19. Parkinson, C. D. and Katayama, I., *Geology*, 1999, **27**, 979–982.
20. Hemley, R. J., in *High Pressure Research in Mineral Physics* (eds Manghnani, M. H. and Syono, Y.), American. Geophysical Union, Washington, DC, 1987, pp. 347–359.
21. Parkinson, C. D., *Lithos*, 2000, **52**, 215–233.
22. O'Brien, P. J., Nikolai, Z., Law, R. D., Khan, M. A. and Jan, Q. M., Terra Nostra, 14th HKT Workshop, (Abstract volume), 1999, pp. 109–110.
23. Chamenda, A. I., Maltauer, M., Malavieille and Bokun, A. N., *Earth Planet. Sci. Lett.*, 1995, **132**, 225–232.
24. Chatelain, J. C., Roecker, S. W., Hatzfield, D. V. and Molnar, P., *J. Geophys. Res.*, 1980, **85**, 1365–1387.
25. Roecker, S. W., *J. Geophys. Res.*, 1982, **87**, 945–959.
26. De, Sigoyer, J. *et al.*, *Geology*, 2000, **28**, 487–490.

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Heavy sediment influx during early Holocene: Inference from clay mineral studies in a core from the Western Bay of Bengal

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Clay mineral studies were carried out in a 650 cm long sediment core collected at a depth of 2200 m from the north-western Bay of Bengal. Illite is the predominant mineral, followed by montmorillonite and chlorite. Illite concentration varies from 49 to 65% from the core top to 380 cm and further down, increases to 85%. Montmorillonite content ranges from 22 to 36% above 380 cm, with a maximum in the upper 20 cm. Lowest values of montmorillonite (3–8%) are observed below 380 cm. Chlorite values range from 12.8 to 29%. Kaolinite is present in traces.

The changes in mineral composition at 380 cm in the core are interpreted to be a transitional period of Pleistocene–Holocene. This is substantiated by the lithological, foraminiferal and geochemical studies of the core. Very high content of illite below 380 cm of the core reflects glacial weathering products of crystalline metamorphic/sedimentary rocks of Himalayas carried by Ganges–Brahmaputra rivers during the late Pleistocene, when the sea level was low. Increase of montmorillonite and kaolinite during the Holocene indicates that the Ganges–Brahmaputra province sediments were diluted with sediments from the peninsular rivers draining metamorphic gneisses, schists, Deccan Traps and Quaternary sediments. This distribution can be explained by circulation pattern and tectonics in the Ganges delta during early Holocene.

The top 380-cm thick sediment deposition during Holocene is attributed to heavy sediment influx during Mid Termination (MT) (12,500–10,000 years BP), due to increased precipitation and run-off resulting from high intensity monsoonal regime.

CLAY minerals are a powerful source for the interpretation of marine depositional processes and their study also reflects weathering conditions imparted on the rock particles that were found in the source terrain[1,2]. For example, well-crystallized smectite and kaolinite were used to elucidate depositional origin on the eastern Nile cone[3]. Chlorite and kaolinite also have been used as valuable indicators of continental sources and differential depositional sites in the eastern Atlantic sediments off North America[4]. The Bay of Bengal covers about 2.2 million sq km and is one of the highest terrigenous input sites of the world ocean. The fan is reported to be about 2800–3000 km long, 830–1430 km wide and 16 km thick, beneath the northern Bay of Bengal. Though the shelf sediments on the east coast of India were studied in detail for clay minerals, very few studies[5–9] were carried out in the deeper Bay of Bengal especially in the Bengal Fan. Chauhan *et al.*[6] reported clay minerals in a core from the eastern Bay of Bengal and suggested peninsular river source to the Holocene sediments. Chaudhri[7] has encountered only Holocene sediments derived from the Himalayas, in cores of 303 cm length from the middle Bengal fan region. Chowdary *et al.*[8] ruled out the peninsular river source to the middle fan during mid-Holocene. In contrast, Shastri *et al.*[9] concluded that the transportation of sediments is from shelf to slope to deeper western Bengal Fan. In view of the above, we plan to address to the provenance of the sediments in a sediment core from the western Bengal Fan. In this paper, we report clay mineralogy and provide an explanation for the heavy sediment deposition during the Holocene.

