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PALAEOGENE HARDGROUNDS AND ASSOCIATED INTRACLAST LAG DEPOSITS AS THE SUBSTRATES OF FERROMANGANESE CRUSTS AND NUCLEI OF NODULES : INFERENCES OF ABYSSAL CURRENT IN THE CENTRAL INDIAN OCEAN BASIN

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ABSTRACT

The Palaeogene substrates of ferromanganese crusts and nuclei of nodules collected from the central Indian Basin chiefly consist of incipient to younger pelagic hard grounds and associated intraclast lag deposits. The clayey lumps, ferromanganese micronodules, crystalline aggregates of phillipsite, relic volcanic glass shards, and *ichthyoliths* (the phosphatic micro-remains of fishes) constitute the coarse fractions of these hard substrates and the nuclei. Alteration of volcanic material into palagonite and its later diagenesis led to the synsedimentary lithification of pelagic zeolitic clays into the hardgrounds. The pre-lithification burrows and post-lithification borings in these clayclast nuclei and substrates are also reported. *Trypanites* type borings and *Thalassinoides* and *Chondrites* type burrows are either filled with ferromanganese oxide or with younger sediment infillings suggesting an omission-suite of a synsedimentary lithified hardground. Hummocky-relief over the hardgrounds and associated intraclast lag deposits are the result of scouring and exhuming by an abyssal current, probably the Antarctic Bottom Water Current, in the basin. The palaeoenvironment and sequence of events of accretion of nodules and crusts are discussed.

INTRODUCTION

The bioturbation structures provide important clues to reconstruct the palaeoenvironment of the sediment deposits (Reineck and Singh, 1980). The unconsolidated soft sediments are bioturbated by the benthic creatures due to their burrowing and feeding activities; whereas consolidated hard sediments are often subject to mechanical excavations with the scratch marks, or the solution pit by boring activities of the epifauna. The coexistence of borings and burrows in a sediment deposit has been considered a criterion of hardgrounds (Bromley, 1968). The hardgrounds are intraformational synsedimentary lithification surfaces resulting from diagenesis of sediment at the sea floor (Bromley, 1967, 1975), and are widely reported from Palaeozoic (Jaanusson, 1961), Mesozoic (Ellenberger, 1946; Fursich *et al.*, 1991) and Palaeogene (Hecker, 1963) sediments exposed on land. However, the present paper reports bioturbated pelagic zeolitic hardgrounds and associated intraclast lag deposits, as the substrates of ferromanganese crusts and nuclei of nodules, that are still present at the abyssal depth of ~ 5 km in the Central Indian Ocean Basin.

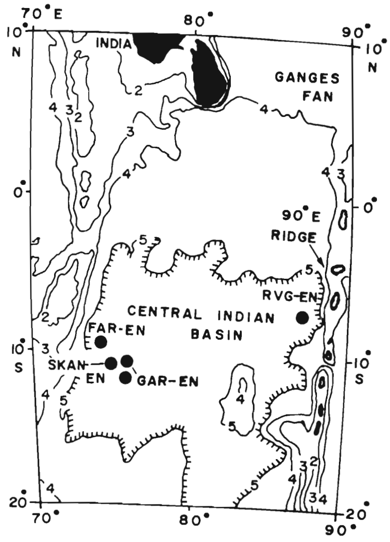

Fig. 1. Physiographic setting and sample locations in the central Indian Ocean Basin. Bathymetric contours are in km.

MATERIAL AND METHODS

Numerous ferromanganese crusts and nodules were collected by dredging the ocean floor during several cruises of RV-Gaveshani, MV-Skandy Surveyor, G.A.-Reay and MV-Farnella for the surveys of polymetallic nodules in the central Indian Ocean Basin (hereafter, central Indian Basin, fig.1, Table 1). The substrates of these crusts and nuclei of nodules (hereafter, substrates and nuclei) have 0.5-3.0cm thick ferromanganese oxides/hydroxides (Fe-Mn) coatings. The surficial features of the crusts show hummocky relief (figs.2A,B) and the associated nodules with boring structures (figs. 3 A-F). The nuclei and substrates consisting of bioturbated reddish-brown to pale-brown hard, but friable sediment, were scrapped by a sharp knife, oven dried, weighed (20g substrate, 3-5g nuclei depending on their size) and dispersed in 10% sodium hexametaphosphate. They were later treated with as H_2O_2 (30%), ultrasonically cleaned for 2 minutes and sieved on 62 micron mesh. The coarse fractions (>62 micron) were weighed and studied under binocular microscopes to count various components for the relative percentage. The silt and clay fractions were determined by standard

