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Evidence of Himalayan erosional event at ~0.5 Ma from a sediment core from the equatorial Indian Ocean in the vicinity of ODP Leg 116 sites

B. Nagender Nath[a,*], S.M. Gupta[a], P.G. Mislankar[a], B.Ramalingeswara Rao[a], G. Parthiban[a], I. Roelandts[b], S.K. Patil[c]

[a]*Geological Oceanography Division, National Institute of Oceanography, Dona Paula, Goa 403004, India*
[b]*Department of Geology, Petrology and Geochemistry, University of Liege, Sart Tilman, Belgium*
[c]*Indian Institute of Geomagnetism, Colaba, Mumbai, India*

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Abstract

A sediment core collected from an area ~100 miles south of the ODP Leg 116 (distal Bengal Fan) in the equatorial Indian Ocean was investigated for microfossils, mineralogy, mineral chemistry, magnetic susceptibility, grain size, major, minor and rare-earth element geochemistry, organic carbon and total nitrogen contents in the bulk sediments. Distinct changes in depositional characteristics (including presence of abundant sand-sized micas and other detrital minerals) occur at two sub-surface depths corresponding to ~0.5 and probably 0.8 Ma time periods. The detrital mineral suite of this core resembles that of turbidite unit I sediments of ODP cores in the distal Bengal Fan. The core site has received an increased supply of terrigenous sediments at these two time periods, the older pulse (0.8 Ma) stronger than the younger pulse. Several lines of evidence such as the nature of the mineral suite, lower magnetic susceptibility values, Si/Al in mica mineral separates; major element composition; discrimination plots of Ca/Ti versus K/Ti and K_2O/Al_2O_3 and La/Yb ratios suggest a highly metamorphosed source such as higher Himalayan crystalline (HHC) series indicating two events of increased physical weathering and erosion in the Himalayan region. While the erosional event of 0.8 Ma is well known, the episode of 0.5 Ma was not reported earlier.

1. Introduction

The Himalayan mountains are responsible for the building up of major sedimentary systems such as Bengal and Indus fans in the Northern Indian Ocean. The delivery of clastic sediments to the northern Indian Ocean from south-central Asia is controlled by the combination of processes such as orogeny and erosion, changes in sea level, regional climatic processes such as monsoons, global climatic variations, etc. (Rea, 1992). To study the

*Corresponding author.
E-mail address: nagender@darya.nio.org (B.N. Nath).

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link between tectonic processes of the uplift of the Himalayan ranges and Tibetan Plateau, initiation of the Asian monsoon, ocean geochemistry, and also to study the turbiditic sedimentation through Neogene period, Ocean Drilling Program (ODP) has drilled three sites (717–719) in the distal Bengal Fan region during Leg 116 (Cochran, 1990). The sites revealed a distinct facies variation starting from the lower Miocene up to the Holocene. Silty turbidites dominate sedimentation from the early (ca. 20 million years ago) to late Miocene (ca. 7 Ma), followed by slowly accumulating mud turbidites (7–0.9 Ma), switching over to silty turbidites during middle and late Pleistocene (younger than 0.9 Ma). Changes in supply rates in sediment are attributed to varied processes such as sea level changes, shifts in depocentres between distal and proximal basins, internal lobe switching, etc. (e.g. France-Lanord and Derry, 1997). From the seismic studies in the Bengal Fan in a transect running from ODP 116 in the distal part to DSDP Leg 22 in the central part, Krishna et al. (1998) have found three unconformities at 7.5, 4 and ~0.8 Ma and a link between intra-plate deformation in the Indian Ocean and the formation of the Himalaya. Banakar et al. (2003) have recently deciphered Himalayan sedimentary pulses from the silicate detritus in growth layers of ferromanganese crusts from the central Indian basin. Excellent reviews were written by Valdiya (1998, 1999, 2002) on the emergence and evolution of the Himalaya, covering aspects of Indian collision with mainland Asia (~65 Ma) to the end of the Pleistocene ice age of 0.2 Ma. While all these records are long and provide a long-term history of mountain building and resultant tectonic and geological changes, some studies have concentrated on the erosional history of the Himalayan and Burman ranges for shorter time periods covering last two glacial periods (e.g., Colin et al., 1999). However, detailed studies on late Pleistocene sedimentation are relatively scarce. Seismic sections (Emmel and Curray, 1984; Krishna et al., 1998), sedimentological studies (Pimm, 1974) and geochemical studies have shown that the Bengal Fan sediments reach almost up to 8°S (Nath et al., 1989, 1992). While the main fan region has kilometres thick younger sediments, shorter sediment sections from the distal part may record middle to late Pleistocene changes in supply from the terrestrial sources in the north. Therefore, an attempt is made to study such changes through a sediment core collected at a site just south of the geomorphic limits of the fan (Fig. 1).

2. Materials and methods

The sediment core #AAS2/6 studied here was collected at 2°30.807′S and 80°00.511′E, about 120 miles southwest of ODP Leg 116 sites in an area south of the distal Bengal Fan, from a depth of 4888 m during the second cruise of the Russian vessel R.V. *Akademik Aleksandr Sidorenko* as a part of the project on polymetallic nodules (Fig. 1). The length of the core was 73 cm and it was composed of siliceous and micaceous clays. The core was sub-sampled at an interval of 5 cm.

One centimetre sub-section at an interval of 5 cm was studied for radiolarian-based biostratigraphy on strewn slides. The slides were scanned under 40 × and 100 × for the radiolarian specimen counting and index species identification, respectively. Size analyses were carried out using a Malvern Mastersizer 2000 laser particle analyser on well-dispersed bulk sediment suspensions after treating with 2 M Na_2CO_3 to remove biogenic opal.

Energy dispersive X-ray (EDAX) analyses were carried out on mineral grains using an OXFORD EDAX analyser attached with a JEOL scanning electron microscope at NIO, Goa. SEM photos were also taken with the same microscope. The accuracy of EDAX analyses was checked by using microprobe standards of basaltic glass of the Makaopuhi Lava Lake (USNM 113495/1 VG-A99) and rhyolitic glass of the Yellowstone Natural Park (USNM 72854 VG-568). The accuracy of the analyses was better than 2% for SiO_2, 3% for K_2O, 4% for TiO_2, 5% for CaO and lower accuracy for Al_2O_3 (lower by 15%).

Clay mineral studies were carried out following the method of Biscaye described in Rao and Nath (1988) using a Philips XRD using Cu Kα radiation. The clay-sized sediment fraction (<2 μm) was separated by standard settling techniques after