A sediment core of 650 cm length was collected during the 42nd cruise of *ORV Sagar Kanya* at a water depth of 2200 m (lat. 16°00'N and long. 87°05'E) (Figure 1). Subsampling of the core was done on-board, mainly at 10 cm interval and also wherever a change in colour was observed. For clay mineral analysis in all 14 subsamples were selected. Less than 2 μm fractions of the sediment were separated[10] and rendered free of $CaCO_3$ and organic matter, by treating with acetic acid and hydrogen peroxide, respectively. Oriented clay slides were prepared and scanned from 3 to 30° 2Θ at 2° 2Θ min^{-1} with a Philips X-ray diffractometer, using nickel filtered CuKα radiation. These samples were again rescanned after treatment with ethylene glycol for 1 h at 100°C for confirmation of montmorillonite[11]. The

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principal peak areas of the clay mineral kaolinite + chlorite, illite and montmorillonite were multiplied by the weighting factors 2, 4 and 1, respectively. Semi-quantitative evaluation of clay minerals was done following Biscaye[12]. The samples were also scanned from 24 to 26° 2θ at 1/2° 2θ min^{-1}, for the resolution of kaolinite and chlorite[13].

Percentage of clay minerals, and montmorillonite (M) to illite (I) and kaolinite (K) to chlorite (C) ratios are shown in Table 1. Illite is the predominant mineral followed by montmorillonite and chlorite (Figure 2). On the basis of clay mineral distribution and M/I ratio the core is divided into two units, each with distinct clay mineral assemblages and source. The demarcation of the boundary at 380 cm also gets support from the grain size, organic carbon, calcium carbonate and foraminiferal studies[14] (Figure 3). Unit II sediments represent the region from 650 to 380 cm and unit I sediments from 380 cm to the core top. The sediments of unit II are blackish-grey silts and are relatively coarser. The sediments of unit I are dark yellowish-brown at the surface and light-to-dark olive-grey downwards, up to 380 cm. They are dominated by clay/clayey silt. The $CaCO_3$ content is low (4 to 6%) in unit II and high (12 to 19%) in unit I. The total organic carbon content varies from 0.04 to 1.4%, with a decreasing tendency from unit II to

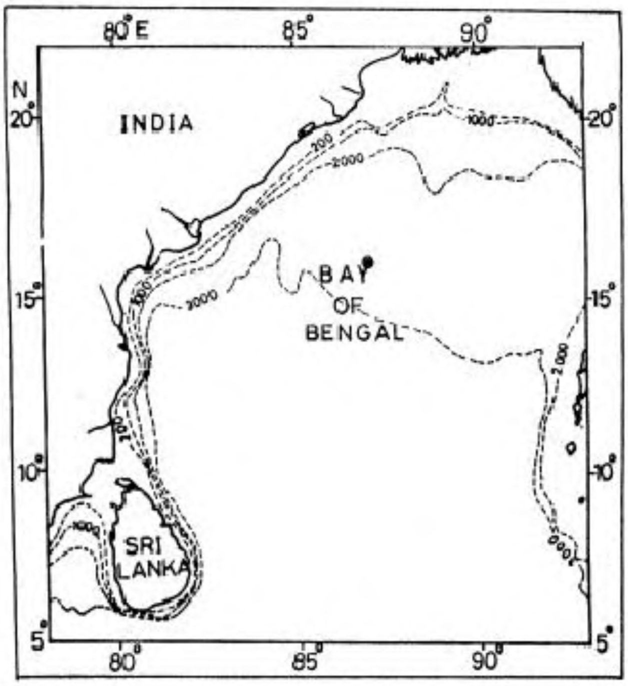

Figure 1. Location map showing position of the core.