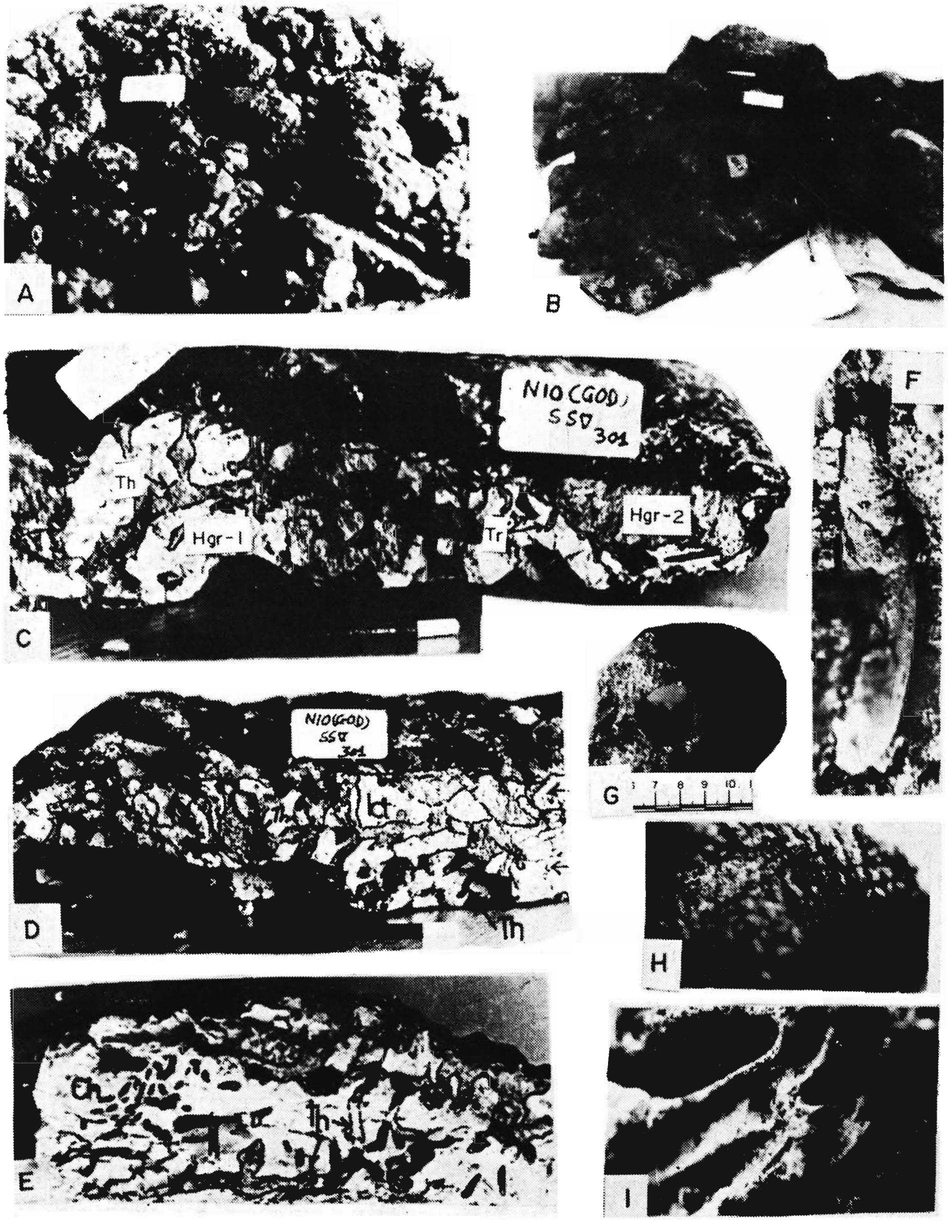

Fig. 2. Description of the surface and sub-surface features of the ferromanganese crusts. (A). Ferromanganese crust SKAN-EN-1 with 2.5cm thick Fe-Mn coating over the hummocky reliefed hardground that resulted due to sculpturing of hardened lithofacies by scouring and exhuming action of an abyssal current (Top view), Length of sticker 10 cm. (B). Ferromanganese crust GAR-EN with 1.5 cm thick Fe-Mn coating over a moderately sculptured hummocky reliefed pelagic hardground. Lobate and hummocky shapes of the surface indicates exhuming and scouring action of the abyssal current. Length of pen 15 cm. (C). The vertical section of crust SKAN-EN-1 (in A) showing two lithofacies of light and dark color in mottled hardground. Th-type burrows filled with dark colored overlying younger sediment in the matrix of light colored older hardground (Hgr-1). Younger hardground (Hgr-2), a dark colored lithofacies is visible in a trough, just below the Fe-Mn crust. *Trypanites*-type (Tr) curvilinear tubular borings are also present. Length of pencil 15 cm. (D). Another section of SKAN-EN1 showing Th-type burrows filled by darker younger overlying sediment. Itc=Intraclast. (E). A section of SKAN-EN 1 showing inverted Y-shaped *Thalassinoides*-type (Th) and *Chodrites*- type (Ch) burrows stuffed with dark colored younger sediment. (F). A close up of younger sediment filling, different from the host hardground in color, coherence and texture, in a cylindrical boring. (G). A typical opening of cylindrical boring (diameter 2.5cm) with a scratch mar on the boring wall depicting two sets of scratches at - 90° suggesting mechanically excavated boring in the hardground. (H). A close up of scratch marks on the boring wall depicting two sets of scratches at 90° suggesting mechanically excavated boring in the hardground. (I). A close up of typical Y-shaped branches of empty burrows with occasional micronodules and ferromanganese coating.

pipetting technique. A part of material was powdered and analyzed for bulk mineralogy by X-ray diffractometer at 2θ/minute scanning between 8-35° using Ni filter and Cu-K (α) radiation. The serial sectioning method of Farrow (1975) and Chamberlain (1978) was followed for preparation of sections of the substrates and nuclei, and each section photographed. With the help of serial section photography (fig. 2C-E, fig. B-F), the burrow and boring patterns were 3-dimensionally reconstructed and identified following descriptions of Hantzachel (1975) and Bromley (1972,1975). Numerous microburrows and borings were picked by the moist fine camel hair brush from the coarse fractions, put onto glass-slides, photomicrographed and are illustrated.

Table 1. Details of ferromanganese crusts and nodules under study from the Central Indian ocean basin.

Sample No.	Nature	depth (m)	Material	Surface features
RVG-EN	Nodular crust	5080	brown pelagic clays	surface borings & hollow burrows
SKAN-EN-1	Nodular crust	5191	-do-	Hummocky relief with filled burrows
SKAN-EN-2	Huge crust	5374	-do-	-do-
FAR-EN	Huge crust	4900	-do-	-do-
GAR-EN	Huge crust	5075	-do-	-do-

Note : Nodular crusts are having 0.5-1.5 cm ferromanganese coating over a large (15-30 cm) subrounded intraclast. Huge crusts are massive brown pelagic clays of hardened lithofacies (-70 cm) with 1-2.5 cm Fe-Mn coatings.