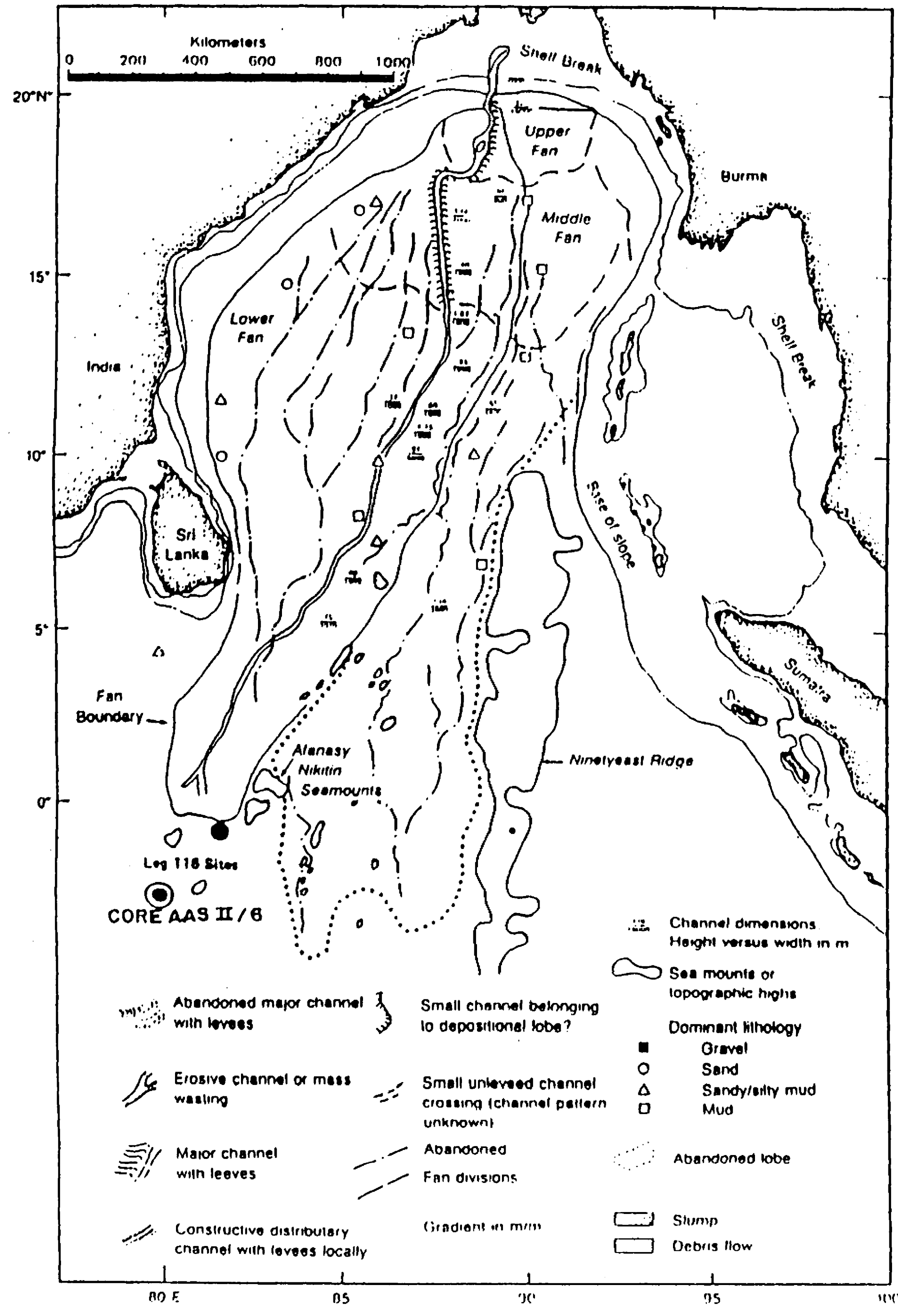

Fig. 1. Physiographic map showing geomorphic features of the Bengal Fan (Emmel and Curray, 1984). Location of the core studied here as well as the drill sites of the ODP Leg 116 in the distal Bengal Fan are shown.

removing carbonate and organic carbon (OC) contents. The clay suspension was pipetted out onto glass slides and both glycolated and untreated clays were used in obtaining X-ray diffractograms. The peak heights were used in calculating the relative percentages of the clay minerals. The XRD analyses on a duplicate set of glass slides have shown consistent results.

The bulk chemical analyses were carried out using ICP–AES at NIO, Goa. The samples were digested in a mixture of HF, $HClO_4$ and HNO_3. The precision was calculated with replicate analyses and the accuracy was determined using international geochemical standards (AGV-1 and SCo-1) of USGS. The precision was mostly better than 7% and accuracy was close to 10% for most elements, better than 1% for Mn. Rare-earth elements were measured with an ICP–MS at the University of Liege, Belgium. Total carbon and nitrogen were measured at NIO, Goa using CNS analyser. OC measurements were made using wet oxidation method of El Wakeel and Riley (1957). The level of precision and accuracy routinely obtained in our laboratory are described in Nath et al. (1997).

Magnetic susceptibility measurements were made at the Indian Institute of Geomagnetism, Mumbai.

3. Radiolarian biostratigraphy

A thorough search was made for *Buccinosphaera invaginata* which is a characteristic species for the youngermost NR-1 zone of Johnson et al. (1989), but only five specimens of this species were found in 0–1 cm section. *Collasphaera tuberosa* was abundant (>25 specimens), whereas *Stylactractus universus* (LAD 0.425 Ma) was absent in core top. *S. universus* is the distinct index fossil for the sections between 5 and 35 cm. Therefore conveniently, the 5–6 cm section can be assigned an age ~0.4 Ma (Hays and Shackleton, 1976). The base of *C. tuberosa* was encountered up to 35–36 cm of the core dating ~0.65 Ma (FAD ~0.65 Ma, Johnson et al., 1989). Sub-samples below 40 cm are devoid of any index fossil except few numbers of *S. universus*. Therefore, though a physical top is present, the top 10 cm section seems to have sediment older than 0.2 Ma and younger than 0.4 Ma. Sections between 10 and 36 cm represent a good preservation of radiolarian sedimentation record for a period of 0.25 Ma between 0.4 and 0.65 Ma. Based on these two datum levels, the sedimentation rate could be ~1 mm/ka for the sections showing pelagic sedimentation. Remaining part of the core has micaceous turbiditic sediments (Fig. 2).

4. Results and discussion

4.1. Sediment grain size

Sediment grain size has been determined here to study the depositional change in conjunction with other tracers. The mean sizes of all the sediment sections studied are larger than 8 μm (Fig. 3) with a maximum mean size reaching as high as 85 μm. They are larger than those of eolian sediments (Chester et al., 1977; Rea, 1994). Thus, these sediments are almost entirely supplied through the liquid medium. The geographic position (at the southern end of one of the feeding channels of the Bengal Fan; Fig. 1) and the high coarse fractions containing a mixture of detrital minerals also indicate a terrestrial supply along the bottom either as normal bedload or through gravity/turbidity flows. Very large grains from the continental rocks can be removed by and transported either through rapid movement of large amounts of material or by rapidly moving down the mountain rivers. Eolian input to the distal Bengal Fan is minor relative to the amount of terrigenous material supplied through bedload by the Ganges–Brahmaputra river system (Hovan and Rea, 1992). A size of >10 μm silt has been chosen to calculate sortable silt and sand (SSS>10 μm) and sortable silt (10–63 μm) on the premise that the particles above this size range behave non-cohesively during the transport and deposition, while the fine end of silt fraction (<10 μm) is typically cohesive in nature and deposits mainly as aggregated material (McCave et al., 1995). A coarser mean size of the non-biogenic fraction would indicate stronger currents during erosion, transport and deposition. The SSS contents in the surface sediments (top 15 cm) are lower (<30%) and contrast with those in the deeper layers where an abrupt increase is noticed at 25 cm (~60%), which continues up to 40 cm (Fig. 3). The first peak occurring at 25 cm