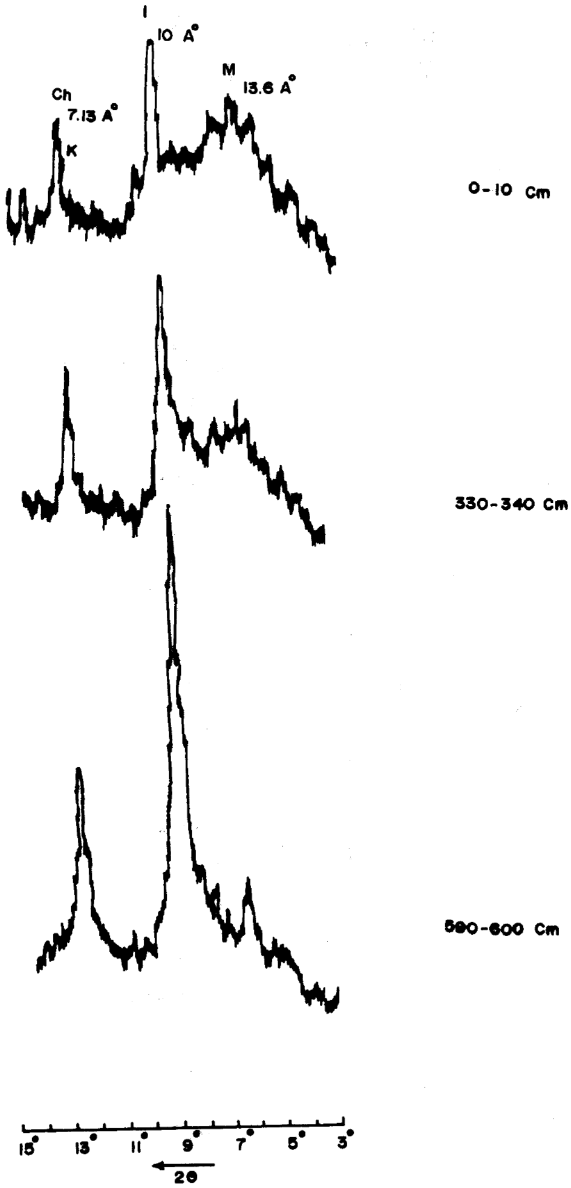

Figure 2. X-ray diffractograms of selected subsamples.

Table 1. Percentage of clay minerals and M/I, K/C ratios

Core depth (mm)	Clay mineral (%) K + C	I	M	M/I	K/C
0–10	14.0	49.2	36.8	0.74	0.89
10–20	13.4	50.0	36.6	0.73	
30–40	17.9	57.9	22.2	0.37	
50–60	12.9	60.6	26.5	0.43	
149–160	14.7	65.3	20.0	0.30	
170–182	15.3	67.0	17.7	0.26	0.47
227–280	14.7	54.0	51.3	0.58	
330–340	14.2	58.3	27.5	0.47	
375–380	29.0	53.0	18.0	0.33	0.33
390–400	28.3	57.3	14.4	0.25	
450–455	13.7	84.5	1.8	0.02	
460–462	13.8	82.2	4.0	0.04	
590–600	15.5	82.5	2.0	0.02	0.13
612–617	12.8	85.2	2.0	0.02	

K + C, Kaolinite + Chlorite; I, Illite; M, Montmorillonite.

unit I. The demarcation at 380 cm between unit II and unit I represents the Pleistocene–Holocene boundary[14].

Illite content in unit II increases to a maximum of 85%, while montmorillonite values are as low as 3 to 8%. Chlorite content varies from 12.8 to 29.0%, with traces of kaolinite. The M/I ratio is < 0.04 and reveals the total predominance of illite during late Pleistocene. The K/C ratio is as low as 0.13.

In unit I, illite content varies from 49 to 65% and montmorillonite content varies from 22 to 36%, with a maximum in the upper 20 cm. Chlorite ranges between 13 and 17%. The M/I ratio increases from 0.30 to 0.75 up core from the boundary, indicating steady increase in montmorillonite since the beginning of the Holocene. The K/C ratio increased from 0.33 to 0.89 since the Holocene.