RESULTS AND DISCUSSION

(A) BIOGENIC STRUCTURES

Two types of biogenic structures are recognized:

(i) Pre-lithification burrows

The burrow tubes are either coated with ferromanganese oxides or filled by younger sediment. They are similar to *Chodrites* and *Thalassinoides* types.

Chondrites Stenberg

Diagnosis : Very thin similar to the plant's root system with highly branched ramifying burrows. The diameter of lateral branches is same but increases at vertical shafts (1-2mm) and branching is at 30-45° from the main shaft.

Remarks : The burrow pattern is similar to that of *Chodrites* but a ferromanganese coating is present over the burrow walls (figs. 2 E, Ch).

Thalassinoides Ehrenberg

Diagnosis : Highly branched burrows of uniform diameter (3-30cm). The branching is in inverted "Y" shaped pattern and burrows are generally swollen at the joints.

Remarks : The present Thalassinoides have smaller diameter (0.5-1.5cm) but the inverted Y-shaped pattern is present. The lesser diameter of the burrow tube might be due to thinner and smaller creatures at 5 km water depth compared to those in the shallow seas (depth <100 m). The burrows are either filled or coated with Fe-Mn oxides or filled by younger sediment (figs. 2 C, D Th; figs. 3 E Th).

Apart from these two typical burrows, some microburrows are found in the coarse fractions, which also vary in diameter and the pattern. They are as follows:

1. *U-type tubes*: Typical U-type microburrow tubes (diameter 0.5- 1.0 mm) filled by the sediment and occasionally embedded with micronodules on the burrow wall (fig. 4F).

2. *Cylindrical planar tubes* : Thin cylindrical curvilinear to planar burrow tubes (diameter <1 mm) filled by the sediment and occasionally embedded with micronodules on the burrow wall (figs. 4 H-I).

3. *Y-shaped burrows* : Similar to *Thalassinoides* but thinner in tube diameter (0.5-2.0 mm) (figs. 4J-L,V). Some of them may be broken parts of *Chondrites* (figs. 4M-P).

4. *Straight burrows* : Straight to gently curved burrows with embedded micronodules (figs. 4 Q-S).

5. *Curvilinear burrows* : Curvilinear planer burrows partially or fully filled by ferromanganese or thickly covered by micronodules (figs. 4 U-W).

6. *Phillipsitized burrows* : Fusiform or bean-shaped phillipsitized burrows (figs. 4 X-Z).

(ii) Post-lithification *Trypanites* borings (Bromley, 1972)

1. *Tubular borings :* Long tubular hollow borings (diameter 0.5- 2.5 cm) with two sets of scratch marks indicating mechanical excavation to bore the hard lithified sediment by sharp and strong appendages of thoracicans and cetaceans (fig. 2 G-H). They are generally open or partially to fully filled by overlying younger sediment. (figs. 2 C Tr, F &I).

2. *Pouch type :* Similar to small pouch or pear-shaped cavities probably made by acrothoracicans (fig. 3 C p). Microborings of flask, bulb and pouch shapes with variable diameters (0.5-1.2mm) are found either stuffed with sediment (figs. 4 D-E).

4. *J-type tube :* J-type borings made by spinoid polychaetes (fig. 3 E-j) that are often modified by the abrasion (Bromley, 1975; Warme and McHuran, 1978, cf. fig.3C-D). Microborings of J-type pattern are completely filled by ferromanganese material (fig. 4T).

