showed distinctly arranged concentric layers. The recovered crusts were mostly detached pieces without substrate.

Keywords: Fe–Mn crusts and nodules, reconnaissance survey, rare earth elements, remotely operated vehicle, seamounts.

The Fe–Mn crusts and nodules are considered to be the repository of many strategic and rare earth elements (REE). Although Fe–Mn crusts have been considered as a potential Co–Ni ore, many rare elements occur in high concentrations in the crusts that offer added incentive for developing mining technologies for their recovery. Elements of special interest, especially for high-tech and green-tech applications that are abundant in Fe–Mn crusts include the REE and yttrium (Y), Te, Ti, Mo, platinum-group elements (PGEs), Zr, Bi, W and Mn[1]. With the dramatic rise in the prices of each these elements, Fe–Mn crusts are considered to be a critical marine resource for near-future exploitation.

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Due to their economic potential, Fe–Mn crusts have been studied extensively from the Pacific Ocean[1]. Fewer studies have reported on Fe–Mn crusts from the Atlantic and Indian Oceans due in part to the topographic dominance of spreading centres in both oceans and greater input of terrigenous detritus. Crusts from the NE and NW Atlantic[2] and the Afanasiy–Nikitin seamount (ANS) complex in the Indian Ocean[3,4] are exceptions, and have been studied in some detail. The Indian Ocean seems the least likely of the three major oceans to host metal-rich Mn-crust deposits of economic interest because of the enormous fluvial input in the northern sector, the three spreading centres that occupy the southern and east central sectors and the active volcanic arcs that rim the northeastern sector of the Ocean. Although the northeastern sector (NER) is in near fluvial setting, there are volcanic arc pyroclastic inputs, and the manganese crusts here may be the largest feature in the Indian Ocean with potential economic crust deposits. The Andaman Sea, a part of this active NER, has not been previously studied in detail for Fe–Mn crust occurrences. Reported occurrences of Fe–Mn crusts and nodules[5,6] encouraged a detailed survey of the crusts and nodules on seamounts and ridges in the Andaman Sea.

The Andaman Sea is unique with subduction- and spreading-associated seamounts and ridges. The numerous seamounts and ridges formed in association with tectonic activities can be favourable loci for Fe–Mn crust accretion. The multibeam bathymetric data acquired through several cruises of *RV Samudra Manthan* were compiled and seamounts and ridges present in the area were classified on the basis of depth at which they occur in the sea and their geomorphology. The reported occurrences of Fe–Mn crusts (compiled from *RV Samudra Manthan* cruise reports) were plotted over 3D bathymetry. It was conceptualized that the numerous seamounts and ridges coupled with several volcanic activities of different ages that are confined in a small and closed area like the Andaman Sea, can be a favourable loci for Fe–Mn crust accretion, and their economic potential was envisaged and exploration methods were strategized. Among these seamounts, West Sewell Ridge (WSR) and Sewell Rise (SR) possess nearly flat summits located at water depths up to 600 m. WSR, a N–S trending linear ridge which takes a turn towards SE in the southern part, is located near the Nicobar island. SR is located further north close to the Andaman Back Arc Spreading Centre (ABSC). Bathymetry of the central part of the ridge shows relatively flat top at –600 to –800 m water depth (Figure 1). SR consists of NE–SW trending structurally controlled mounts with narrow flat top and extremely steep flanks on both sides with a general slope of 11° on the northwestern flank and 27° on the southeastern flank (Figure 1). Considering factors such as slope and water depth of the summit region, in the exploration of Fe–Mn crusts and nodules was taken up onboard *RV Samudra*

Ratnakar covering WSR and SR, within the water depth of 2000 m.