The sediments of unit II comprise high illite, low montmorillonite and low M/I and K/C ratios. This reflects the glacial weathering products of crystalline metamorphic/sedimentary rocks of the Himalayas carried by Ganges–Brahmaputra rivers. It appears that the large quantity of sediments must have been transported and deposited by turbidity currents during late Pleistocene, when the sea-level was 120 cm lower[15] than present.

The sediments of unit I consist of relatively low illite, high montmorillonite, high M/I and K/C ratios. These are most probably derived from the peninsular rivers like Mahanadi, Godavari and Krishna. Mahanadi drains metamorphic rocks (gneisses and schists with local acid and basic igneous bodies) and Quaternary sediments[16] under humid tropical conditions. This results in enhanced chemical weathering products such as kaolinite and montmorillonite. The Godavari and Krishna drain through Deccan Traps covered by black cotton soils in the upper reaches and Precambrian formations in the lower reaches. Therefore, montmorillonite followed by kaolinite are the dominant weathering products. The increase in the K/C ratio in the Holocene sediments also supports this inference. The cumulative effect of the peninsular river sediment contribution is therefore visible in the clay mineral assemblage of the core in unit I. The change in clay mineral assemblage from unit II to unit I indicates that the sediments derived from the peninsular rivers are transported abundantly to the site than that of Ganges-derived sediments during the Holocene. The high sedimentation rate at the core site during Holocene may be related to the SW monsoon, when river sediment discharge from Ganges–Brahmaputra and peninsular rivers was at its peak. The possible reasons for these changes are circulation pattern, and tectonics in the Ganges delta during Holocene.

Though the circulation patterns[17] clearly indicate that transport mechanism of montmorillonite to the core site is possible, the exact path of these river sediments to the deep sea is yet to be established. Earlier studies on clay mineralogy of the shelf sediments of the east coast of India[18,19] indicated that the sediments derived from the Krishna–Godavari province are transported northwards, under the influence of NE-flowing currents associated with SW monsoon winds. But the present study indicates that the entire sediment input is not shifted towards the extreme north, but some material is invariably transported across the shelf to get deposited in the deep-sea fan. The NE-flowing currents during the SW monsoon also direct the Ganges-derived sediments towards the east. As the present core is located towards the west, less sediment might have got deposited at the site. Reduction of sediment supply from the Ganges–Brahmaputra rivers can also be explained by tectonic activity in the Ganges delta[20]. Due to the subsidence of the delta during early Holocene[20], large sediment flux was deposited in the deltaic region and therefore, relatively low sediment flux was transported to the Bengal Fan. This is evident by accumulation of a thick (to 40 m) highstand sediment sequence in the lower flood plains[20].