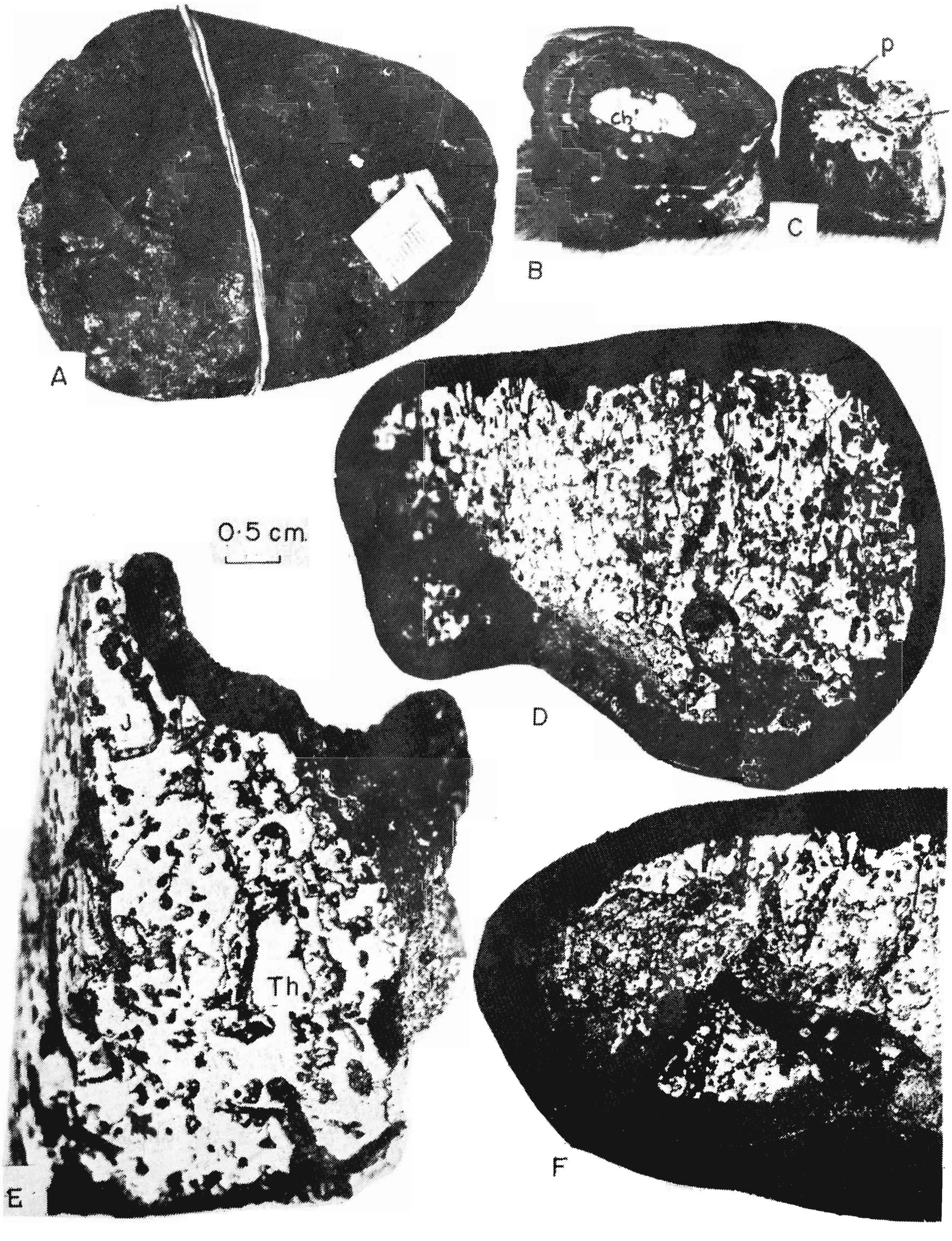

Fig.3. Burrowed and bored nodular crusts. Scale in the background is applicable to figures B-F. (A). RVG-EN nodular crust with surficial indentation of curvilinear biogenic structures. (B). Cross section of a manganese nodule showing the clayclast nucleus with boring structures that are partially or fully filled either with sediment or with Fe-Mn coating. Sticker length 10 cm. (C). A bioturbated intraclast with tubular (t) and pouch (p) type boring as the nucleus of manganese nodule from GAR-EN dredge- haul. (D). A polished section of nodular crust FAR-EN with 4-5 mm Fe-Mn coating over thickly bioturbated intraclast nucleus from the FAR-EN hardground. Tubular boring is visible. (E). A polished section of RVG-EN nodular crust (in A) with 4-5 mm thick Fe-Mn coating over intraclast nucleus. J-type boring (J) and inverted Y-shaped burrow (Th) are visible apart from numerous microburrows and borings. (F). A highly bioturbated intraclast nucleus of ferromanganese nodule showing a curvilinear hollow burrow with Fe-Mn coating over the burrow walls suggesting partially filled or coated burrows as the indicator of omission surface of a typical background.