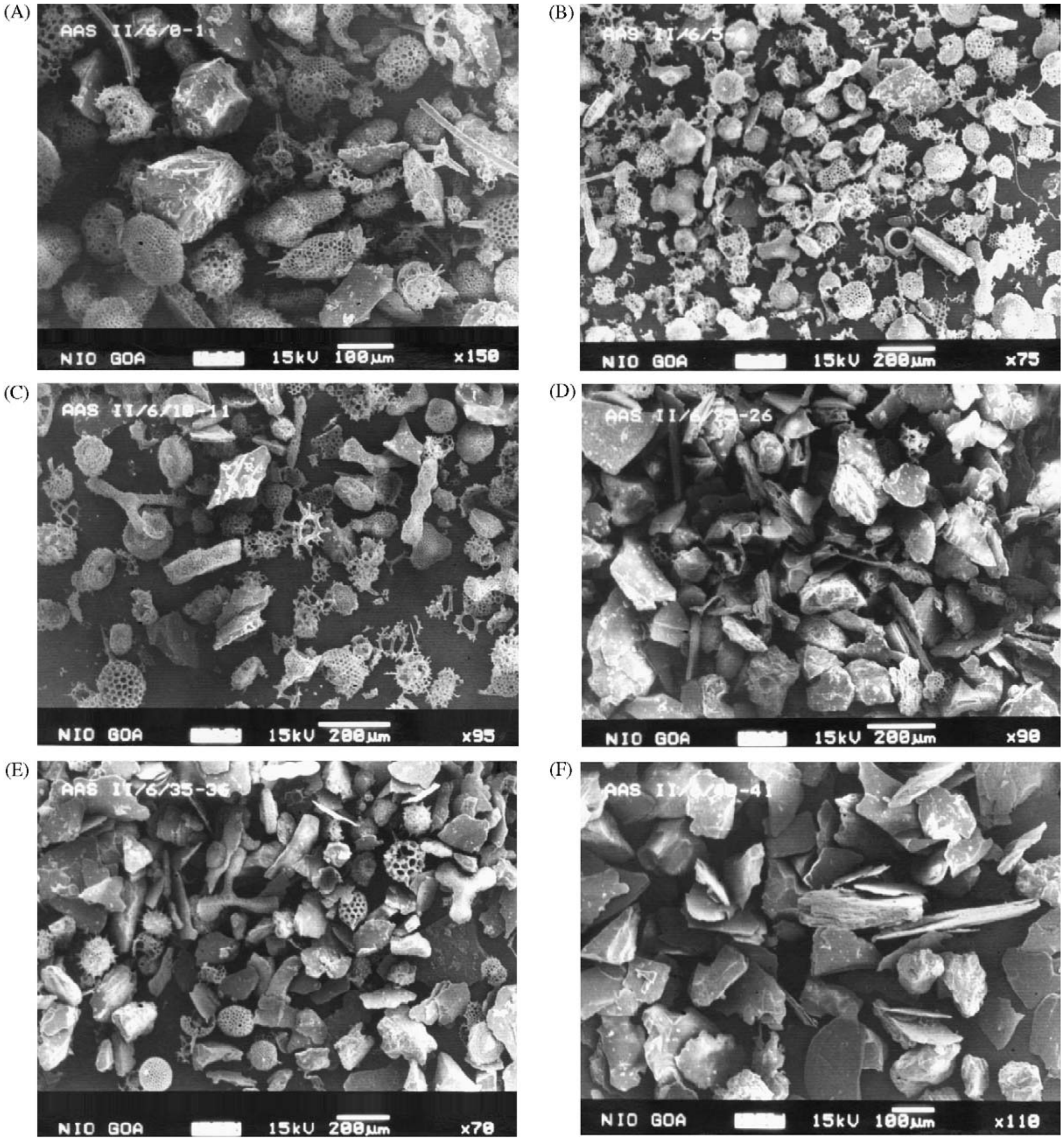

Fig. 2. SEM photos of the coarse fraction (>63 µm) of the different sub-sections revealing the characteristic features of the core. The top sections are rich in radiolarian fauna. Mica is abundant and radiolarians are almost absent in the deeper layers. A distinct change is found at a depth of 35–40 cm.

corresponds to an age of ~0.5 Ma and has the highest volume weighted mean size of 85 µm (Fig. 3) and may represent a depositional change. The sediments younger than 0.5 Ma are pelagic radiolarian-rich in nature and show lower SSS and SS contents and smaller mean size compared to deeper sediments, which have almost double the volume indicating a relatively faster flow.

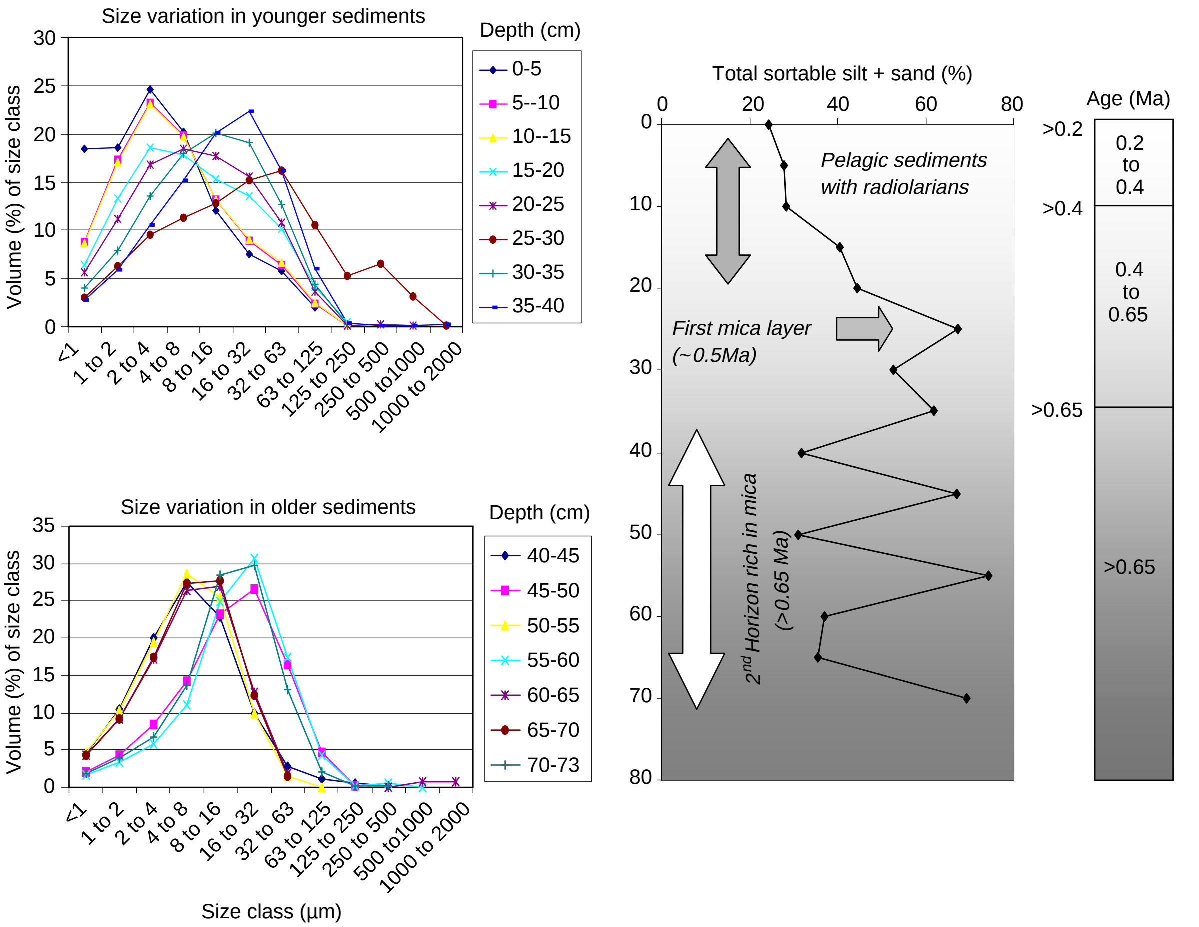

Fig. 3. Size variation of all the sections are shown on the left. For clarity, size data of the top eight sub-sections are shown on the top left and the deeper seven sub-sections on the bottom left. Downcore variation of total SSS contents (% of size fractions $>10\,\mu m$) are shown on the right.

