

Marine Geology

V.P. RAO*

National Institute of Oceanography, Dona Paula, Goa

SEDIMENT TRAPS EXPERIMENTS - MONSOON - RELATED CHANGES IN THE WATER COLUMN

Sediment-trap experiments carried out in the northern Arabian Sea, Bay of Bengal and equatorial Indian Ocean continued to provide new insights and potential tools for reconstructing the recent past. Mohan et al. (2006) showed that the trap data collected during January to September 1993 yielded a rich assemblage of intact and non-living pteropod tests, which showed distinct seasonality in abundance. Pteropod/planktonic foraminiferal ratios displayed marked seasonal variations and are positively correlated with the fluxes of CaCO₃, organic carbon and biogenic opal. These suggest that the pteropods respond to changing hydrographic conditions influenced by SW monsoon and could be used as a potential tool for palaeoclimatic reconstructions of the recent past. Similarly, the temporal variations of coccolithophores from the central Arabian Sea sediment trap data of October 1993 to August 1994 also showed seasonality, with higher fluxes during the northeast monsoon and lower fluxes during spring intermonsoon (Mergulhao et al., 2006). The higher fluxes were attributed to the enhancement of primary productivity in the central Arabian Sea due to southward extent of nutrients from the northeast Arabian Sea by the prevailing surface currents. Lower fluxes were attributed to low nutrients in the warm shallow surface mixed layer and downwelling to the south of Findlater Jet, respectively in the central Arabian Sea. Mohan and Guptha (2006) studied the sediment samples collected from southern Bay of Bengal trap (water depth 3011 m) during Feb.-March 1992 and showed the presence of corroded specimens of *Globorotalia menardii*. Contrastingly, all the other spinose and less resistant spinose foraminiferal species are found devoid of any signs of dissolution in the same trap. As the water depth of the trap is located above the lysocline, it is interpreted that the corroded specimens of *G. Menardii* tests could have been supplied by lateral advection and mixed up with the settling particles at southern Bay of Bengal.

Ramaswamy and Gaye (2006) studied the fluxes of foraminifera carbonate, coccolithophorid carbonate and biogenic opal in the sediment traps at six sites in the Arabian Sea, Bay of Bengal and equatorial Indian Ocean and attributed the fluxes to regional variations in the salinity, temperature and nutrient distribution. They found that in the western Arabian Sea, coccolithophorids are the major contributors to biogenic fluxes during periods of low nutrient concentrations. Coccolithophorid fluxes are high throughout the year in the eastern Arabian Sea. In the northern and central Bay of Bengal when salinity values drop sharply during the SW monsoon there is a drastic reduction in planktonic foraminiferal carbonate, but coccolithophorid

carbonate and diatom fluxes remain steady or continue to increase. It has been inferred that the enhanced fresh-water supply from rivers should increase oceanic CO₂ uptake. Its salinity supply favours the production of diatoms, while salinity drop produces conditions unfavourable for most planktonic foraminiferal species.

Nair et al. (2005) measured biogenic and barium fluxes using nine sediment traps deployed in the western, central and eastern part of the Arabian Sea. Results demonstrated a strong correlation between Ba excess and biogenic opal and organic carbon (C_{org}) fluxes indicating biogenic origin of Ba. It appears that the processes that precipitate particulate Ba are less active during periods of high biogenic flux. Export flux calculations showed that ~35% increase in Ba fluxes and a concomitant increase in Ba/C_{org} ratios between 919 and 2002 m water depth in the western Arabian Sea. This increase may be due to barite formation within faecal pellets of meso-zooplankton thriving at deeper levels or to scavenging of Ba by Mn-oxyhydroxides. The estimated preservation efficiency of Ba in the Arabian Sea sediments ranges between 50% and 61%. This is two-fold higher than the global average, suggesting that Ba may be a promising proxy for palaeoproductivity estimation.

MARINE SEDIMENTARY RECORDS - PALEOCLIMATE / PALEOCEANOGRAPHY

The sedimentary records from various parts of the eastern and western Arabian Sea, distal Bengal Fan and Equatorial Indian Ocean were examined for understanding the monsoon related changes (productivity, denitrification, sea surface temperature and salinity) in the water column during the late Quaternary (Singh et al., 2006; Banakar, 2005; Banakar et al., 2005; Chodankar et al., 2005; Kessarkar and Rao, 2006). These workers measured the stable isotopes of planktic and benthic foraminifers, organic carbon, $\delta^{13}\text{C}_{\text{org}}$ distribution and alkenones in sediment cores of the eastern Arabian Sea and showed increased productivity corresponded to diminished water column denitrification (reduced sedimentary $\delta^{15}\text{N}$) during the last glacial maximum (LGM). The distinct decoupling of denitrification from productivity was explained by vigorous ventilation of the thermocline as a result of simultaneously intensified formation of high-salinity water and deep-winter mixing in the northern Arabian Sea related to extreme cold climate. Singh et al. (2006) identified distinct regimes of monsoonal variability: the last glacial, the deglacial and the Holocene. They also suggested that the pteropod abundance maximum of Heinrich periods and the younger Dryas are indicative of weaker oxygen minimum zone (OMZ) and deeper aragonite compensation depth in the eastern Arabian Sea. Pattan et al. (2005a) used geochemical proxies for understanding the variations in terrigenous sediment discharge in a sediment core from the eastern Arabian Sea representing the last 140 ka. They found increased