The Fe–Mn crusts and nodules occur on the rock surfaces of seamounts that have been swept clean of sediment for millions of years. Based on the present knowledge of the morphology and size of seamounts from the MBES 3D Digital Terrain Model (DTM), numerous mounts in SR and WSR were selected for this exploration. The dive sites were pinpointed on gentle to moderately steep slopes within the water depth range 800–1200 m, where sediment cover is less or absent as identified based on the sub-bottom profiles (Innomar CESS 2000 deep) (Figure 1). Remotely operated vehicle (ROV) surveys were carried out upslope on the seamounts along a track length of approximately 200 m at each dive (Figure 1).

From the ROV surveys, it was observed that the crusts and nodules coexist; however, there is a significant difference between the mode of distribution of the nodules and crusts. The latter are observed more at a water depth between 800 and 900 m, whereas the former occur over a wider range of depths varying from 600 to 1100 m. Furthermore, crusts occur on the massive exposures of WSR and SR (Figure 2 *e* and *f*), whereas nodules are found to

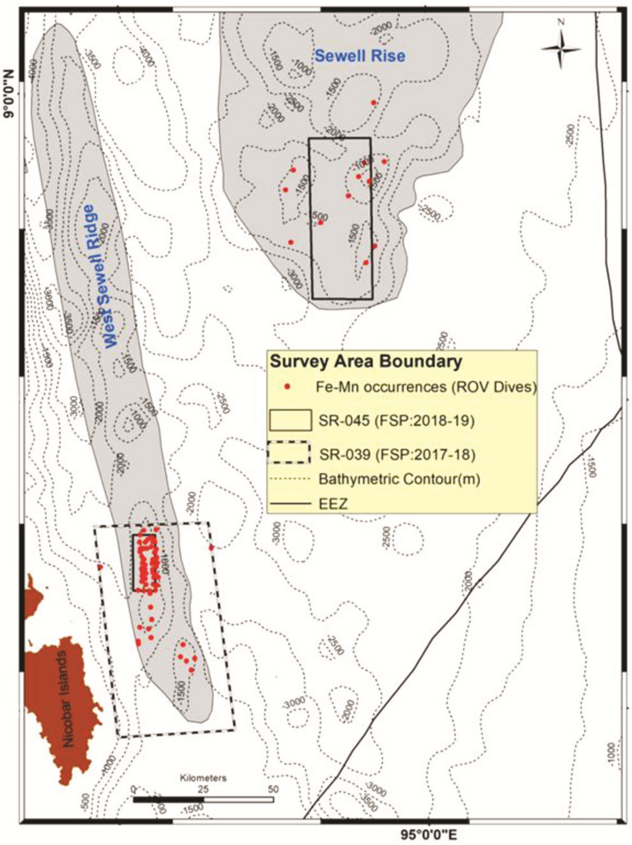

Figure 1. Location map of the study area showing the remotely operated vehicle (ROV) dive sites as well as the observed and sampled Fe–Mn crusts based on near-bottom ROV video snapshots.