Alternating layers of high and low SSS and the mean size values in the deeper sections between 40 and 73 cm may represent cyclic advancement and regression of turbiditic flows in the Bengal Fan region. The deeper layers with higher SSS contents have mica and other coarser-grained minerals of terrestrial origin and are devoid of biogenic skeletons.

4.2. Magnetic susceptibility

The most widely used magnetic property in the palaeoclimatic research is the magnetic susceptibility of the sediments, which is proportional to the concentration of magnetic minerals in sediments (Bloemendal and deMenocal, 1989; Yamazaki and Ioka, 1997 and references therein). Magnetic susceptibility is studied here to indicate the depositional change as the downcore variations in magnetic susceptibility of the pelagic and hemi-pelagic sediments mainly reflect variations in the relative concentration of terrigenous material (Kent, 1982). Two distinct lows (Fig. 4), the first between 15 and 25 cm and the next between 35 and 60 cm, are seen in the downcore profile. As the mica is abundant in the core, the susceptibility was measured on separated micas. The values were lower than the detection limit. Therefore, the two troughs in susceptibility profiles seem to be governed by the dominance of micas in those layers. The sediment cores studied here seem to preserve the primary magnetic susceptibility signal as the downcore troughs, corresponding to about 0.5 and >0.65 Ma ages, are synchronous with the presence of micas, variation in SSS content and terrestrial C/N ratios (Fig. 4) and apparently not altered due to oxidation of organic matter (Karlin and Levi, 1985).

4.3. Sand-fraction mineralogy

The dominant minerals identified in the two detrital zones within the core are micas (mostly muscovites and biotites) and quartz, and minor amounts of hornblende, feldspars and traces of kyanite, sillimanite and zircon (Figs. 5 and 6; Table 1 for basis of identification). A mixture of mineral grains, containing both smooth, rounded edges and striations along one direction on the one hand and angular form of grains such as kyanite on the other, suggests physical breakdown and transportation for long distances through high-energy environment.

The above mineral assemblage is similar to those found in the silty turbiditic zone I (younger than 0.9 Ma) of drilled cores from the distal Bengal Fan, which were attributed by Amano and Taira (1992) to the higher Himalayan crystalline (HHC) series. A time period of ~0.8–0.9 Ma is the starting point of the youngest phase of increased runoff of

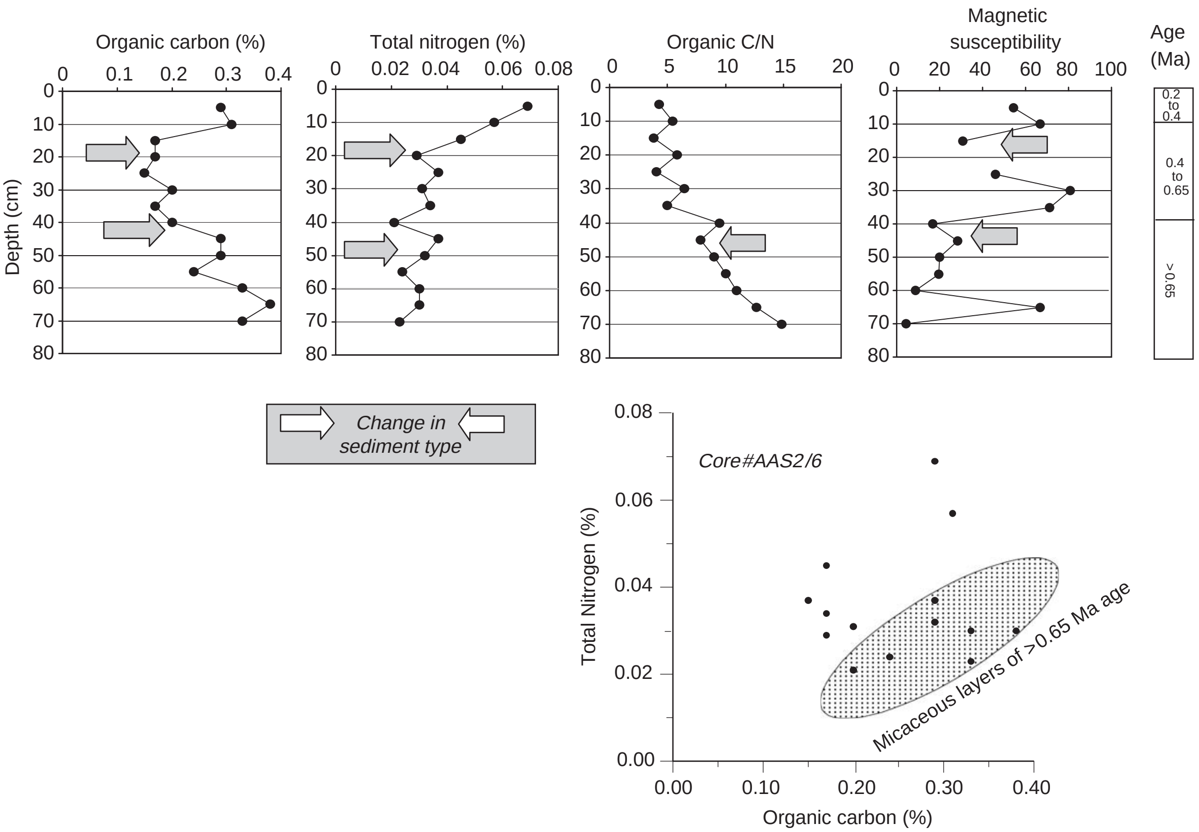

Fig. 4. Downcore variation of OC (%), TN (%), C/N ratios and magnetic susceptibility. C/N ratios are distinctly higher in the deeper sections with abundant mica. Troughs in magnetic susceptibility coincide with mica-rich layers. Bottom half of the figure shows a scatter plot between OC versus TN, where the micaceous layers more than 0.65 Ma fall in a different cluster. However both the data groups are linearly related individually.