* E-mail: vprao@nio.org

terrigenous discharge of ~25% corresponding with chemical weathering during glacial than in the interglacials. The last ~5 ka sediments received lowest and uniform terrigenous sediment discharge may be due to weak monsoon and stabilized sea level. Saraswat et al. (2005) reconstructed the sea surface temperature (SST) in the equatorial Indian Ocean using Mg/Ca ratio in *Globigerinoides ruber* over the last 137 kyr. They reported that the SST was 2.1° C cooler during the LGM as compared to the present. The data showed that the surface equatorial Indian Ocean was comparatively warmer during isotope stage 5e than today (29.9°C vs. 28.5°C). They proposed common mechanism controlling the SSTs in both equatorial Indian Ocean and Pacific Ocean. Thamban et al. (2007) carried out high-resolution proxy studies on a sediment core collected within the OMZ of the eastern Arabian Sea and showed abrupt event of monsoon precipitation throughout the Holocene. The early Holocene monsoon intensification occurred in two abrupt steps at 9500 years and 9100 yrs BP and weakened gradually thereafter at 8500 years BP. A weakening in precipitation occurred at about 7000 yrs BP.

Anil Kumar et al. (2005) studied the rock-magnetic measurements along with other sedimentological and isotopic characteristics of the sedimentary components for 15 gravity cores recovered along the western continental margin of India. The results suggest that during the last glacial maximum, the cores off northwestern India received abundant continental supply leading to the predominance of eolian/fluvial sedimentation. The influence of hinterland flux was less evident in the SW region. But convective mixing associated with the NE monsoon resulted in increased productivity. During the early Holocene intense SW monsoon conditions resulted in high precipitation on land, which in turn contributed to the increased magnetic susceptibility values in the continental margin sediments. The late Holocene organic-rich sediments were subjected to early diagenesis at different intervals in the core.

Naidu (2004) and Naidu and Niitsuma (2003) studied the downcore distribution of carbon and oxygen isotope variations in planktic and benthic foraminifera from the western Arabian Sea to understand the evolution of surface and bottom-water hydrographic changes associated with summer monsoon upwelling process at the Oman Margin over the last 19 kyr. They found depleted $\delta^{18}\text{O}$ excursions around 9 ka in surface, subsurface and bottom water living foraminifera indicating rapid transfer of the termination 1B signal through the vertical circulation of the Arabian Sea in response to peak monsoon intensity. A steep increase in $\delta^{13}\text{C}$ values of benthic foraminifer between 9 and 8 ka reveals advection of Red Sea intermediate water into the Arabian Sea. Naidu and Malmgren (2006) also reconstructed the annual, summer and winter sea surface temperatures (SSTs) in the western Arabian Sea for the last 22 kyrs using artificial neural networks (ANNs) based on quantitative analyses of planktic foraminifera. Their results reveal that annual, summer and winter SSTs were 2, 1.2 and 2.6°C lower during the glacial period than in the Holocene. SST increased by 2.5°C during termination 1A (Glacial to Holocene transition). The study reveals a strong seasonal SST reversal

between winter and summer from 18 to 14 calendar kyr owing to the combined effects of weak upwelling and strong cold northeasterly winds. A 3°C rise in winter SSTs during the glacial to Holocene transition coincides with a strengthening of the monsoon, suggesting a link between winter SSTs and monsoon initiation from the beginning of the Holocene. Similarly, tropical cooling in the late Holocene was observed since 8 ka BP.

Nath et al. (2005) used sedimentological and geochemical proxies in order to show the evidence of Himalayan erosional events in a sediment core from the equatorial Indian Ocean. They demonstrated that the core site received an increased supply of terrigenous sediments for at least two time periods, corresponding to 0.5 and probably 0.8 Ma. The characteristics of the sediments suggest a highly metamorphosed source such as Higher Himalayan Crystalline Series (HHCS) indicating two events of increased physical weathering and erosion in the Himalayan region. On the other hand, Kessarkar et al. (2005) studied the sedimentological and radiogenic isotope characteristics of the sediments in sediment cores from distal Bengal Fan and reported changing sedimentary environment at about 12 ^{14}C kyr. They reported Pleistocene hemiturbidites, older than 13 ^{14}C kyrs, from the Himalayas. These sediments are overlain by calcareous pelagic sediments from 12 ^{14}C kyrs BP. The change in lithofacies suggest that the sediment deposition by turbidity current activity ceased in the distal Bengal Fan at 12 ^{14}C kyrs BP, perhaps because of rapid rise in sea level during the melt water pulse 1A and Holocene. Pattan et al. (2005b) reported sedimentological and major and trace-element geochemistry of a sediment core from the central Indian Basin to better understand the changes in productivity and intensity of terrigenous supply. The age model of the sediment core is based on U-Th dating, the occurrence of Youngest Toba Tuff of 74 kyrs and Australian microtektites at 0.77 Myrs. The results on CaCO_3 and organic carbon suggest well a oxygenated bottom-water environment during the past ~1100 kyrs. Between 1100 kyrs and 400 kyrs siliceous productivity was lower, complimented by higher supply of terrigenous material, mostly derived from High Himalayan Crystalline Series. During the last 400 kyrs siliceous production was increased with substantial reduction in terrigenous sediment supply. The results suggest that the intensity of Himalayan weathering and erosion associated with monsoons was comparatively higher prior to 400 kyrs.