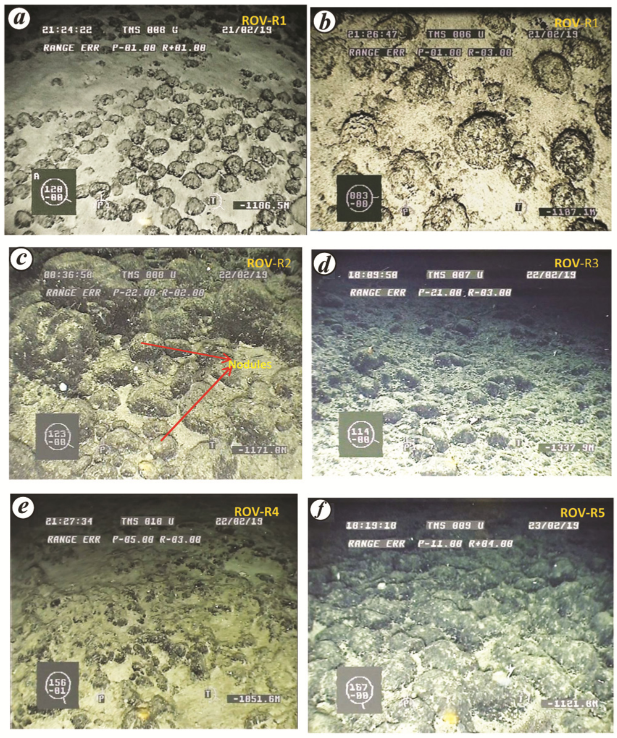

Figure 2. ***a***, ***b***, Photographs of cluster of Fe–Mn nodules embedded in sediment cover from (***a***) Sewell Rise and (***b***) West Sewell Ridge. ***c***, ***d***, Photographs of Fe–Mn nodules trapped in the bouldery outcrops from (***c***) Sewell Rise and (***d***) West Sewell Ridge. ***e***, ***f***, Photographs of Fe–Mn encrustations over hard substrata from (***e***) Sewell Rise and (***f***) West Sewell Ridge.

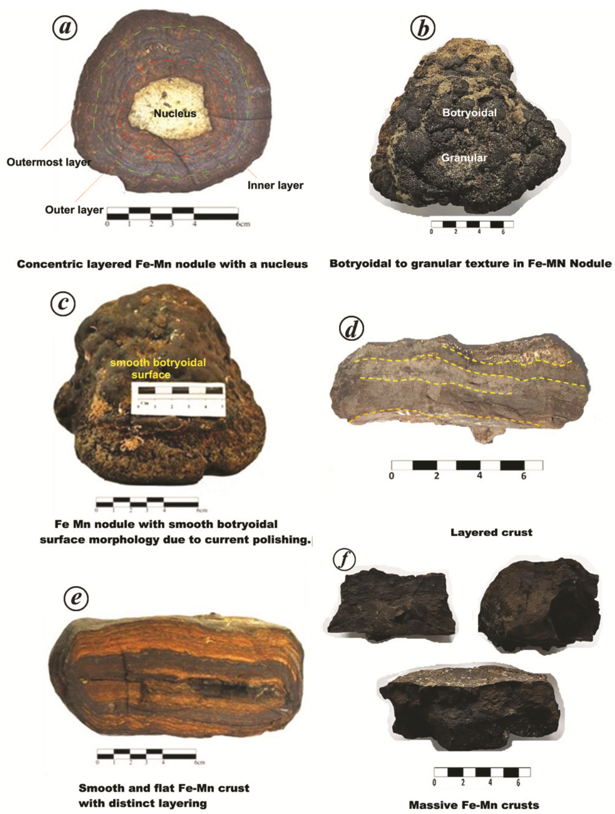

Figure 3. Morphology of nodules (***a–c***) and crusts (***d–f***) collected from West Sewell Ridge and Sewell Rise.

Table 1. REE, Co and other critical metal concentrations in Fe–Mn crusts and nodules collected from West Sewell Ridge and Sewell Rise