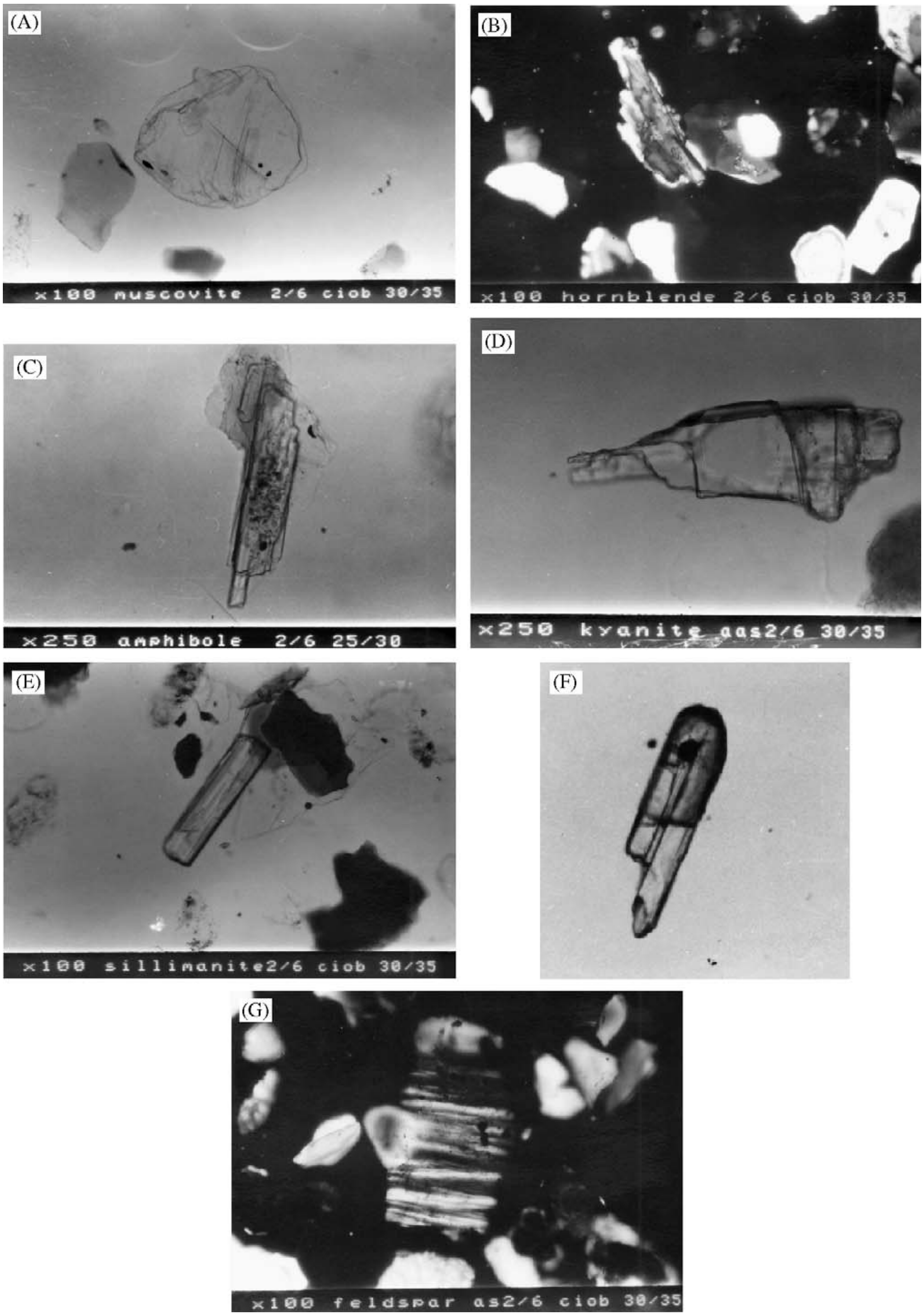

Fig. 5. Mineral grains found in the mica-rich layers. Photomicrographs of (A) muscovite, (B) and (C) hornblende, (D) kyanite, (E) sillimanite, (F) zircon and (G) feldspar.

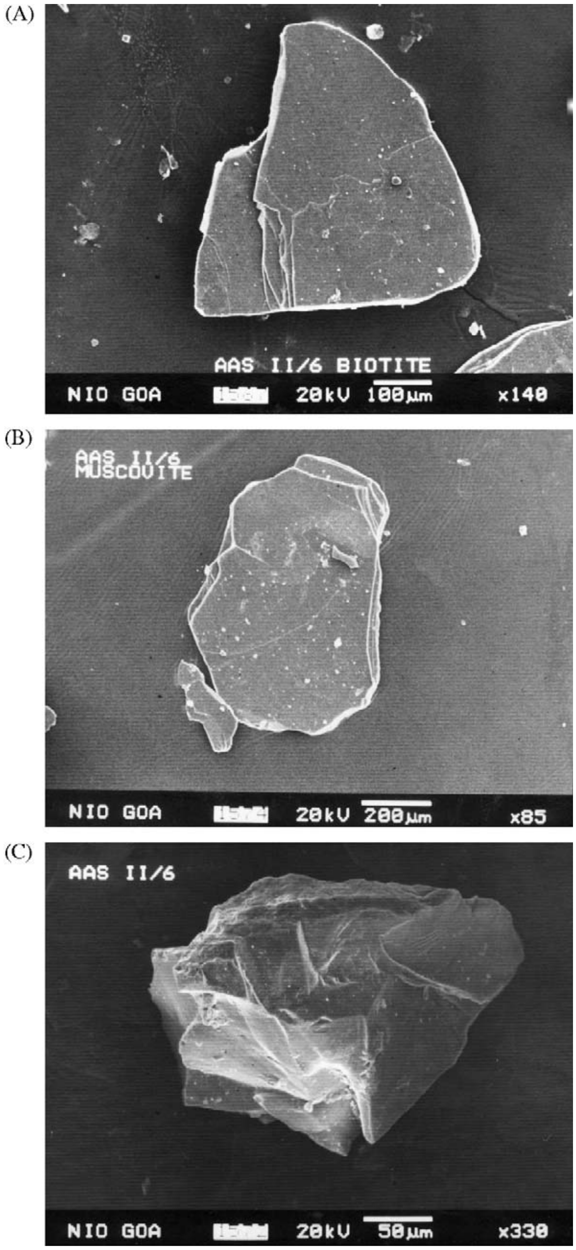

Fig. 6. SEM photos of (A) biotite, (B) muscovite and (C) quartz.

the Himalayan rivers, which continued into the Holocene (see Valdiya, 1999 and references therein). The metamorphic rocks of the HHC contain abundant quantities of biotite and muscovite (~30%; Sorkhabi et al., 1993, 1996; Derry and France-Lanord, 1996), and simplified composition of the HHC rocks would be quartz, feldspar and micas (Sorkhabi et al., 1993). The green-coloured hornblendes (with bluish and brownish tinge) can be correlated to those of amphibolite and gneiss of the higher Himalaya (see Amano and Taira, 1992; Sorkhabi et al., 1998). HHC has been the primary source of sediments to the Bengal Fan since Miocene (Derry and France-Lanord, 1997). The sediments are entirely devoid of tourmaline, TiO_2 polymorphs and ilmenite, and barely have a grain each of epidote and garnet which are a characteristic of weakly metamorphosed sedimentary rocks (Sorkhabi and Arita, 1997) reducing the possibility of the lower Himalaya as the source. Local intraplate volcanoes may not be the sources to these detrital minerals, as muscovite is a very rare product of explosive volcanism. Our inference on source rock identification is similar to earlier studies on DSDP cores from the middle Bengal Fan region, which essentially contains sand from gneissic and metasedimentary terranes of the Himalaya (Ingersoll and Suczek, 1979).

4.4. Mineral chemistry

Chemical analyses were carried out on mineral separates both to decipher the source component and also to confirm the microscopic identification of minerals. Muscovite, biotite and quartz grains are analysed for this work. Si, Al and K dominate muscovite (their oxides total $>92\%$). Biotite, in comparison, has very high iron (19–38% of Fe_2O_3) and much lower Si, Al and K (65–70% of their oxides). The major element composition of these micas fall between the granitic and metamorphic end-members with an inclination towards metamorphic origin (Fig. 7). Our muscovite data matches excellently with the TEM-EDAX data on mica–clay minerals of ODP Leg 116 cores derived from the Himalaya (see Fig. 7 for comparison; ODP data is of Aoki et al., 1991). Therefore, we interpret that both coarse-grained flaky micas in our core and the mica–clay minerals found in distal Bengal Fan cores of ODP 116 were supplied by the Himalaya by turbiditic currents through the Bengal Fan leading to an unsorted texture during the uplift and erosional episodes of

Table 1
Mineral grains recovered and their optical properties

Mineral	Optical properties
Muscovites	Transparent flakes with basal cleavage, low relief with bluish grey interference colour and inclusions. Grains also show acute bisetrix interference figure with low optic angle
Biotites	Smooth edges with basal cleavage. Other features are brown in colour with distinct pseudo-uniaxial interference figure
Hornblende	Elongated, prismatic with dented ends, with one set of perfect cleavage along longitudinal direction. Fractures along the cleavage plane. Greenish in colour with marked pleochroism from light brown (x) to green brown (z) with an extinction angle of ~16°, have high relief
Quartz	Variable in form and size. The smaller grains are also sub-rounded. Larger grains are sub-rounded, turbid with vacuoles. Polycrystalline quartz grains seen occasionally
Kyanite	Colourless, angular to sub-angular, elongated with rectangular outlines with perfect two sets of cleavage at right angles with inclusions parallel to one of the cleavage direction
Sillimanite	Colourless, tubular prismatic grains with striae parallel to length, extinction straight positive elongation with second-order birefringence colour
Zircon	Elongated, well rounded morphology at one end and broken at the other end, colourless with high index with rod-shaped inclusion along the length of the grain, straight extinction with very high order birefringence