The residence time of neodymium is short when compared to the mixing time of the oceans. Padmakumari et al. (2006) used Nd-isotopic composition of the thoroughly cleaned planktonic foraminifers from a sediment core of the NE Indian Ocean and reported a striking shift in ϵ_{Nd} (~4 epsilon units) from the LGM to Holocene. The variations in ϵ_{Nd} also showed a remarkable correspondence with those of the oxygen-isotope composition of planktonic foraminifera. The shift in ϵ_{Nd} from the LGM to Holocene is due to a change in the weathering pattern in the Himalaya-Tibet and the Indo-Burman ranges: glacial erosion during the LGM and a strong monsoonal effect during the Holocene.

PRESENT AND PAST SEA LEVEL CHANGES ALONG THE INDIAN MARGINS

Sea-level changes can be of two types: (i) changes in the mean sea level and (ii) changes in the extreme sea level. The former is global phenomenon while the later is regional. Unnikrishnan et al. (2006) estimated of mean sea level rise from past tide-gauge data at selected stations along the Indian coasts. The sea-level rise is slightly <1 mm/yr. However, this data needs to be corrected by including the rates of vertical land movements, whose measurements are not available at present. The simulation results show increase in frequencies of tropical cyclones in the Bay of Bengal, particularly intense events during the post-monsoon period.

Rao et al. (2003a and b) investigated the late Quaternary sea-level and environmental changes from the relic carbonate deposits of the western margin of India. Relic carbonates occur largely on the outer continental off the western India at depths between 18 and 110 m. They occur as dolomite crusts, aragonite sands, aragonite-cemented limestones, oyster shells, corals and encrusted coralline algal and foraminiferal-dominated nodules. These carbonates were recovered from specific geomorphic features that were identified from sonar profiles and included patch reefs with a relief upto 10 m and linear reefs with reliefs between 2 and 15 m. Detailed petrological and mineralogical investigations on these carbonates to determine their use as proxy indicator of sea level. Suitable samples from 62 stations along the entire margin were radiocarbon-dated. The ages of the carbonates range between 17,250 to 6,730 ¹⁴C yr BP. The age vs. depth plot of the relic deposits indicates that the Gulf of Kachchh was inundated much early, at least by 15 ka. The relic deposits between Cape Comorin and Mangalore plot on or, closely follow the glacio-eustatic sea-level curve. Despite abundant siliciclastic flux discharged by the Narmada and Tapi during the early Holocene, the platform off these rivers is largely devoid of this flux and carbonate sedimentation continued until 6,700 ¹⁴C yr BP. It is suggested that the river-derived sediment flux diverted southwards under the influence of the SW monsoon current and, thereby increased turbidity on the shelf and slope southeast of the carbonate platform and facilitated the formation of deeper-water foraminiferal nodules off Vengurla and Goa.

PROVENANCE OF THE SEDIMENTS ALONG THE CONTINENTAL MARGINS

The transport pathways of fine-grained sediment from the suspended particulate matter and surface sea bed sediments along Ayeyarwady continental shelf were investigated by several workers to understand the physical processes in sediment distribution. The Ayeyarwady continental shelf, Andaman Sea is a complex sedimentary system characterized by large sediment influx (~360 m. ton/yr), wide shelf, strong tidal regime (7 m high tides) and is incised by the Martaban Canyon. Surface and water-column profiles of suspended matter during April-May 2002, and satellite images from the northern Andaman Sea and Gulf of Martaban were also investigated (Ramaswamy et al., 2004). The studies revealed perennially high suspended sediment concentrations in the Gulf of Martaban. These

were due to re-suspension of sediments by strong tidal current, shallow bathymetry and seasonal sediment influx from rivers. Satellite images indicated that in the central portion of the Gulf of Martaban, the turbidity front oscillated about 150 km in phase with spring-neap tidal cycles. The sediment discharged by the Ayeyarwady River is transported mainly eastward, along the coast, into the Gulf of Martaban. Turbidity profiles showed that bottom nepheloid layers actively transported some of the sediments into the deep Andaman Sea via the Martaban canyon. Rao et al. (2005) studied the characteristics and distribution of surface sediments on this continental shelf. Grainsize distribution revealed three distinct areas in terms of sediment texture; a near shore mud belt in the Gulf of Martaban and adjacent inner shelf, outer-shelf relict sands and mixed sediments with varying proportions of relict sand and modern mud in the Martaban canyon. The bulk of the terrigenous sediment discharged by the Ayeyarwady River is displaced eastwards by a combination of tidal currents and clock-wise flowing SW monsoon current and deposited in the Gulf of Martaban resulting in shoaling of its water depths. Part of the sediment discharge reaches the deep Andaman Sea via the Martaban canyon and the rest is transported westward into the Bay of Bengal by the counter clock-wise flowing NE monsoon currents.

Mineralogy and Sr-Nd-isotopic composition of the clay fraction of the Holocene and late Pleistocene sediments from 12 gravity cores along the western margin of India helped delineate the provenance and the response of isotopes with respect to the source rock composition (Kessarkar et al., 2003). The major sediment sources are illite, chlorite-rich sediments from the Indus, smectite-dominated sediments from the Deccan Traps, and kaolinite and smectite-enriched sediments from gneissic rocks. It was found that Sr isotopes are sensitive to weathering and lateritization. Weathering however does not influence Nd isotopes. Kaolinite-enriched sediments coupled with high Sr ratios and low eNd on the SW margin of India suggest intense chemical weathering in the hinterland. It was found that the influence of the sediment from the Ganges-Brahmaputra, transported by the Bay of Bengal waters during the NE monsoon surface current, on the composition of the sediments of the SW Indian margin is insignificant.