Location	Sample Id	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	∑REE	Ni	Co
West Sewell Ridge	Crust-1	227.38	859.69	53.10	194.63	48.26	11.85	52.56	8.48	50.01	9.42	26.72	4.20	26.15	4.02	1576.47	497	1159
	Crust-2	200.82	794.83	47.17	168.66	42.23	10.24	47.39	7.53	44.12	8.41	24.11	3.74	23.82	3.69	1426.76	2087	1209
	Crust-3	279.93	1024.73	64.40	243.45	57.90	14.35	63.53	10.26	61.46	11.60	33.82	5.29	32.69	5.00	1908.39	2072	2213
	Crust-4	197.52	863.87	45.06	164.19	41.22	10.20	46.91	7.50	44.76	8.65	25.52	4.05	26.15	4.04	1489.64	2580	1397
	Nodule-1	187.15	835.21	43.32	164.93	39.77	9.74	44.68	7.09	41.20	7.83	22.27	3.53	21.97	3.41	1432.09	4870	899
	Nodule-2	153.08	658.46	35.74	134.39	33.15	7.97	37.32	5.80	34.84	6.69	19.10	2.97	18.79	2.85	1151.13	3000	889
	Nodule-3	154.79	723.70	34.69	123.07	33.37	8.64	37.11	5.84	34.74	6.66	18.82	3.05	19.32	3.00	1206.81	5252	1489
	Nodule-4	134.94	665.93	31.23	118.60	29.14	7.11	32.79	5.07	30.44	5.87	16.91	2.64	17.05	2.66	1100.37	7860	951
	Nodule-5	132.26	625.91	29.96	107.56	27.36	6.91	31.45	4.89	29.21	5.76	16.36	2.60	16.76	2.58	1039.54	3451	923
Sewell rise	Crust-1	208.08	897.6	46.66	162.06	42.85	9.69	54.18	7.13	37.12	8.32	19.71	3.62	21.69	3.18	1696	3070	2021
	Crust-2	205.47	736.4	47.64	168.02	43.43	9.87	52.16	7.11	37.87	8.62	20.27	3.75	22.63	3.38	1550.2	2435	1444
	Crust-3	204.05	868.5	45.97	151.73	41.47	9.56	53.11	7.08	37.12	8.34	19.22	3.6	21.29	3.18	1628.7	1432	1380
	Crust-4	247.8	1027.9	52.69	172.29	47.28	12	58.84	7.51	43.81	8.66	24.61	3.86	23.26	4.17	1899.5	2854	2095
	Crust-5	216.07	809.57	48.36	164	43.26	10.1	53.21	7.01	36.89	8.41	19.09	3.45	20.56	3.08	1606.4	1319	1214
	Crust-6	210.09	899.11	47.23	160.99	43.17	9.72	53.58	7.03	37.85	8.57	19.73	3.59	21.33	3.19	1689.3	2094	1350
	Crust-7	209.65	888.77	47.86	165.49	44.1	9.82	53.7	7.06	37.5	8.49	19.62	3.59	21.5	3.26	1689.7	2714	1537
	Nodule-1	64.74	432.8	14.52	40.03	12.42	2.72	15.61	1.8	8.17	1.72	3.97	0.72	4.63	0.71	635.85	3255	650
	Nodule-2	111.71	728.3	23.24	73.09	20.37	4.77	25.32	2.8	13.01	2.6	5.83	1.05	6.46	1.02	1060.6	7674	2168
	Nodule-3	76.19	442.5	15.87	52.21	14.19	3.45	18.43	2.18	10.95	2.39	5.61	1.04	6.5	1	708.37	5458	1028
	Nodule-4	125.11	666.3	26.55	92.06	23.8	5.61	27.9	3.35	16.38	3.52	8.04	1.47	9.11	1.45	1079.8	6294	1281
	Nodule-5	41	222.61	8.45	38.16	7.95	2.18	9.46	1.08	5.54	1.25	2.95	0.55	3.36	0.52	373.21	3964	541
	Nodule-6	41	222.61	8.45	38.16	7.95	2.18	9.46	1.08	5.54	1.25	2.95	0.55	3.36	0.52	507.02	6550	907

Table 2. Bulk PGE analysis of Fe–Mn nodules and crusts from West Sewell Ridge and Sewell Rise (all measurements in ppb)

