

MARINE GEOLOGY

V. Purnachandra Rao¹ and R. Shankar²

¹National Institute of Oceanography, Dona Paula, Goa - 403 004

²Department of Marine Geology, Mangalore University, Mangalagangothri - 574 199

The last three decades have witnessed an increasing effort in the scientific exploration of seafloor because of depleting resources on the continents. This led to the initiation of diverse marine geological studies of the world oceans. An overview of the major contributions made by Indian marine geologists in the nineties are summarized below.

- . Sedimentary processes in the Northern Indian Ocean
- . Deep sea stratigraphic record, correlation and chronology
- . Gas-charged sediments: Methane and Gas hydrates
- . Mineral Deposits: Authigenic green clays, Phosphorites, Hydrothermal deposits and Polymetallic nodules and associated sediments.
- . Rock magnetism measurements and Suspended Particulate Matter in marine and coastal sediments.

Sedimentary processes in the Northern Indian Ocean

Large volumes of fresh water flux and wind borne material are contributed annually into the Northern Indian Ocean, an ideal region for understanding biogeochemical processes in response to monsoons, and also marine carbon cycle and deciphering the paleoclimatic history. Sediment trap experiments carried out in the Arabian Sea and Bay of Bengal have revealed that the interannual variability of particle fluxes in the Arabian Sea are directly controlled by the strength and intensity of the SW

monsoon and winter cooling during NE monsoon. Monsoon winds influence primary productivity and particle fluxes by introducing nutrients in the photic zone from deeper waters. Nutrient pumping is partly due to mixed layer deepening and advection of nutrient-rich waters from upwelling centers¹. In the Bay of Bengal particle fluxes are controlled by fresh water and suspended sediment discharge from rivers². The settling of lithogenic matter in the oceans is coupled to production and settling of biogenic matter. A "ballast" hypothesis has been proposed to explain why organic carbon fluxes in the Arabian Sea, a high productive area, are lower than the Bay of Bengal. Lithogenic matter in organic aggregates serve as a ballast and increase the density of large aggregates. Thus lithogenic matter helps in removal of organic carbon from the sea surface thereby increasing the drawdown of atmospheric carbon dioxide into the ocean. In the Arabian Sea there is a decrease in lithogenic fluxes from east to west due to clockwise surface circulation during the southwest monsoon period which diverts river discharge to the eastern part of the sea³⁻⁵. While in the Bay of Bengal a north-south decrease in lithogenic flux is seen with fluxes decreasing away from river mouths. Besides, it was also observed that the planktic foraminiferal flux displays bimodal distributional pattern related to monsoons⁶. Higher fluxes recorded during SW monsoon were dominated by *Globigerina bulloides*⁷. Four species, *Neogloboquadrina dutertrei*, *Globigerinella aequilateralis*, *Globigerinita glutinata* and *Globoturborotalita rubescens* exhibit elevated fluxes in the low salinity regions⁸. The $\delta^{18}\text{O}$ values of the *Globigerinoides ruber* is higher in the western Arabian Sea than in coeval samples from the central and eastern Arabian Sea, reflecting the SST gradient across the Arabian Sea caused by the southwest monsoon⁹.

Extensive studies were carried out on the fine-grained sediments deposited on the continental margins of India and successfully identified the mineral assemblages derived from different source rocks (Deccan Trap Province and Gneissic Province) and Peninsular and extra peninsular rivers. The influence of strong tidal currents, surface currents and cross shelf transport on mixing of sediments from different sources was identified¹⁰⁻¹². For example, the macrotides at the Gulf of Kutch act as barriers (tidal barriers) to longshore transport of sediments from the Indus to the south of the Gulf of Kutch. Similarly, the sediments derived from the Ganges do not reach the shelf off the Peninsular rivers and Godavari derived sediments extend northwards under the influence of southwest monsoon currents.