Chauhan et al. (2005) analysed 64 sequential satellite images (October 1999 - March 2001) of IRS-P4 ocean colour monitor (OCM) for total suspended matter (TSM), synchronous sea-truth data acquisition, and salinity variations in order to reconstruct the dispersal pathways of fluvial flux in the northern Bay of Bengal during the NE monsoon. From the spatial extent of the plumes of TSM (160-120 km) off the Ganges-Brahmaputra (G-B), it is evident that the fluvial flux does not diminish concurrently with the termination of the SW monsoon, as suggested by time-series trap experiments in the northern bay. During the NE monsoon, the G-B plumes move north to south initially off the mouth, and thereafter advects SW alongshore in the form of coastal sediment plumes, reducing the salinity of coastal waters along the entire northern bay. The results suggest that reduced recovery of the fluxes in the sediment traps subsequent to the SW monsoon are not linearly related

to the magnitude of fluvial flux of the G-B, but stems from the prevalent dispersal patterns.

Alagarsamy and Zhang (2005) made a comparative study of trace metals in Indian and Chinese rivers in order to understand geochemical variations on a global scale in terms of climate, geological conditions and anthropogenic impact. The average particulate trace-metals concentrations of Indian rivers $\sim 300\text{--}1000\text{ mg g}^{-1}$ is higher than that of Chinese rivers $150\text{--}300\text{ mg g}^{-1}$ and the global average $170\text{--}350\text{ mg g}^{-1}$. Molar ratios of alkaline and alkaline earth metals to Fe and Al (segregation factors) were calculated. Regional differences in segregation factors were attributed to variable weathering rates due to differing mineralogy, preferential removal of alkaline and alkaline earth metals relative to oxide-forming elements (Fe and Al) and a regional climate shift north to south from temperate to sub-tropical conditions. Elevated Pb in Chinese rivers and Co and Zn in Indian rivers were due to anthropogenic inputs of these heavy metals.

Nigam et al. (2005) and Panchang et al. (2005) studied the foraminiferal distribution in the surface sediments of the Mandovi and Zuari estuaries of Goa. In the Zuari estuary the total foraminiferal number increased from 1143 specimens/g sand in the year 1972 to 3057 specimens/g in the year 2003. On the other hand, the total foraminiferal number in the lower reaches of the Mandovi river estuary, Goa fall from 138/g dry sediment sample in 1994 to 40/g sediment s in 2001. The decrease in foraminiferal number in Mandovi and their increase in Zuari were attributed to increase and decrease of mining activities and related pollution intensity in Mandovi and Zuari estuaries, respectively.

GEOCHEMISTRY OF THE NEAR - SURFACE SEDIMENTS - EARLY DIAGENETIC CHANGES

Knowledge on early diagenetic changes in organic-rich sediments is important in understanding the processes involved in authigenic mineralization. Prakash Babu and Nath (2005) studied the surficial sediments within the oxygen minimum zone (OMZ: 150-1200 m) of the upper continental slope of the eastern Arabian Sea to identify the process responsible for P enrichment in OMZ. A five step sequential extraction scheme was followed. High fractions of organic (P_{org}) and biogenic (P_{bio}) phosphorus, relatively low molar $C_{\text{org}}/P_{\text{org}}$ ratios and $C_{\text{org}}/P_{\text{reactive}}$ ratios close to Red Field ratio in sediments of the SE Arabian Sea suggest accumulation under high surface production and low residence time of labile forms of P due to high sedimentation rates. Despite higher productivity in surface waters, low fractions of P_{org} , P_{bio} , relatively higher molar $C_{\text{org}}/P_{\text{org}}$ ratios and $C_{\text{org}}/P_{\text{reactive}}$ ratios less than Red Field ratio in sediments from the NE Arabian Sea may indicate a higher degree of regeneration and diagenetic transformation of labile forms of P to other phases. Authigenic P (P_{aut}) varies by a factor of 2-8 in sediments from the OMZ when compared to well-oxygenated deep sea sediments. While P_{total} remains constant significant P transformation seems to occur in NE Arabian Sea, which is suggested by high P_{aut} fraction compared to low P_{aut} fraction in the SE Arabian Sea sediments. Supply rates of P, variable rates of P dissolution

under varying dissolved oxygen contents in the bottom waters and early diagenetic transformation of P within the sediments seem to influence P geochemistry in sediments of the OMZ. Similarly, the organic-rich sediments collected within and below the OMZ of the Oman margin were analysed using a sequential leaching technique to characterize the diagenetic behavior and speciation of Mn and Fe (Alagarsamy et al., 2003). They found the absence of non-detrital Mn in the cores below the OMZ site and attributed to the lack of easily reducible oxides in surficial sediments and to the reduction and export of any moderately reducible oxides. The Mn-enrichment in the upper layer of sediments at the abyssal site, reflect the presence of an oxidizing sedimentary layer which acts as Mn trap during its cycling. An easily reducible Fe oxide layer was observed in the abyssal sediments at an identical depth to the Mn enrichment suggesting that Fe associated with Mn oxides also has undergone sub-oxic diagenesis. The Fe associated with organic matter did not indicate diagenetic modification and is preserved in abyssal sediments. Another interesting feature observed was that for the cores below the OMZ, the iron oxides were associated with Mn-oxide peak, rather than deeper in the sediments as observed by earlier studies in the Atlantic.