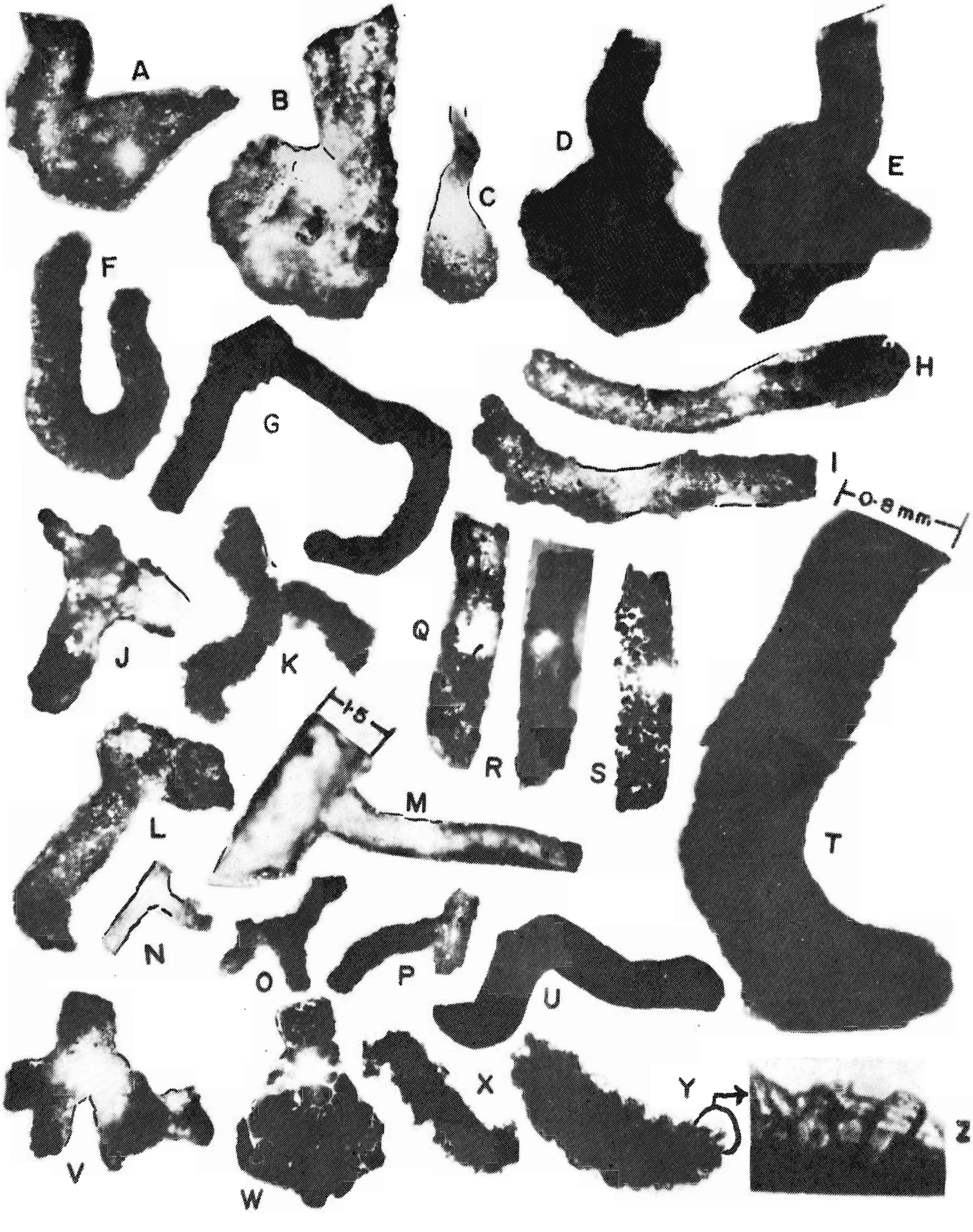

Fig.4. Microburrows and borings from the coarse fraction. Scale in fig. M is applicable to all except T and Z. (A-C). The spout and pitcher type of microborings filled by the sediments. (D-E). Borings filled with Fe-Mn oxides. (F). U-type burrows with occasional embedded micronodules. (G). Highly branched burrow (? *Chondrites*) filled by ferromanganese. (H-I). Straight to curved burrows with embedded micronodules in the burrow clasts. (J-K, & V). Typical Y-shaped branching in microburrows. (M-P). Broken shaft of *Chondrites* with lateral branches at 45°. (Q-S). Straight to curvilinear burrow wall embedded with micronodules. (T). J-type microboring filled by Fe-Mn oxides. (U-W). A curvilinear microburrow almost completely filled with Fe-Mn oxide. (X-Y). Phillipsitized burrow tubes with prismatic phillipsite crystalline aggregates. (Z). A part of phillipsitized burrow cast (in fig. Y) showing rossette-shaped prismatic phillipsitic crystalline aggregate (X100).

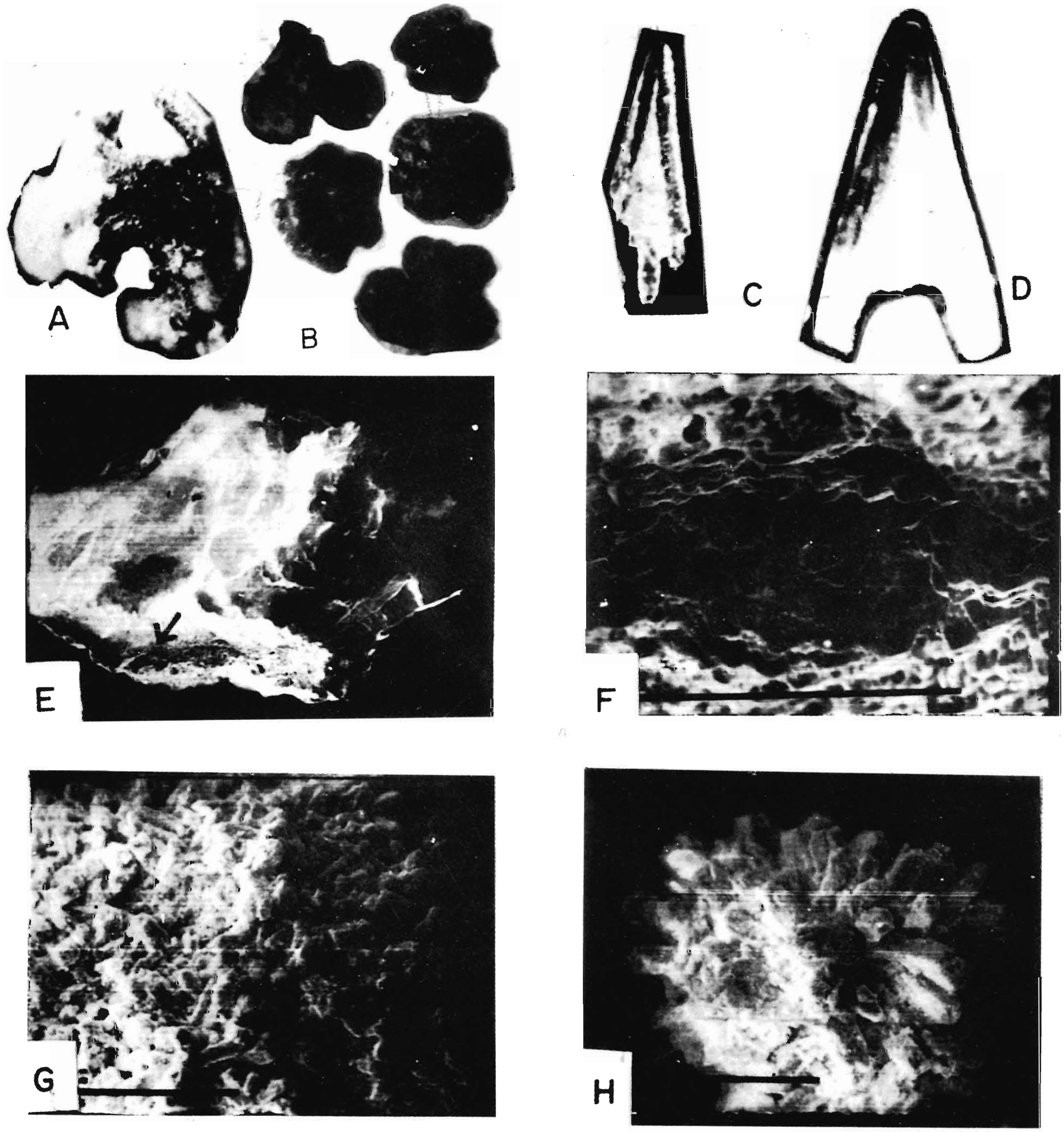

Fig. 5. Components of the coarse fraction. (A) The clayey lump or aggregate X80, (B) ferromanganese micronodules X80, (C) Tanged triangle the Ichthyolith X80, (D) Triangle double flex a Palaeogene ichthyolith X80, (E) SEM photomicrograph of a relict volcanic glass shard with concoidal fractures and weathering pits and dissolution features leading to palagonitization. Scale bar-50 microns. (H) Fully grown tabular prismatic rosette-shaped spherulitic aggregates of phillipsite. Scale bar 100 micron.