Location	Sample	Ru	Rh	Pd	Os	Ir	Pt
West Sewell Ridge	Nodule	24.14	33.08	23.78	0.98	7.92	522.49
	Crust	38.57	48.00	20.30	1.59	11.23	936.10
Sewell Rise	Crust	57.99	115.26	30.99	1.99	32.12	1223.75
	Crust	36.08	38.53	7.13	5.03	13.97	1015.26

be more immersed in the foraminiferal ooze (Figure 2 *a* and *b*) and in rocky terrains trapped by local small exposures on the western and eastern slopes (Figure 2 *c* and *d*). Detailed micro-morphology mapping using ROV videography showed crust surface morphology to be closely related to the substrata rock type, local terrain morphology, water depth and denudation process. Microtopography and surface morphology of the Fe–Mn occurrences are variable. They could be massive, smooth, macro-botryoidal, flat, granular, gritty, coarse and knobby in nature. ROV video tapes indicate that sediment cover is more prominent on the Alcock Rise than SR and WSR. Less occurrence of Fe–Mn crust in conjunction with prominent sediment cover over the Alcock Rise indicates that seamounts located away from the immediate influence of Irrawadi sediments have better potential as loci of hydrogentic Fe–Mn crust formation. Moreover, these older seamounts of SR and WSR with extensive summit areas have remained stable enough (not collapsing under gravity) to support continuous growth of crusts for millions of years, as exemplified by the typical north equatorial Pacific seamounts[1]. Hence, seamounts and ridges of SR and WSR located at water depth ranging from 800 m to 1200 m appear to be potential areas of Fe–Mn crusts and nodules.

The nodules collected onboard from WSR and SR were mostly black, brownish-black and pitch black in colour (Figure 3 *b* and *c*). Various morphological nodular types have been identified in the area. They include irregular, discoidal, spherical, sub-spherical and ellipsoidal types. Spherical and ellipsoidal types were most abundant. Diameter of the nodules varied from 5 to 13 cm. Nodules were rough, botryoidal and granular/saccharoidal, and most of the samples were texturally botryoidal (Figure 3 *b* and *c*). Distinctly developed concentric layers were observed to grow around the mafic volcanic rock (?) nuclei and many nodules showed more than three layers, with thickness varying from a few millimetres to 3.5 cm (average thickness being 2.1 cm) (Figure 3 *a*). Rounded to sub-rounded, irregular and triangular-shaped altered/unaltered mafic fragments acted as the nucleus for Fe–Mn growth. The shape of the nodule developed according to the shape of the nucleus. Alternate laminations were mainly of Fe–Mn oxides, greyish-brown to metal black in colour. They intercalations of brecciated quartz and bioclasts in these layers, interrupting their continuity. The layers are non-porous, botryoidal and rarely dendritic to acicular.

The Fe–Mn crusts had developed as layers and as thin coating on the exposed rocky outcrops and boulders. The recovered crusts were mostly detached pieces without substrate. They were brownish-black to pitch black in colour and tabular to elongate in shape (Figure 3 *d–f*). The size of the substrate rock recovered varied from a minimum of 2 cm × 3 cm to a maximum of 25 cm × 8 cm. Observed surface texture of manganese crusts showed smooth to rough surface, and also granular/saccharoidal and friable nature. Layers were massive or laminated (Figure 3 *d* and *e*). Thick crusts were composed of 2–4 distinct layers and thickness of the layers varied from 0.1 to 4.5 cm. Colour variations highlight layering. In the Mn crust sample recovered without substrate, the top surface was identified by sediment infiltration into vugs, pore spaces and remnants of attached sessile biota. The bottom surface was irregular and showed remnants of substrate rock. The substrate rocks were altered, fine-grained to medium-grained, grey-coloured basaltic (?)/mafic rocks. The nodules and crusts analysed were separated manually along prominent macroscopic boundaries, for an event-wise study of the entire crust stratigraphic section.

The maximum REE value recorded in the WSR Fe–Mn crust sample was 1908 ppm. The Co content was also high in the Fe–Mn crusts (0.14%) compared to the nodules. Enrichment of Ni (0.78%) was observed in the nodules (Table 1). Further, in the WSR, platinum content was 522 ng/g in the nodules, whereas in the crusts it increased up to 936 ng/g (Table 2).