Pattan et al. (2005c) studied the trace-element chemistry of a 5-m-long sediment core from the Central Indian Basin. Sediments from the top 1 m of the core showed low ΣREE abundances close to that of shale suggesting terrigenous source. The down-core SREE abundances show a nearly two-fold increase with depth and the REE strongly co-varies with Mn, Ti, P and smectite. The positive Ce-anomaly, Mn/Ti and Ce/Ti in the top 1 m of the core suggest sediment deposition under more oxic bottom-water conditions. The negative Ce-anomaly between 4 and 5 m depth indicates sub-oxic /anoxic environment. However, the other redox sensitive parameters, which include Mn content, organic carbon, U/Th, Cu/Zn and V/Cr ratios at the same level indicate deposition of sediment under oxygenated bottom-water conditions. The contrasting results at the same level points out that the negative Ce-anomaly is caused by early diagenetic processes and by the formation of authigenic phosphate and Fe-rich smectite. These results suggest that Ce-anomaly of bulk sediments as an indicator of palaeo-ocean bottom-water redox conditions needs to be used with a caution.

MINERALS AND ENERGY RESOURCES

Phosphorites and Dolomites

Sedimentary phosphorites either occurring on land or in the oceans are largely marine in origin. Phosphorites have been reported to occur in the Cretaceous sequences of the onshore and also Quaternary sequences in the offshore (at depths between 180 and 320 m) of Tamil Nadu, India. The origin of these phosphorites has been investigated in detail (Rao et al., 2007). The Cretaceous phosphorites occur as light-brown to yellowish brown or white nodules in Karai Shale of the Uttatur Group in the onshore Cauvery basin. Nodules exhibit phosphatic nucleus encrusted by a chalky shell of carbonate. The nucleus of the nodules consists of

light and dark coloured laminae, phosphate peloids/coated grains and detrital particles interspersed between the laminae. SEM studies reveal trapping and binding activity of microbial filaments. A mat structure with linearly arranged microbial filaments and hollow, cell-based coccoid cyanobacterial mat are present. It is suggested that the nuclei of the nodules represent phosphatic clasts related to phosphate stromatolites formed at intertidal conditions. At high-energy levels the microbial mats were disintegrated into phosphate clasts, coated with carbonate and then reworked into Karai Shale. Quaternary phosphorites in the offshore Tamil Nadu also resemble phosphate stromatolites. It is suggested that benthic microbial mats probably supplied high phosphorus to the sediments. Availability of excess P seems to be a pre-requisite for the formation of phosphate stromatolites. Microbial processes played an important role in phosphorite formation. Rao et al. (2003c) made detailed investigations on the dolomite crusts occurring at 64 m depth on the carbonate platform off western India for their genesis. The crusts consist of dolomitized microlaminae interspersed with detrital particles. The laminae under SEM are made up of tubular or cellular structures of probably cyanobacterial origin. It has been seen that progressive mineralization obliterates cells and filament morphology. Sulphide minerals and stable isotope composition of dolomite in the crusts indicate hypersaline and anoxic conditions during dolomite formation. The crusts are similar to dolomite stromatolites and biogeochemical processes related to decaying microbial mats under anoxic conditions played an important role in dolomite precipitation.

Ferromanganese Nodules

Pattan and Parthiban (2007) compared the chemical composition of the ferromanganese nodules buried at different depths in a 5-m sediment core and those occurring on the surface of the sea floor in order to understand the enrichment processes of different major, trace and rare elements and the genesis of nodules. Buried nodules are smaller in size compared to those in Atlantic and Pacific Oceans. The size of the nodules decreases with depth in the core. Buried nodules from siliceous ooze are enriched in Fe, Co, Ti, U, Th, Y, Cr and REEs and hydrogenetic and early diagenetic processes are involved in their enrichment. Buried nodules from red clay are of hydrogenetic origin. REEs are enriched more than 1.5 times in buried nodules from red clay compared to siliceous ooze. Shale-normalized REE patterns show more oxidizing conditions in the nodules of siliceous ooze. Chemical composition, surface texture and morphology of the buried nodules are similar to those of the surface nodules. Buried nodules do not exhibit distinct pattern within the core depth suggesting that they neither grow nor dissolve after burial in the sediment column.

Banerjee (2004) investigated geochemistry of the manganese nodules and reported enriched concentrations of platinum and Iridium in them. The oceanic manganese nodules contain on an average 100 times more platinum than that of the Earth's upper continental crust. Thus the manganese nodule resources at the Central Indian Basin could be a potential source for precious metals including platinum, palladium and silver.