Remarks : The oligotrophic benthic endofauna burrow the unconsolidated sediment, which, sometimes may remain open and empty due to hardening of the burrow wall if a sediment deficient environment prolongs for a long time resulting in a diagenetic synsedimentary lithification and in the stabilizing of the sea floor (Purser, 1969). Such hardened burrow walls get mineralized by the glauconite, phosphate (Bromley, 1967), pyrite (Hallam, 1969) or ferromanganese coatings (Jenkyns, 1971) as a result of hydrogenic or diagenetic mineral fillings. These mineralized burrow walls produce conspicuous trace fossils peculiar to sediment omission-suite of the typical hardgrounds (Bromley, 1975). The mineralized burrow walls (fig. 2C-E) suggest

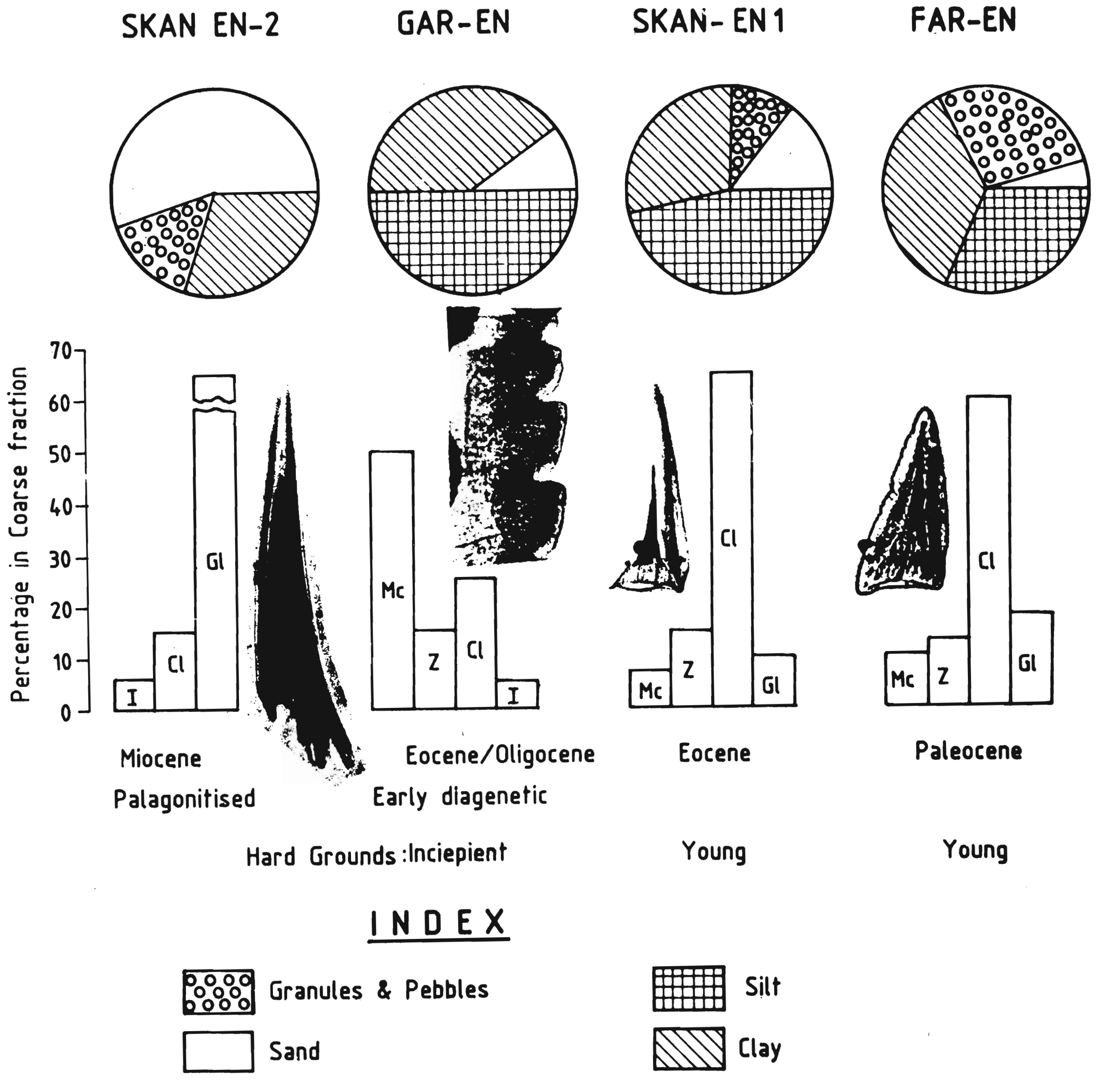

Fig. 6. Grain size analysis, coarse fraction components and ichthyolith ages of the samples showing relative maturity of hardgrounds. Pie diagrams indicate % of granule pebble, sand, silt and clay fractions. Bar diagrams show % of various components in the coarse fraction of the samples. Index : M=micronodules; Cl=clayey lumps or intraclasts, Z= phillipsite crystalline aggregates; V= volcanic glass shards; I= ichthyoliths.

a period of non-deposition leading to hardened burrow walls due to diagenetic synsedimentary lithification (fig. 2 C-E, Hgr-1). It was followed by ferromanganese oxide coating over the burrow walls and subsequently filled by younger sediment (fig. 2 C-E Hgr-2) representing a second cycle of sedimentation. The occurrence of completely filled *Trypanites* borings (fig. 2C Tr.) and microborings (fig. 4 A-E, & T) represent the post-lithification feature and a conclusive proof of sedimentary omission-suite of hardgrounds at the sea-floor (Bromley, 1975, cf. p.416).