Deep sea stratigraphic record, correlation and chronology

Over the past few years because of the Deep Sea Drilling Project (DSDP) and Ocean Drilling Programme (ODP) a number of Cenozoic sequences from tropical to polar regions were recovered, which provided an unprecedented opportunity to study the deep sea stratigraphic record. An extensive programme was taken up to examine Cenozoic deep sea sections from the northern Indian Ocean and southwest Pacific at the Banaras Hindu University in the eighties.

Seven DSDP Sites were selected from various parts of the northern Indian Ocean including three from Bay of Bengal¹³ and four from the Arabian Sea^{14,15} to examine the deep sea stratigraphic record. Further, five DSDP Sites lying in a north-south transect from equatorial to cool sub-tropical waters in the southwest Pacific were examined¹⁶ for variations in sediment accumulation rate in different water masses and their effect on completeness of the stratigraphic record.

Of the seven Sites examined in the northern Indian Ocean, Site 214 (water depth: 1665 m) on the Ninetyeast Ridge, Site 219 on the Chagos Laccadive Ridge (water depth: 1764 m), Site 237 on the Mascarenes Plateau (water depth: 1640 m), Site 238 on the Central Indian Ridge (water depth: 2382 m) were found to contain an almost entire Neogene stratigraphic record (last 23.2 My) comprising foraminiferal rich nanno ooze.

On the other hand, all the DSDP Sites studied from the southwest Pacific contain superb and undisturbed Neogene sequences comprising nanno foram ooze. Of these, Site 586 B (water depth: 2208 m) lies on the Ontong-Java Plateau, Site 587 (water depth: 1101 m) on the Lansdowne Bank and Site 588 (water depth: 1533 m), Site 590 (water depth: 1299 m) and Site 592 (water depth: 1098 m) are situated on the Lord Howe Rise in the southwest Pacific.

Data generated on the DSDP sections from the northern Indian Ocean and southwest Pacific by Srinivasan and co-workers in the nineties provided new information with regards to the demarcation of Neogene epoch boundaries and refined the stratigraphic data published earlier in the Initial Reports of the Deep Sea Drilling Project.

An integrated paleomagnetic stratigraphy, isotope stratigraphy and biostratigraphy enabled to correlate the deep sea sequences of various Sites in the northern Indian Ocean and also with the sequences from the southwest Pacific. The paleobathymetric trends indicated by the Neogene deep sea benthic foraminifera from the DSDP Sites of Ninetyeast Ridge revealed that the ridge is not aseismic as considered earlier¹⁷.

The precise biochronology established employing graphic correlation method helped to identify the diachrony of planktic foraminiferal events in the Indian and southwest Pacific Oceans^{16,18}. This has also facilitated to recognize deep sea hiatuses and variations in sediment accumulation rate in specific time slices within various DSDP sequences. The study revealed the highest rate of accumulation at about 5.2 Ma (~ 90 m/my) coincident with Miocene/Pliocene transition.

High resolution stratigraphic record analysis revealed a number of deep sea hiatuses and dissolution intervals corresponding to rapid enrichment of $\delta^{18}\text{O}$ and sea level regressions. Studies on the northern Indian Ocean deep sea cores indicate major deep sea hiatuses at 23-22 Ma; 20-18 Ma; 16-15Ma, 13.5-11 Ma and 5.2-4.7 Ma reflecting them to represent intervals of increased Antarctic Bottom Water activity and psychrospheric circulation¹⁹.

Gas-charged sediments

i) Methane-bearing sediments: Methane is a greenhouse gas. Its increasing concentrations in the atmosphere contribute to global warming. High resolution shallow seismic reflection data obtained in the inner continental shelf sediments off western India from 10° N to 22° N reveal characteristic anomalous seismic signatures in the form of acoustic maskings (seeps, wipe-outs, V-shaped depressions, pockmark-like structures etc. of methane-rich horizons²⁰. The areal extent, thickness, porosity and partial analyses of the sampled hydrocarbons of these gas-charged sediments were computed to estimate the potential of methane. About 2.60 million tons of methane was estimated to have been trapped in the sediments of the inner continental shelf. The annual methane flux was estimated to be around 0.03 Tg. The world wide seepage of methane (8-65 Tg) through the seabed of the continental shelves can not be ignored for the estimation of global oceanic flux of methane and its budget²¹.