Sediments Indicative of Hydrothermal Activity

Iyer (2005) reviewed the morpho-tectonic features and volcanogenic components occurring in the Central Indian Basin and reported geologically recent evidences for incipient hydrothermal events. He showed the occurrence of (a) spillites that probably formed due to low-temperature hydrothermal action on the precursory basalts, (b) slabs and fragments of zeolites which are the consequent products of palagonitisation of the basaltic glasses, (c) chemical variations in the ferro-manganese crusts, and (d) abundance of volcanogenic-hydrothermal material that includes ochrous sediments and magnetite spherules. The volcanogenic-hydrothermal material suggests its origin by interaction of Fe-rich hydrothermal solutions with surrounding sediments. The volcanic spherules occur in sediments of 10 ka and 425 to 650 ka age and are orders of magnitude younger than the 50 to 60 Ma age of the basin. This suggests episodes of localized hydrothermal events in the central Indian basin.

Mascarenhas-Pereira et al. (2006) studied the volcanic material recovered from a volcanic terrain in the fracture zone defined as Rodriguez triple Junction in the Central Indian Basin. The material includes volcanic glasses associated with pumice, micronodules and palagonite-like lithic fragments. Morphologically the tephra consist of platy- and blocky-type shards. Rarity of vesicle in the shards suggests that they are formed in depths deeper than 4000 m, below the volcanic fragmentation depth. Chemical analyses indicate that the tephra are mainly rhyolitic and formed from melts of siliceous composition. The tephra are rare in sediments younger than 239 kyr. The size, composition and morphological characteristics of the tephra suggest intraplate volcanism, triggered by reactivation of tectonic activity in the fracture zone during the late Pleistocene.

Gas Hydrates and Methane-derived Carbonates

The presence of gas hydrates along the Indian continental margins has been speculated by earlier workers based on identification of Bottom Simulating Reflection (BSR) on the multi-channel seismic records and computed gas hydrate stability thickness map. The BSR alone is not adequate to infer gas hydrates as suggested by drilling results elsewhere. Keeping the above in view, Ramana et al. (2006) carried out multidisciplinary investigations in order to better understand the subsurface distribution of gas hydrates. These observations include geophysical anomalies (BSRs, pockmarks, gas upthrust zones, vents, blanking zones, etc.), geochemical (sulphate reduction trend and methane profile) and microbiological proxy indicators (sulphate and nitrate-reducing bacteria and fermenters) which favour the presence of gas hydrates. Multidisciplinary studies on three sediment cores from the Krishna-Godavari Basin, Andhra Pradesh yielded positive results of the indication of gas hydrates (Kocherla et al., 2006). White carbonate precipitates have been identified in the sediments. These precipitates are rich in high-magnesium calcite and aragonite and typically associated with methane oxidation. Anoxic diagenetic realm was indicated by the presence of framboidal pyrites. Highly depleted carbon isotopic compositions of the handpicked carbonate crystals are

suggestive of anaerobic oxidation of methane. Geophysical records showed features such as BSR, gas-charged sediments and pock-marked sea floor, indicative of possible methane gas hydrate. Further studies are in progress for comprehensive understanding of the processes involved.

Karisiddaiah et al. (2006) studied the pore-water chemistry of the 10 sediment cores collected at water depths between 2665-3210 m from the eastern Arabian Sea. The results indicate that the dissolved oxygen content of the near bottom waters ranges from 81 to 150 mM. The total organic carbon and sulphate contents of the sediments vary from 0.2 to 0.9% and from 39.8 to 12.7 mM respectively. Similarly, chloride concentration varies from 561 to 407 mM. The down-core methane, ethane and propane concentrations range from 1.5 to 12.5 nM, 0.04-1.2 nM and 0.09-0.46 nM, respectively. The slow sulphate reduction in the sediments is probably due to low content of C_{org} , moderate sedimentation rates as well as low porosity and absence of strong anoxic environment.

Extraterrestrial Material

Tektites are impact-generated glassy ejecta distributed in four strewn fields. The youngest of them is Australasian tektite strewnfield (0.77 Ma). Shyam Prasad and Khedekar (2003) studied 137 Australasian microtektites from 4 sediment cores from the Central Indian Basin. The studies revealed more than 2000 impact-generated features in the size range of 0.3 to 600 mm. Destructive erosive and accretionary-type impacts were recognized. Smaller microtektites seem to have the largest number of impacts indicating that target temperature is an important factor for retaining impact-generated features. Shyam Prasad et al. (2003) also found two layers of Australasian impact ejecta in the Indian Ocean. They reported that the tektites are occurring at the sediment/water interface and microtektites buried in older horizons beneath the seafloor at stratigraphic levels conforming to the radiometric age of the strewn field. Thus at first glance, there appear to be 2 layers of Australasian impact ejecta in the Indian Ocean. However, the manganese nodules are associated with the tektites which, although millions of years old, are invariably resting on recent sediments. Therefore, the mechanism that retains nodules at the sea floor also seems to be operative on the tektite, thus leading to this apparent 'age paradox' of tektite/microtektite distribution in the Indian Ocean, although they both belong to the same impact event.