(B) THE HOST SEDIMENTS

Coarse Fraction Composition

The coarse fraction of the samples fall in two sizes, i.e., (i) granule to pebble and (ii) sand. Granules and pebbles are subangular to subrounded clayey lumps or aggregates (fig. 5A). The sand fraction consists of clayey lumps, micronodules, ichthyoliths, relic volcanic glass shards and brownish- buff colored euhedral spherulitic crystalline phillipsite (Fischer and Schmincke, 1984) aggregates (fig. 5). The phillipsitic crystalline aggregates,

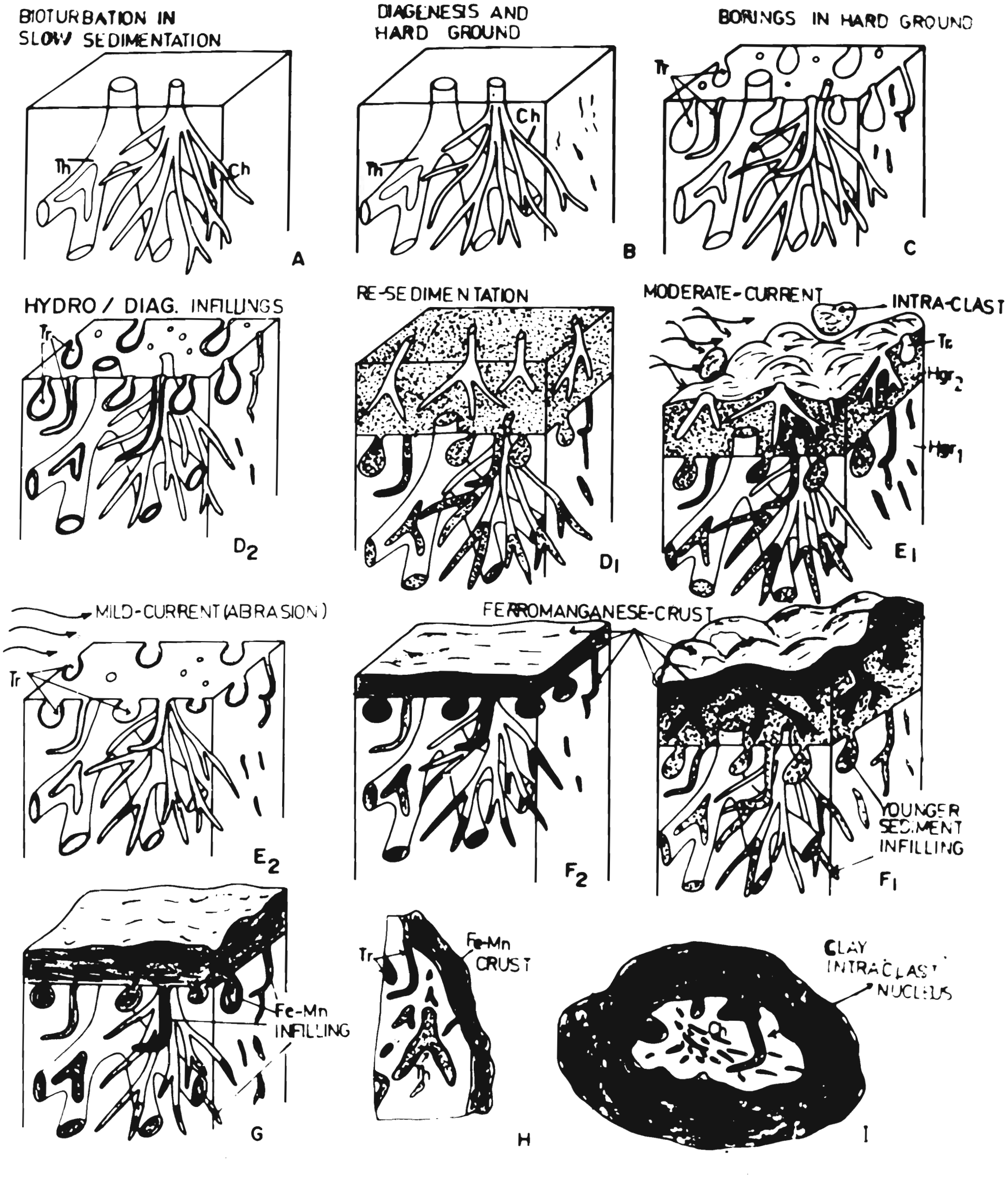

Fig. 7. Schematic diagrams depicting sequence of events in formation of pelagic hardgrounds and·associated intraclast lag deposits to serve the bioturbated substrates and nuclei of the ferromanganese crusts and nodules. (A). Slow rate of sedimentation and bioturbation in soft unconsolidated pelagic sediments; Th= *Thalassinoides*, Ch= *Chondrites*. (B). Hollow burrows preserved due to the prolonged period of non-deposition followed by the diagenesis resulting into syn-sedimentary lithified hardground in quiet and calm bottom water. (C). The epifauna bored the hardground in tubular, pouch and flask-shaped borings (Tr= *Trypanites* type). (D1). If the sedimentation resumed, the empty burrows and borings get filled by younger sediment, which also gets bioturbated. (E1). A further check in sedimentation led the early diagenetic changes forming younger incipient hardground (Hgr-2) overlying the older mature one (Hgr-1). Slightly turbulent bottom water scours and exhumes such incipient hardgrounds leading into intraclast lag deposit and hummocky reliefed hardground. (F1). Encrustation of Fe-Mn oxides on empty biogenic structures in the intraclasts and the hummocky-reliefed hardground. (D2). If, non-sedimentation continues, the biogenic structures remain open and unfilled, and their walls get encrusted by Fe-Mn oxides. (E2). Increase in the bottom water current energy abrades the hardgrounds distorting the shapes of the biogenic structures. (F2). Continued encrustation of Fe-Mn oxides completely fills the open biogenic structures in encrusted hardgrounds. (G). A combination of E1 and E2 steps produces the walls of burrow and boring with Fe-Mn coating and the tubes filled by the overlying younger sediment. (H). A part of the polished section of a intraclast nucleus similar to Fig. 3E after scouring and exhumation by the bottom water current. (I). Intraclast lag deposits and hardgrounds produced by the scouring and exhumation action of the abyssal current provide the nuclei and substrates for the ferromanganese nodules and crusts respectively. Empty biogenic structures in the hardground intraclasts are filled by younger sediments and Fe-Mn encrustation similar to the illustration in Fig. 3.

micronodules and clayey lumps suggest diagenesis of the sediment. The relative abundance of coarse fraction components is presented in fig. 6 along with characteristic ichthyoliths from the samples indicating Palaeogene age (Gupta, 1987, 1991).