ii) Gas hydrates: Seismic profiles on the outer continental shelf-middle slope show pockmarks and prominent plumes characterized by strong echoes in the sediments and overlying water column indicating significant contribution of gas from the slope sediments and the seepages may demonstrate the existence of source rocks. The continental slope, continental rise region also revealed the presence of Bottom Simulating Reflectors (BSRs), which are believed to be caused by acoustic impedance contrast between high velocity gas hydrate bearing sediments and the underlying low velocity sediments filled with free gas. The BSR is found to be parallel to the seafloor topography and occurs nearly 300-600 m beneath the

seafloor at water depths of > 525-2000 m; it occasionally shows discontinuity. Distinct blanking zones and acoustic voids have also been observed above the BSR. Folds, diapiric-like features and faults present in the slope-rise areas may probably serve as traps and conduits for upward migration of fluids/methane gas from the deep²².

Marine Mineral deposits

i) Authigenic green clays: Large flux of iron, weathered from the continental regions, is being delivered to the sea annually. It is important to know where and how it is deposited in the ocean. Verdine and glaucony are two iron-rich authigenic green clay facies which form in shallow marine environments. Detailed investigations both from the sediments of the eastern and western continental margins of India document the existence of verdine and glaucony facies and largest verdine-bearing facies in the offshore reaches between Ratnagiri and Cape Comorin covering an area of about 100,000 sq. km, equivalent to the Amazon river mouth²³

ii) Phosphorites: Detailed investigations were made on the genesis of phosphorites along the continental margins of India and seamounts. Based on petrology, mineralogy, elemental chemistry, radiogenic (Sr and Nd) and stable isotope (C, O, and S) chemistry of the phosphorites, the occurrence of *phosphate stratiform stromatolites* were reported from the continental margin off Chennai. This is the first report documenting the Pleistocene analogs of ancient phosphorites²⁴. A comparative study of Pleistocene high-grade phosphorites off western India has demonstrated that phosphate is in the form of apatite microparticles which resemble fossilized bacteria and/or microbial filaments and emphasized the role of microbial mediation in phosphogenesis²⁵. Studies on the phosphorites from flat-topped seamounts of both the Pacific and Indian Oceans have also demonstrated the microbial origin of phosphorites, in contradiction to the hitherto held view that they are of guano-derived nature²⁶.

iii) Hydrothermal deposits : Back arc basins are considered favourable for the formation of hydrothermal minerals. Andaman Sea is an example of trench arc back arc system where underthrusting of the Indian lithospheric plate is taking place below the southeast Asian plate. Studies using multibeam bathymetry, magnetics and free air gravity measurements of a part of the central Andaman Basin revealed a complex topography depicting the volcanic arc system and the back arc spreading ridge. Several fault systems trending N-S with throws ranging from 300 to 2400 m

run parallel in the basin. The west Andaman fault is the most prominent and probably defines the boundary of the volcanic arc. The northeast segment has a rift valley filled with 0.6 km thick sediments. The oldest identifiable magnetic anomaly (5A) over the southwestern segment of the spreading center implies an age of 11.5 My. The average half spreading rate of the Andaman back arc spreading centre seems to be 1.86 cm/yr and spreading center has been active for the past 2 My²⁷. The dredge samples from different physiographic features of the back arc basin consist of massive and vesicular basalts and vein type metal sulfide (pyrite and chalcopyrite) particles, indicating hydrothermal activity in the basin²⁸.