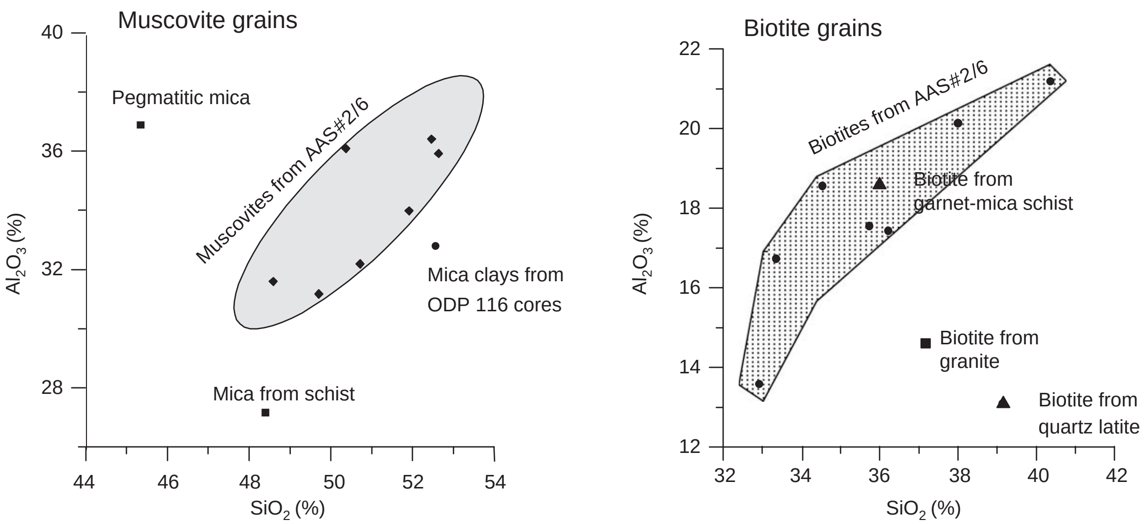

Fig. 7. Plot of SiO_2 versus Al_2O_3 of (A) biotite and (B) muscovite mineral separates. Composition of biotites and muscovite from different rock types are from Heinrich and Levinson (1953), Lambert (1959a, b), Larsen and Draisin (1950) and Larsen et al. (1937).

the Himalaya. Our interpretation is consistent with the published clay mineral data of the rivers contributing to the Bengal Fan. Illite is the dominant mineral supplied by Ganga–Brahmaputra rivers (~70%), while the major peninsular Indian rivers supply smectite (~70%) (Konta, 1985; Naidu et al., 1985; Ramaswamy et al., 1997). Quartz had typically more than 99% of SiO_2.

4.5. Clay mineralogy

Semi-quantitative analyses of clay mineral abundances have shown that illite is the most dominant clay mineral ranging between 60% and 80%. Slow scanning has shown that chlorite is the next abundant clay mineral (8–16%). Illite and chlorite (I + C) added together reach as high as

91%. The deeper sections (>35 cm) having mica sections show higher I+C contents (83–91%) compared to shallower sections (60–66%). The younger section containing mica corresponding to ~0.5 Ma has higher chlorite contents. Dominance of I+C sediments over kaolinite and smectite minerals is consistent with the interpretation that the Bengal Fan sediments younger than 1 Ma are rich in I+C (Derry and France-Lanord, 1996; Aoki et al., 1991). Illite and chlorite are mostly detrital clay minerals resulting from physical weathering on land and glacial scour, particularly of crystalline rocks (Chamley, 1989). These minerals may have been derived from the weathering in the Himalayan region as these conditions prevail there. Kaolinite, which is mostly formed in areas with higher chemical weathering may have come from the Indian shield (Nath et al., 2000 and references therein). Smectite in the central Indian basin sediments is mainly derived from the weathering of basinal basaltic rocks (Rao and Nath, 1988; Bouquillon et al., 1989).

4.6. Bulk sediment chemistry

Marked increases in lithogenic elements Al, Ti, Fe, K, Cr and Li at two sub-surface depths (Fig. 8) coincide with increase in micaceous minerals in coarse fraction suggesting an increased supply of terrigenous sediments during these time periods corresponding to ~0.5 and >0.65 Ma. They also occur as abrupt high (bulges) suggesting the episodic nature of the terrestrial flux, probably as turbiditic flows.

K_2O/Al_2O_3 ratio, which is an index of alteration, ranges between 0.14 and 0.27 in this core. Both the layers with micaceous sediments show a ratio around 0.2. The ratios and age match with those found in the distal Bengal Fan sediments (ODP 116) younger than 1 Ma and fall within the range of HHC series (Derry and France-Lanord, 1996). Though both illite and kaolinite are aluminosilicates, K is present in illite and not in kaolinite. Therefore, K/Al ratios should reflect the variation of these two minerals (Yarincik et al., 2000). Higher K_2O/Al_2O_3 ratios indicate the dominance of illite and also imply a physical erosion of high-grade metamorphic rocks such as HHC. The ratios also reflect the mixing of a 'primary' end member composed of illite derived from micas ($K_2O/Al_2O_3 = 0.33$–0.45) and a secondary end member chlorite ($K_2O/Al_2O_3 = 0$) (France-Lanord et al., 1998). Mineral analyses of muscovite extracted from these sediments have shown a K_2O/Al_2O_3 ratio between 0.3 and 0.5 and agree well with the interpretation made above.

Further, a plot of K/Ti and Ca/Ti (Fig. 9) has shown that the sediment layers with pelagic signatures plot on the linear regression line, but all other sections fall in an array joining the composition of IC sediments of the Bengal Fan and HHC. $\delta\,^{18}O$ studies on IC clays from the Bengal Fan (Derry and France-Lanord, 1996) have shown that they are mostly derived from high-temperature micas by simple mechanical grinding. The micas and other detrital minerals found in this core also show morphological features suggestive of mechanical breakdown without chemical etching features (SEM photos, Fig. 6).

Sr contents in the core range between 61 and 134 ppm and higher values are confined to the pelagic sections, with decreased concentrations in the layers containing mica (61, 68, 75, 88 and 96 ppm) and comparable to those found in the sediments younger than 1 Ma (78–90 ppm; Derry and France-Lanord, 1996) in ODP cores indicating similar sources and weathering histories.