Mineralogy

The X-ray diffractograms of the substrates and nuclei indicate presence of phillipsite, chlorite, and K-felspar minerals in the order of abundance. The chlorite is the principal product of low grade alteration of palagonite and basaltic glasses (Viereck *et al.*, 1982). The phillipsite is of diagenetic origin and K-feldspar is of authigenic origin, as it has been widely reported from the volcanoclastic marine sediments from the Atlantic and Pacific Oceans (Kastner and Gieskes, 1976). The presence of lithogenic (chlorite), biogenic (ichthyoliths), diagenetic (micronodules and phillipsite crystals) and volcanic (glass shards) components in the substrates and nuclei suggest that these are the pelagic zeolitic clays.

Diagenesis

The presence of volcanic glass shards suggest volcanic input into the sediment (fig. 5 E-F; fig. 6). Alteration of volcanic glass is influenced by the pore water chemistry of the marine sediments (Stonecipher, 1978). Due to the uptake of Mg^{++} and K^{+} from the pore water and release of Ca^{++} during the low temperature alteration, the volcanic glass changes into palagonite (Brey and Schmincke, 1980). Later, palagonite alters into smectite and phillipsite due to mobilization of ions in the pore water (Gieskes and Lawrence, 1981). In an advanced stage of diagenesis, the metastable phillipsite interacts with interstitial amorphous silica and K^{+} ions altering into K-feldspar (Iijima, 1978). Though the authigenic feldspar are less common in altered volcanoclastic marine sediment, their presence indicates an advanced stage of alteration of volcanic material (Kastner and Siever, 1979). Mobilization of Fe-Mn ions around the micronuclei-like clayey lumps and phillipsitic aggregates leads to the formation of manganese micronodules. The early diagenetic changes have resulted in the formation of random clayey lumps, phillipsitic crystalline aggregates and micronodules. As the diagenesis progressed, the clayey lumps fused together to form clayey pebbles. The increasing amount of pebbles and intraclasts (fig. 6) indicates an advanced stage of diagenesis, which led to syn-sedimentary lithification of the zeolitic clays resulting in the formation of pelagic hardgrounds.

PALEOENVIRONMENT AND EVENTS

The absence of foraminifera suggests that the sediments were deposited below the calcium carbonate compensation depth (CCD); whereas absence of radiolaria show a silica deficient depositional environment at the sea floor. Ichthyoliths, the phosphatic skeletal debris of fishes, are the only datable microfossils and suggest red-clay depositional regime on the sea-floor (Gottfried *et al.*, 1984). The relics of volcanic glass shards (Gupta, 1988) indicate a volcanoclastic sedimentary environment. The unconsolidated sediment was bioturbated by the abyssal megabenthos like penntulids, brisingids, abyssal cetacean and crabs (Sharma and Rao, 1992) resulting in *Chondrites* and *Thalassinoides* type burrows (fig. 7A), followed by a considerably longer period of non-deposition in calm and quiet bottom water. Due to prolonged period of non- deposition, diagenetic changes altered the volcanic glass into the zeolitic lumps (Iyer and Sudhakar, 1993) leading to the syn-sedimentary lithification and preservation the hollow burrows (fig. 7B). The epifauna like acanthoracican bored the hardened sea-floor (hardground) for the shelter (*Trypanites* type borings, fig. 2C Tr., fig.7 C Tr.). Later, sedimentation resumed and empty burrows and borings got filled with overlying younger sediment (fig. 2 C-D, Hgr-2; fig.7 D-1). In some cases, empty walls of burrows and borings got coating of the diagenetic ferromanganese oxides or by the micronodules (fig.3E, fig.7 D2, E2, G). Subsequently, the mild bottom water currents abraded the bioturbated, incipient to mature hardgrounds resulting in modification of burrow and boring structures (fig.2 C Tr; fig.3 E; fig.7 E2); whereas the moderate currents scoured and exhumed the hardgrounds resulting in hummocky relief and intraclast lag deposits (figs. 2 A-B, figs. 7 E1, F1). These intraclast lag deposits and the hummocky reliefed hardground suggest the presence of an abyssal bottom water current in the basin. Recent studies (Gupta, 1988; Sharma and Mahapatra, 1990; Banakar *et al.*, 1991; Gupta and Jahauri, 1994) suggest that the Central Indian Ocean Basin has been intruded by the Abyssal Antarctic Bottom Water (AABW) Current through the deeper saddles of 90°E Ridge. Therefore, it is surmised that these hardgrounds were exhumed and scoured by the same in the geological past. Later, the hardgrounds and intraclast lag deposits served as the substrates and nuclei for the formation of ferromanganese crusts and nodules (fig.7E-I).

CONCLUSION

The substrates and nuclei of ferromanganese crusts and nodules chiefly consist of bioturbated pelagic Palaeogene zeolitic hardgrounds which were scoured and exhumed by the Abyssal Antarctic Bottom Water Current into hummocky reliefed hardgrounds and intraclasts lag deposits. These substrates and intraclasts provided the accretionary sites and the seeds, a prerequisite, for the ferromanganese crusts and nodules in the central Indian Ocean Basin.

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