Based on microprobe data and several geochemical tracers including REEs, the occurrence of hydrothermal Fe-Mn crusts from the Rodrigues Triple Junction, Indian Ocean was reported. This is the first report on the hydrothermal mineralisation at the Indian Ocean spreading centers²⁹.

iv) Polymetallic nodules and associated sediments: The combined efforts of active young scientists working in the National Priority Project "Surveys for Polymetallic Nodules" brought India (a) Pioneer Investor status and (b) a seabed area of 1,50,000 sq. km in the Central Indian Basin (CIB) for exclusive exploration. While accomplishing the task, each scientist has chosen a topic of research and published papers on different aspects of nodules and sediments and tectonic history of the Central Indian Basin.

a) Using multibeam bathymetric system an area of about 300,000 sq. km was surveyed in the CIB and several physiographic features were identified. This includes about 800 seamounts ranging in height between 50 and 2870 m and southern extension of 79° E fracture zone. Seafloor lineaments and several largely east-west oriented crenulations in the form of folds and fault scarps were identified. They were caused due to crustal compression as a result of two episodes of collision between the north bound India and the stable Eurasia during Paleocene - Eocene epochs^{30,31}.

b) Major, minor and rare-earth element (REE) chemistry of the surface sediments has demonstrated that the terrigenous sediments derived from the Ganges-Brahmaputra river system occur in the CIB up to 8° S, which is about 3000 km from the source³². The various types of sediments in the CIB have been the result of varying continental detritus input, productivity of surface waters, effects of equatorial current system and bottom water mass³³. Particle scavenging or diagenetic precipitation explains Ba behaviour in the marine environment and its association with oxide forming transition elements. REE fractionations are controlled by lithology of the sediments and are affected by diagenetic processes³⁴.

c) The siliceous ooze sediment provided conducive environment for the formation of high grade nodules. The nodule coverages are high on the crests and slopes (12-15%) and low in the valleys and plains (0.3 to 1.44%). Sediment coverage increases from nil on the crests to very thin on the slopes and from thick to very thick in the plains and valleys. High nodule concentrations along the slopes and near the crests of the seamounts and abyssal hills are a result of availability of rock fragments as nuclei which are derived from rock outcrops^{35,36}

d) Detailed petrographic and mineral chemical analyses of polymetallic nodules have shown distinct fine-scale phases of manganese oxides with clear chemical and mineralogical identity. Their development was affected by the variable abundance of biogenic detritus entrapped within these nodules. The extensive post-depositional reorganised features indicate the porous nature of the nodules and poses a serious question about the validity of their radiometric dating methods³⁷. Rare-earth element systematics in Fe-Mn deposits selected from different topographic settings and sedimentary domains have shown that the Fe-Mn oxide phases of nodules are major sinks for Ce and invoked the chemisorption of Ce onto iron-oxyhydroxides and their epitaxial intergrowth with manganese mineral δ -MnO₂³⁸. The size and abundance of ferromanganese micronodules are more in oxic environments than in suboxic environments³⁹. They also occur in high sedimentation areas of the Bay of Bengal sediments⁴⁰.

e) Sediments at the foot of a large cratered seamount in the CIB show an unusually high abundance of volcanic particles, glass shards, Fe-rich montmorillonite and nontronite. Volcanic magnetite spherules and zeolite slabs are also found in the vicinity of the seamounts. Detailed investigations show that these particles have formed as a result of alteration of the basaltic rocks under the influence of hydrothermal solutions. These investigations provide substantial evidence for different volcanic episodes that occurred in the CIB until 10 Ka⁴¹.

f) Ash beds at varying depths within the sediments of the CIB suggest their origin from the Youngest Toba eruption of 75 Ka. This is in contradiction with the earlier view which invoked intraplate volcanism to explain the volcanic debris⁴²

g) The Cobalt-rich 0.8% Fe-Mn crusts from the Afanasy-Nikitin Seamount have provided understanding of the evolution of Indian Ocean during the Neogene. The late Miocene intensification of intermediate water OMZ and Pliocene contraction of the OMZ were shown to control the chemistry and mineralogy of the crust. A pulse of high detritus input to this area during late Miocene (8 Ma) appears to be an

indication of short span of intensified erosion of Himalaya as a result of intra-plate deformation event in the Indian Ocean. The reorganisation of the Antarctic Bottom Water (AABW) flow in the Indian Ocean during 13-14 Ma was shown to be responsible for the large scale formation of Fe-Mn crusts⁴³.