Lithium, like other detrital elements, shows increase at two sub-surface depths containing detrital mica (Fig. 8). Lithium mimics clay content rich in illitic clays as well as biotite (Sirocko et al., 2000), and the enrichment of Li in mica-rich layers is therefore consistent. Barium shows a distinctly different pattern compared to other elements. Ba in pelagic sediments is linked to productivity of upper oceans (e.g., Dymond et al., 1992). Ba enrichment in the surface layers (2000 ppm; Fig. 8) indicates a biological link and is similar to those found in pelagic sediments south of this location (Nath et al., 1989) and supported by the presence of abundant radiolarian fossils in the same layers (Fig. 2). The Ba contents drastically reduce at about 35 cm, coinciding with the sediments dominated by terrigenous matter, to less than shale values (PAAS 650 ppm; Taylor and McLennan,

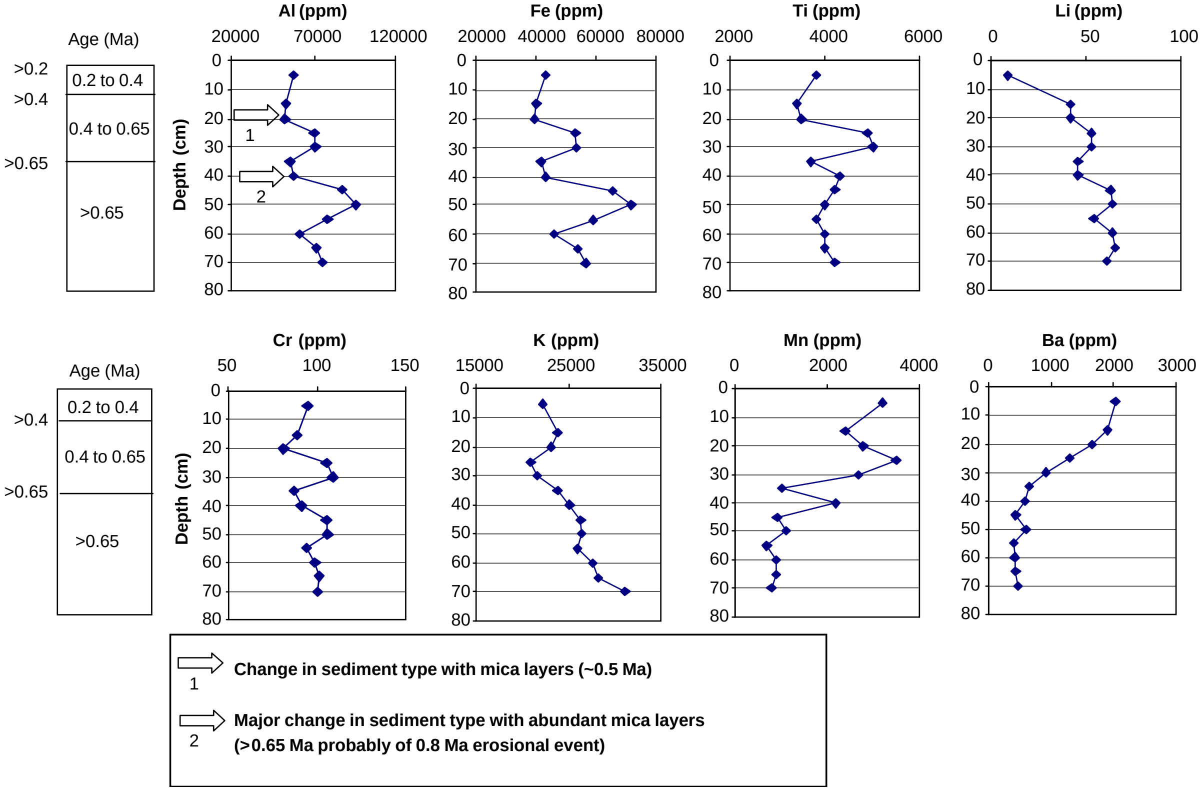

Fig. 8. Downcore variation of lithogenic elements, Mn and Ba. All except Ba show two distinct changes coinciding with increase in terrigenous mineral content.

1985) suggesting a lack of biogenic Ba in these deeper sections.

As rare-earth elements are excellent indicators of provenance and depositional environment (e.g., Taylor and McLennan, 1985; Nath, et al., 1992, 2000), all the sections have been analysed for these elements. Shale-normalized REE patterns of mica-rich layers differ drastically from the mica-poor layers by the presence of steep heavy REE patterns. The patterns are different from nearshore and continental shelf sediments derived from peninsular Indian rocks (Nath et al., 1997, 2000). Shale-normalized La/Yb ratios, which are indicators of REE fractionation from their usual subtle behaviour show an excellent variation down the core, <1 in surface pelagic layers; close to 1 in the first micaceous layers and very high (>1.3) in the second micaceous layer (Fig. 9), responding to the changes in the depositional environment. Increased La/Yb ratios in the deeper layers are typical of continental material entering the sea. HREE depletion indicated by high La/Yb ratios found in the deeper sediments are typical of felsic sources (Taylor and McLennan, 1985; Nath et al., 1997, 2000).

4.7. *Organic carbon, total nitrogen and OC/N ratios*

The organic carbon (%OC) values are in general low (0.17–0.38%). Low %OC values noticed here are typical for deep-sea sediments from the equatorial Indian Ocean (e.g., see Nath and Mudholkar, 1989), where the sedimentation rates are very low (Mueller and Mangini, 1980; see Nath et al., 1992 for sedimentation rate in the area). In general, the trends in total nitrogen (%TN) parallelled those of %OC, with changes in

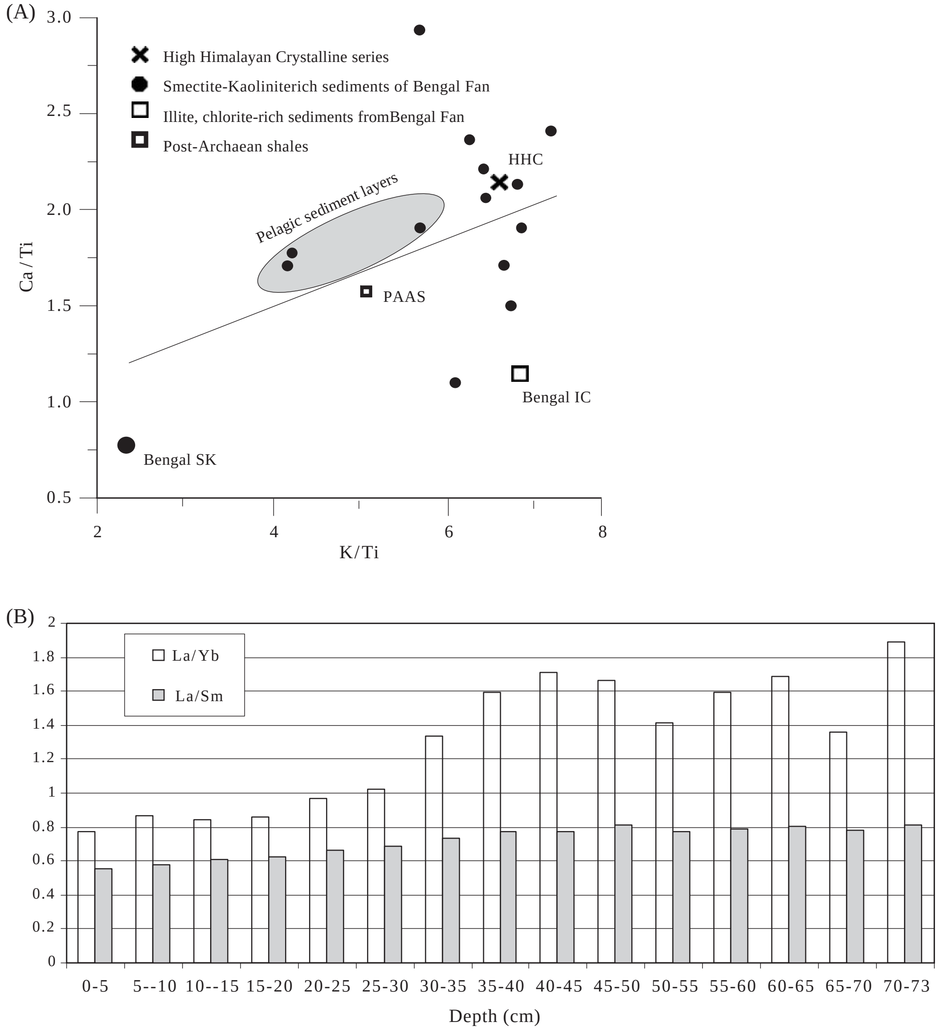

Fig. 9. (A) Plot of Ca/Ti versus K/Ti (bulk analyses of sediments) shows that the sediment sections containing mica fall in an array close to the composition of HHC series and illite + chlorite-rich clays of the Bengal Fan and away from smectite + kaolinite-rich clays. The sediment layers with pelagic signatures plot on the linear regression line, but fall away in a different array. Composition of HHC, Bengal IC and SK sediments is from France-Lanord and Derry (1997). (B) Variation in REE fractionation indices with depth. Changes at 20–25 cm and 35–40 cm are drastic. The top four sections have lower La/Yb ratios than the typical ratios for continentally derived material.