REFERENCES

- Alagarsamy, R. 2003, Organic matter composition in sediments of the Oman margin: *Chem. Ecol.*, v. 19, p. 419-429.
- Alagarsamy, R. and Zhang, J., 2005, Comparative studies on terrace metal geochemistry in Indian and Chinese rivers: *Curr. Sci.*, v. 89, p. 299-309.
- Anilkumar, K., Rao, V.P., Patil, S.K., Kessarkar, P.M., Thamban, M., 2005, Rock magnetic records of the sediments of the eastern Arabian Sea: evidence for late Quaternary climatic change: *Mar. Geol.*, v. 220, p. 59-82.
- Banakar, V.K., 2005, $\delta^{13}C$ depleted oceans before the termination 2: More nutrient-rich deep water formation or light carbon transfer?: *Indian J. Marine Sci.*, v. 34, p. 249-258.
- Banakar, V.K., Oba, T., Chodankar, A.R., Kuramoto, T., Yamamoto, M. and Minagawa, M., 2005, Monsoon-related changes in sea surface productivity and water column denitrification in the eastern Arabian Sea during the last glacial cycle, *Mar. Geol.*, v. 219, p. 99-108.
- Banerjee, R., 2004, Manganese nodules as a possible source of precious metals: *Curr. Sci.*, v. 87, p. 278-279.
- Chauhan, O.S., Rajawat, A.S., Pradhan, Y., Suneeti, J. and Nayak, S.R., 2005, Weekly observations on dispersal and sink pathways of the terrigenous flux of the Ganga-Brahmaputra in the Bay of Bengal: *Deep Sea Res. Part II*, v. 52, p. 2018-2030.
- Chodankar, A.R., Banakar, V.K. and Oba, T., 2005, Past 100 kyr surface salinity gradient response in the eastern Arabian Sea to the summer monsoon variations recorded by $d^{18}O$ of *G. sacculifer*: *Global Planet. Change*, v. 47, p. 135-142.
- Iyer, S.D., 2005, Evidences of incipient hydrothermal events in the Central Indian Basin: a review: *Acta Geol. Sinica*, v. 79, p. 101-110.
- Karisiddaiah, S.M., Borole, D.V., Rao B.R., Paropkari, A.L., Joao, H.M., Kocherla, M., Sarkar, G.P., Biswas, G., Kumar, N., 2006, Studies on pore water sulphate, chloride and sedimentary methane to understand the sulphate reduction process in eastern Arabian Sea: *Curr. Sci.*, v. 91, pp. 54-60.
- Kessarkar, P.M., Rao, V.P., Ahmad, S.M., Patil, S.K., Anilkumar, A., Anil babu, G. Chakraborty, S. and Sounder Rajan, R., 2005, Changing sedimentary environment during the late Quaternary: Sedimentological and isotope evidence from the distal Bengal Fan: *Deep Sea Res.*, 52, 1591-1615.
- Kessarkar, P.M., Rao, V.P., Ahmad, S.M. and Anil Babu, G., 2003, Clay minerals and Sr-Nd isotopes of the sediments along the western margin of India and their implications for sediment provenance: *Mar. Geol.*, v. 202, p. 55-69.
- Kessarkar, P.M. and Rao, V.P., 2006, Organic carbon in the sediments of the southwestern margin of India: Influence of productivity and monsoon variability during the Late Quaternary: *J. Geol. Soc. India*, v. 69, p. 42-52.
- Kocherla, M., Mazumdar, A., Karisiddaiah, S.M., Borole, D.V., Rao, B.R., 2006, Evidences of methane-derived authigenic carbonates from the sediments of the Krishna-Godavari basin, eastern continental margin of India: *Curr. Sci.*, v. 91, p. 318-323.
- Mascarenhas-Pereira, M.B.L., Nath, B.N., Borole, D.V., Gupta, S.M., 2006, Nature source and composition of volcanic ash in sediments from a fracture zone trace of Rodriguez Triple Junction in the central Indian Basin: *Mar. Geol.*, v. 229, p. 79-90.
- Mergulhao, L.P., Mohan, R., Murty, V.S.N., Guptha, M.V.S., Sinha, D.K., 2006, Coccolithophorids from the Central Arabian Sea trap results: *Jour. Earth System Sci.*, v. 115, p. 415-428.
- Mohan, R., Guptha, M. V. S., 2006, Corroded planktonic foraminifers (*Globorotalia menardii*) in the southern Bay of Bengal sediment trap sample of February 1992.: *J. Geol. Soc. India*, v. 68, p. 225-229.
- Mohan, R. Verma, K., Mergulhao, L.P., Sinha, D.K. and Guptha, M.V.S., 2006, Seasonal variations of pteropods from the western Arabian Sea sediment trap: *Geo-Marine. Lett.*, v. 26, p. 265-273.