h) The studies on extra-terrestrial materials deposited in the sediments of the CIB have revolutionized our earlier concepts. Tektites are impact generated glassy ejecta distributed in four strewn fields. The youngest of them is the Australasian tektite strewn field (0.77 Ma). The occurrence of tektite in the land masses and microtektites in the oceans led some workers to believe that these two belong to two separate impact events. This constitutes the age paradox. The microtektites, minitektites, a tektite and tektite fragment having similar compositions in the same stratigraphic horizon belonging to the Australasian tektite event have been reported in the sediments of the CIB⁴⁴⁻⁴⁷. This provided evidence that the entire Australasian tektite strewn field is generated by a single impact and that the age paradox problem is no longer valid. Impact generated microcraters have also been reported on microtektites. These are interpreted to have been the result of interparticle collisions in the ejecta of a major meteorite impact which was responsible for the Australasian tektite strewn field.

Rock magnetism measurements and Suspended Particulate Matter (SPM) in marine and coastal sediments

Shankar and Manjunath⁴⁸ studied the river input of sediments to the Ocean System from the southwestern coast of India and also characterized the changes in the nature of sediments as they pass from the riverine through the estuarine into the marine environment.

It has been observed that Magnetic susceptibility of Netravati and Gurpur river-bed sediments is controlled by the lithology of the catchment rocks. Data on how magnetic minerals are concentrated in river-bed sediments in terms of sorting, grain size and kurtosis, have been brought out by Manjunath and Shankar⁴⁹. In addition, the behaviour of magnetic minerals as they enter the oceanic realm through the estuary has been studied. Several environmental factors/processes that influence the magnetic susceptibility, and hence the magnetic mineral content, have been brought out. For example, deposition of magnetic minerals in meander loops and in the nearshore zone, anoxic conditions in the inner shelf etc⁵⁰. Such data are important in order to understand the movement, distribution and concentration of magnetic minerals which result in alluvial/beach/offshore placer deposits.

Rock magnetic techniques have been employed to understand the late Quaternary paleoclimate of the eastern Arabian Sea. The philosophy underlying this approach that changes in climate/environment may be studied by characterizing the changes in the magnetic grain size, concentration and mineralogy of magnetic minerals deposited during different periods. Prabhu and Shankar⁵¹ carried out rock magnetic studies for two sediment cores from eastern Arabian Sea which are first of their kind from an Indian Laboratory. The results are summarized below:

Magnetic susceptibility (χ_m) is an indicator of the concentration of magnetic minerals. The peaks and troughs in χ_m down the core have been assigned tentative ages based on the sedimentation rate of 2.8 cm/Kyr for a nearby site⁵². Variation in χ_m is correlated with the $\delta^{18}O$ stratigraphy of a sediment core from the Somali Basin⁵³. It implies the higher concentrations of magnetic minerals were deposited during interglacial periods (isotope stages 1, 3 and 5) than during glacial periods. Thus, Magnetic susceptibility (χ_m) measurement can be employed as an additional proxy for paleoclimatic interpretations.

The ratio of Anhyseretic Remanent Magnetisation to Magnetic Susceptibility (ARM/ χ_m) is an indicator of the magnetic grain size. Low (ARM/ χ_m) ratios suggest coarse magnetic grain size. χ_m and ARM/ χ_m are negatively correlated. High input of magnetic minerals with coarser grain size are characteristic of interglacials and vice-versa. Therefore, climate not only modulates the quantum of magnetic minerals delivered to a basin, but also exerts a control on the magnetic grain size.

A rock magnetic methodology has been devised to estimate the heavy and opaque mineral contents of beach and offshore placers. This method is simple, rapid, relatively inexpensive and non-destructive and does not necessitate the presence of a radioactive mineral in the samples⁵⁴.

Studies of suspended particulate matter (SPM) and water from the riverine environment have shown that the SPM is enriched in Al, Fe, Ni and Co but strongly depleted in Ca in comparison with temperate and major rivers of the world⁵⁵. These are an imprint of the intense chemical weathering in the tropical southern India.