concentration at a depth of 15 cm and a major change at 40–45 cm depth. The differences, if any, between these two elements are reflected by atomic organic C/N values (Fig. 4), which increase conspicuously from ca. 5 to ca. 10 and more in the sediments deeper than 40 cm. The C/N ratio is considered to be indicative of the source of OC. While the molar ratios of OC to TN of the shallower sediments (3.8–6.5) are close to the ratios prevalent in fresh marine plankton (6–8), the deeper sediments with micaceous minerals have high ratios (9–15) and fall between values typical of fresh plankton and terrestrial higher plants (20 +) (Mueller et al., 1994; Parsons, 1975). Nitrogen-poor terrestrial organic matter has higher C/N ratios. (Meyers, 1994, 1997; Rulkötter, 2000). Higher C/N ratios in the deeper sections with dominant coarse silt and sand (see Section

4.1) reflect the dependence on sediment size, as coarser sediments are enriched in vascular plant remains with higher C/N ratios (Keil et al., 1998). Lower ratios in the shallower horizons could be interpreted as a greater marine OM contribution. However, the former may be true as the sediments with lower ratios in this core are abundant in planktonic remains of radiolarians indicating a pelagic nature and the deeper sediments are almost completely devoid of planktonic skeletons and therefore could of terrestrial origin (Fig. 2). This also coincides with the data on the Bengal Fan sediments from the ODP 116 sites (France-Lanord and Derry, 1994). A rapid decrease of total OC% supplied and a change in the type of terrestrial carbon occurred at the beginning of 0.9 Ma, with a decrease in $\delta\ ^{13}C$ for post-0.9 Ma sediments in the Bengal Fan suggesting lower abundance of C4 plants in the Ganga–Brahmaputra basin during that time (France-Lanord and Derry, 1994). A plot between OC and TN (Fig. 4) shows that the ratios in deeper horizons distinctly trend away from the shallower horizons indicating two sources. In addition, the OC contents of ~0.3–0.38% in the deeper micaceous turbiditic section are very close to (slightly lower) the mean OC concentration of illite–chlorite sediments (0.44) and much lower than those in smectite–kaolinite-rich sediments of the Bengal Fan (1.39; OC values of Bengal Fan are from France-Lanord and Derry, 1997) indicating an IC source of the Bengal Fan derived during the Himalayan uplift.

5. Conclusion

(1) In summary, the two layers comprising of conspicuously high mica contents are derived from the high Himalayan crystallines (HHC). Other geological characteristics have shown either these sediments are closer to HHC or the illite + chlorite clays of the Bengal Fan region, and contribution from the Lesser Himalaya (LH), Tibetan Sedimentary Series (TSS), southern Tibet and Deccan Plateau of India and rock formations in Sri Lanka seem to be less dominant. The nature of mineral suite present and the chemical composition of the core could not have been derived from LH, since LH contain quartzite, pelitic rocks, dolomitic carbonates and black shales. Our observations are in agreement with the source identification made during drilling in the middle and distal fan regions (DSDP Site 218 and ODP Sites 717–719) and also with the finding from the drilling legs that the sediments younger than 0.9 Ma are derived either from HHC or IC clays from the Bengal Fan region.

(2) The correlated shifts in sediment grain size, magnetic susceptibility, detrital minerals in sand and clay-sized fractions and bulk chemical composition in this core at >0.65 and about 0.5 Ma indicate two erosional events in the Himalaya during middle to late Pleistocene. The older one (>0.65 Ma) may most probably represent the well-known 0.8 Ma event of the Himalaya. There is a consensus on the occurrence of erosional event at this time period (Amano and Taira, 1992; Meyers and Dickens, 1992; see Valdiya, 1999 for an excellent review). The causes and consequences of this event are well characterized (Cochran et al., 1990; Amano and Taira, 1992; Derry and France-Lanord, 1996, 1997). The marked change in sediment supply beginning near 0.8 (or 0.9) Ma correlates with a significant cooling of the global climate and ice volume expansion, shifting from a world of 41 ka periodicity to the strong 100 ka cyclicity in $\delta\ ^{18}O$ record (Raymo et al., 1997 and references therein). Glaciers spread far and wide over Potwar, Kashmir, Kangra, Ladakh and Tibet areas, besides the whole of Himadri terrane (Great Himalaya), during the tectonic events that occurred in the Himalaya during 1.6–0.8 Ma BP (Sorkhabi et al., 1998; Valdiya, 2002). Increased mid-Pleistocene glaciation in the Himalayan region might have contributed to the change in weathering environment and increased sediment fluxes (Derry and France-Lanord, 1996).

(3) An additional erosional event of high energy (but lower intensity than 0.8 Ma) seems to have occurred at 0.5 Ma. To our knowledge, the 0.5 Ma event is not reported in the literature. However, data on mineral component of

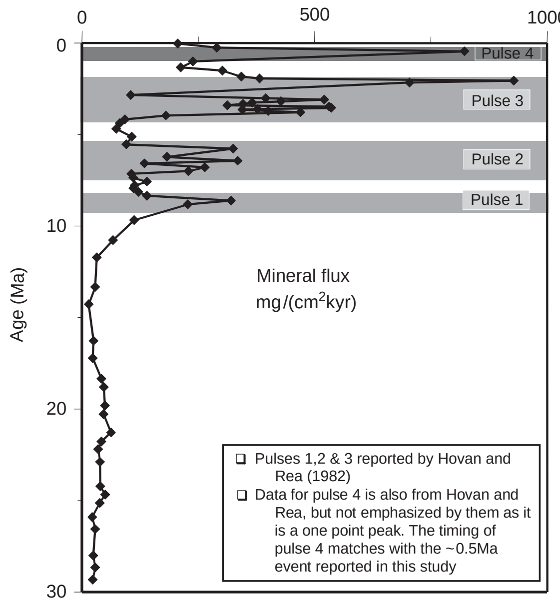

Fig. 10. Mineral flux profile of a drill core from the Bengal Fan region (Site 758) from Hovan and Rea (1992). Their data show a pulse of mineral flux at about 0.45 Ma, second only to the largest mineral flux peak of 2 Ma. However, Hovan and Rea (1992) only emphasize the three major pulses of increased terrigenous sediment flux at ~9.5–8.5, 7–5.6 and 3.9–2 Ma.

pelagic sediments from the ODP site 758 in the northern Indian Ocean (Hovan and Rea, 1992) show a major pulse of mineral flux of 822 mg cm^{-2} ka^{-1} corresponding to an age of ~0.45 Ma, second only to the largest mineral flux peak (928 mg cm^{-2} ka^{-1}) of 2 Ma (Fig. 10). However, Hovan and Rea (1992) stress on three other major pulses of increased terrigenous sediment flux at ~9.5 Ma (lasting for a million years); 7–5.6 and 3.9–2 Ma from the Himalayan rivers. The 0.45 Ma peak occurs at a depth of ~6 m in the ODP core, which is located ~900 miles north of our sediment core, which means closer to the Ganges–Brahmaputra river system than ours and, thus, excellently corroborating our interpretation.

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