The REE content of the samples from SR varied between 158 and 1899 ppm with a mean value of 1116 ppm, which was higher than that recorded in the WSR Fe–Mn nodules and crusts. In SR crust and nodule samples, enrichment of Co (up to 2168 ppm) was observed, in contrast to the WSR samples. Similar to WSR nodules and crusts, Fe–Mn nodules and crusts also showed higher enrichment of Ni (7674 ppm) (Table 1). Furthermore, in SR crusts also showed high Pt values from 1015 to 1223 ng/g (Table 2).

The ROV video scanning in WSR and SR in the Andaman Sea showed extensive occurrence of Fe–Mn encrustations and nodules within the Exclusive Economic Zone (EEZ) of India. The present study reveals that the most likely areas of occurrence of nodules and crust are on flat or gently inclined surfaces, such as summit terraces and platforms of SR and WSR. Further, data on metal content indicate that WSR and SR warrant further exploration because of the high concentrations of Co (0.21%), ∑REE (0.18%) and Ni (0.76%). Also, ∑REE (range between 1094 and 2285 ppm) in the Fe–Mn crusts and nodules from WSR and SR are also promising as compared to the inner volcanic arc Fe–Mn crusts in the Andaman Sea[5]. Since there is high demand for REE, Co and other critical metals, the vast occurrences of Fe–Mn crust within India's EEZ could be significant. Efforts are on to assess the economic viability of these Fe–Mn crusts and nodules in terms of REE, Co, Li and other critical elements.

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Ethnic food habits of the Sumi tribe, Nagaland, India

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The Sumis are one of the major tribes among the Nagas of North East India who are known for their brave and benevolent nature. They primarily inhabit the Zunheboto district of Nagaland, NE India, and are known for their unique culinary practices. Most of the raw materials used for the preparation of ethnic food products are natural resources indigenously available, as majority of the people live in villages surrounded by dense forest. The traditional method of preparation and mode of consumption vary according to the clan or village, and the food products are prepared at the household level. The diversity of ethnic food habits also differs within the various sub-tribes according to their custom, region and ethos. The art of indigenous food preparation, the products and their culinary value have been well documented.

Keywords: Culinary practice, ethnic food habits, natural resources, tribal people.

NAGALAND is the 16th state of the Indian Union, established on 1 December 1963. It lies between 25°06′N and 27°04′N lat, 93°20′E and 95°15′E long, and covers an area of 16,579 km^2 (ref. 1). It is a land of exuberant tribes marked by mountainous terrain and fields, and food is reflected as a part of its rich culture. The Sumi Nagas form one of the major tribes in Nagaland, and they predominately inhabit the Zunheboto district. Sumis are known for their bravery, nobility, generosity and their unique food habits which contribute to the rich cultural diversity of Nagaland. Majority of the Sumis are Christians, who practice jhum cultivation and live in villages. Each village consist of several clans and more than two dialects are spoken within the same tribe. The family organization is patriarchal and endogamy is the preferred mode of marriage. Even today, bridal prices are paid and it is considered a privilege by the other tribes in Nagaland to marry a Sumi man, because of his faithful and honourable nature.

Ethnic people cook traditional foods using raw materials that are locally available[2–4]. With the onset of human civilization, the dietary culture of many communities across the world has been shaped by the indigenous food products[5]. Besides, ethnic foods also provide cure as medicine[6,7]. The knowledge on the use of edible plants, their processing and conservation for consumption and use as medicine is due to increasing and cumulative learning by the societies having a close connection with nature[8]. The traditional knowledge on ethnic food preparation among the Sumis is generally confined to the women folk or elders in the society, and such knowledge is passed thereon. The food products are prepared at the household level, for which the raw materials are gathered from the forests, fields or cultivated in kitchen gardens. The degree of diversity on the method of food preparation and products varies between villages and individuals. However, they have mastered the art of food processing and in turn these foods form an essential part of their culture and customs.

The present study was conducted in various areas, viz. Kohima, Dimapur and Zunheboto in Nagaland. Interactive questionnaire was used to document the traditional

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