- Naidu, P.D., 2004, Isotopic evidences of past upwelling intensity in the Arabian Sea: *Global Planet. Change*, v. 40, p. 285-293.
- Naidu, P.D. and Malmgrin, B.A., 2006, Seasonal sea surface temperature contrast between the Holocene and last glacial period in the western Arabian Sea (Ocean Drilling program site 723A): Modulated by monsoon upwelling. *Palaeoceanography*, v. 20, pp. 9.
- Nair, T.M.B., Ittekot, V., Shankar, R. and Guptha, M.V.S., 2005, Settling Barium fluxes in the Arabian sea Critical evaluation of relationship with export production, *Deep Sea Res., Part II*, v. 52, p. 1930-1946.
- Nath, B.N., Gupta, S.M., Mislankar, P.G., Rao, B.R., Parthiban, G., Roelands, I. and Patil, S.K., 2005, Evidence of Himalayan erosional event at approx. 0.5 Ma from a sediment core from the equatorial Indian ocean in the vicinity of ODP Leg 116 sites: *Deep Sea Res.*, v. 52 (II), p. 2061-2077.
- Nigam, R., Panchang, R. and Banerjee, P., 2005, Foraminifera in surface sediments of mandovi River Estuary. Indicators for mining pollution and high stand in Goa, India: *J. Coast. Res.*, v. 21, p. 853-859.
- Padmakumari V. M., Ahmad, S. M., Dayal, A. M., Sounder Rajan, R. and Gopalan, K., 2006, Seawater Neodymium isotopic composition in the Northeastern Indian ocean during the LGM to Holocene: response to Glacial and Monsoonal weathering in Himalaya-Tibet: *J. geol. Soc. India*, v. 68, p. 425-432.
- Panchang, R., Nigam, R., Baig, N. and Nayak, G.N., 2005, A foraminiferal testimony for the reduced adverse effects of mining in Zuari estuary, Goa: *Int. J. Environ. Stud.*, v. 62, p. 579-591.
- Pattan, J.N. and Parthiban, G., 2007, Do manganese nodules grow or dissolve after burial? Results from Central Indian Ocean Basin. *J. Asiatic Earth Sci.*, v. 30, p. 696-705.
- Pattan, J.N., Masuzawa, T., Borole, D.V., Parthiban, G., Jauhari, P. and Yamamoto, M., 2005b, Biological productivity, terrigenous influence and non-crustal element supply to the central Indian ocean basin. *Paleoceanography during the past approx. 1 Ma: J. Earth Sci. Sys.* v. 1, p. 63-74.
- Pattan, J. N., Masuzawa, T. and Yamamoto, M., 2005a, Variations in terrigenous sediment discharge in sediment core from southeastern Arabian Sea during the last 140 ka: *Curr. Sci.*, v. 89, p. 1421-1425.
- Pattan, J.N., Pearce, N.J.G. and Mislankar, P.G., 2005c, Constraints in using Cerium anomaly of bulk sediments as an indicator of paleo-bottom water redox environment: a case study from the central Indian Ocean basin: *Chem. Geol.*, v. 22, p. 260-278.
- Prakashbabu, C. and Nath, B.N., Processes controlling forms of phosphorous in surficial sediments from the eastern Arabian Sea impinged by varying bottom water oxygenation conditions: *Deep -sea Res., part II*, v. 52, p. 1965-1980.
- Ramana, M.V., Ramprasad, T., Desa, M., Sathe A.V. and Sethi, A.K., 2006, Gas-hydrate related proxies inferred from multidisciplinary investigations in the India offshore areas: *Curr. Sci.*, v. 91, p. 183-189.
- Ramaswamy, V. and Gaye, B., 2006, Regional variations in the fluxes of foraminifera carbonate, coccolithophorid carbonate and biogenic opal in the northern Indian Ocean: *Deep Sea Res.*, v. 53, p. 271-293.
- Rao, P.S., Ramaswamy, V. and Thwin, S., 2005, Sediment texture distribution and transport of Ayeyarwady continental shelf, Andaman Sea: *Mar. geol.*, v. 216, p. 239-247.
- Rao, V.P., Montaggioni, L., Vora, K.H., Almeida, F., Rao, K.M. and Rajagopalan, G., 2003a, Significance of relic carbonates deposits along the central and southwestern margin of India for late Quaternary environmental and sea level changes: *Sed. Geol.*, v. 159, p. 95-111.
- Rao, V.P., Rajagopalan, G., Vora, K.H., Almeida, F., 2003b, Late quaternary sea level and environmental changes from relic carbonate deposits of the western margin of India, *Proc. Indian Acad. Sci.: Earth and Planet. Sci.*, v. 112, p.1-25.
- Rao, V.P., Kessarkar, P.M., Krumbien, W.E. and Schneider, R., 2003c, Microbial dolomite crusts from the carbonate platform off western India *Sedimentology*, v. 50, p. 819-830.
- Rao, V.P., Kessarkar, P.M., Nagendra, R. and Babau, E.V.S.S.K., 2007, Origin of Cretaceous phosphorites from the onshore of Tamil Nadu, India: *J. earth Sys. Sci.*, v. 116, p. 525-536.
- Saraswat, R., Nigam, R., Weldeab, S., Mackensen, A. and Naidu, P.D., 2005, A first look at past sea surface temperature in the equatorial Indian Ocean from Mg/Ca in foraminifera: *Geophys. Res. Lett.*, v. 32, p. 4.
- Shyam Prasad, M., Gupta, S.M., Kodagali, V.N., 2003, Two layers of Australasian impact ejecta in the Indian ocean?: *Meteor. Planet. Sci.*, v. 38, p. 1373-1381.
- Shyam Prasad, M. and Khedekar, V.D., 2003, Impact of microcrater morphology on Australasian microtectites. *Meteor. Planet. Sci.*, v. 38, p. 1351-1371.
- Singh, A. D., Kroon, D. and Ganeshram, R. S., 2006, Millennial scale variations in Productivity and OMZ intensity in the Eastern Arabian Sea: *J. Geol. Soc. India*, v. 68, p. 369-377.
- Thamban, M., Kawahata, H. and Rao, V.P. 2007, Indian summer monsoon variability during the Holocene as recorded in sediments of the Arabian Sea: Timing and implications: *J. of Ocean.* v. 63, p. 1009-1020.
- Unnikrishnan, A.S., Kumar, K.K., Fernandes, S.E., Michel, G. S. and Patwardhan, S.K., 2006, 'Sea level changes along the Indian coast: Observations and projections: *Curr. Sci.*, v. 90, p. 362-368.