Estuaries being a transitional environment are characterized by a number of processes involving both the aqueous and the particulate phases. Hence, studies have been carried out to understand the adsorption/desorption of base metals from particulates as they enter the oceanic realm. Laboratory mixing experiments have been conducted to determine the flocculation of dissolved base metals as the river water mixes with sea water⁵⁶. Most of the flocculation takes place during the first half-an-hour of mixing. Salinity plays an important role in the flocculation of trace

elements, most of which are removed by flocculation at salinities $> 25\text{ppt}$ ⁵⁷. With increasing salinity in the estuarine-coastal environments, trace metals are desorbed from particulates⁵⁸.

Study of estuarine material by Shankar and Manjunath have shown that inner shelf sediments are resuspended, transported landward and flushed into Netravati-Gurupur estuary which is an unfilled estuary with residual tidal currents⁴⁸. This suggests that continental shelf is not always a sink for river-transported sediments. This process has implications to (a) estuarine morphology, (b) siltation in the Old Mangalore Port resulting in navigational problems and consequently boat accidents, loss of life and property, (c) construction of a vented dam across the Netravati river, and (d) disposal of effluents into the coastal ocean all along the West coast of India.

Sedimentation rates on the inner shelf off the southwestern coast of India are 0.72 and 0.56 mm/yr. at water depths of 35 m and 45 m respectively. These are much lower than those for the northern continental shelf because of the low concentration of SPM in the small rivers in the southern sector. The occurrence of outer shelf sands of 9-11 Kyr BP at different depths below MSL indicates neotectonic activity. The southern sector is subsiding relative to the northern sector⁵⁹.

A number of Holocene processes operative in the deep Arabian Sea have been discerned based on the bulk and partition geochemistry and magnetic susceptibility of surficial sediments: Aeolian processes, reducing conditions and upwelling in the Owen Basin, bathymetric control of environment by the Owen Ridge, hydrothermal activity of the Carlsberg Ridge, *in situ* weathering of basement rocks etc. R-mode factor analysis of the geochemical data suggests that four dominant factors are responsible for the observed geochemical variations in the samples, namely; Carlsberg Ridge hydrothermal activity, terrigenous contribution, hydrogenous (authigenic) precipitates and biological contribution. Preliminary studies of the magnetic fraction indicate that it is predominantly composed of pseudo-single domain and viscous magnetite^{60,61}. Uranium geochemistry also has helped in understanding the Holocene processes. Uranium seems to have four origins in different parts of the Arabian Sea: Hydrogenous, hydrothermal, biogenic and terrigenous.

A core from the Laccadive Trough (water depth: 1724 m) has been studied for radiocarbon, organic carbon (OC), nitrogen (N), OC/N and $\delta^{13}\text{C}$. The study revealed the following^{62,63}.

Sedimentation rate decreases from 4.11. to 3.15 cm/Kyr for Pleistocene and Holocene respectively. This is because riverine sediments are trapped in estuaries and continental shelf as a result of Holocene sea level rise.

However, sedimentation rate is high (6.36 cm/Kyr) during the Pleistocene-Holocene transition period as a result of sediment slump or turbidite emplacement due to high terrigenous influx during transition.

The onset of environmental conditions representative of Holocene is dated at ca 9,300 yr BP.

The Holocene increase in OC/N and $\delta^{15}\text{N}$ is due to enhanced denitrification in the ODZ because of higher productivity.

One of the first publications on ocean-floor massive sulphide deposits by Hekinian *et al.* ⁶⁴ reported the gold, silver and platinum contents of the East Pacific Rise (21°N) deposits. Subsequently, much attention has been focussed on the gold and silver contents of Indian continental sulphide deposits which have a marine origin. However, there is an important and urgent need to look at the Pt content of continental sulphide deposits and their tailings as well ⁶⁵.

Today, all the information that we have generated in the field of marine geology in India is largely based on data from surface and near surface sediments. It is high time that hydraulic piston coring (HPC) device will soon be developed by the National Institutes and extensively used to recover cores from the deep sea regions. This would immensely help our deep sea hydrocarbon exploration programme that we are going to initiate in the coming years.

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