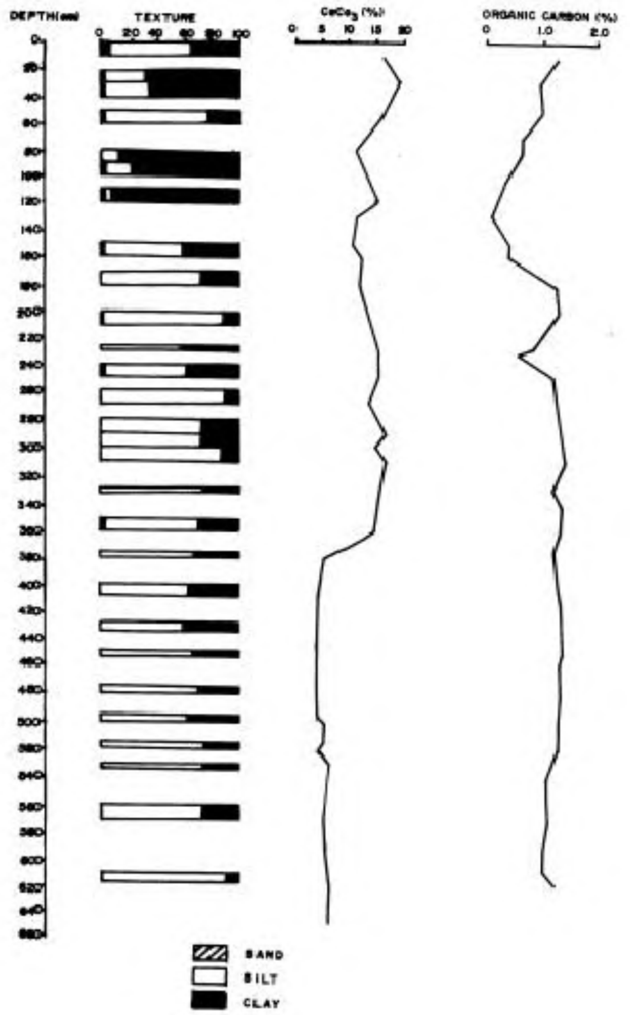

Figure 3. Lithological, textural and geochemical log of the core.

On the basis of oxygen isotope stratigraphy[21], the LGM level (18,000 BP) was reported at 80 cm core depth. According to Cullen[5], the LGM level varied between 60 and 100 cm in the cores of the central Bay of Bengal. The sedimentation rate of 2–4 cm/ky was reported for the Bay of Bengal by various authors[22,23]. Suresh and Bagati[24] reported low concentration of calcium carbonate in the upper part of the cores in the middle Bengal Fan and suggested high influx of clastic material derived from the Godavari, during the post-glacial period. The present study indicates a deposition of 380 cm since the beginning of Holocene to the present. This high sediment influx might have resulted due to the high-intensity monsoonal regime during MT 12,500–10,000 yrs BP. According to Cullen[5], the increased precipitation and run-off is due to the increased eastward advection of equatorial surface waters by the SW monsoon current. Goodbred and Kuehl[25] explained that after ca. 11,000 years BP, there was a drop in fan sedimentation[28] as a result of rising sea level and tectonic trapping of the Ganges–Brahmaputra sediment on the flooded Bengal Basin. The high discharge in the early Holocene suggests its relation to a stronger SW monsoon in South Asia. Similar patterns of high monsoon-related sediment discharge have been noted throughout the tropics and subtropics, suggesting a widespread fluviosedimentary response[25].

Unit II sediments correspond to Pleistocene and illite is the predominant mineral. The glacial weathering products of the Himalayas carried by the Ganges–Brahmaputra are a major source for these sediments. The increase in montmorillonite proportion during Holocene (unit I) supports the fact that the Ganges-derived sediments are diluted by supply from the peninsular rivers as a result of circulation pattern and tectonics in the Ganges delta during the early Holocene. Heavy sediment influx during the early Holocene may be due to high-intensity monsoonal regime during MT.

1. Maldenado, A. and Stanley, D. J., *Sedimentology*, 1981, **28**, 21.
2. Stanley, D. J. and Liyange, A. N., *Mar. Geol.*, 1986, **73**, 263.
3. Venkataratnam, K. and Ryan, W. B. F., *Mar. Geol.*, 1971, **11**, 268–282.
4. Lange, H., *Sedimentology*, 1982, **29**, 427–443.
5. Cullen, J. L., *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 1981, **35**, 315–316.
6. Chauhan,O. S., Mascarenhas, A., Paropkari, A. L. and Rao. Ch. M., *Late Quaternary Sedimentation in the Eastern Bengal Fan* (ed. Desai, B. N.), Oxford Publishing Co. Ltd, 1991, pp. 479–485.
7. Chaudhri, R. S., *Geol. Surv. India Spec. Publ.*, 1992, **29**, 181–187.
8. Chowdary, G. V. V. S., Raman Rao, S. V. and Swamy, A. S. R., *ibid*, 197–200.
9. Shastri, A. V. R., Suresh, K. V., Ramesh, M. V. and Kamalakar, S., *ibid*, 189–195.
10. Folk, R. L., *Petrology of Sedimentary Rocks*, Hemphill, Texas, 1968, p. 170.
11. Carrol, D., *Geol. Soc. Am.*, *Spec. Pap.*, 1970, **125**, 85.
12. Biscaye, P. E., *Geol. Soc. Am. Bull.*, 1965, **76**, 803–832.
13. Biscaye, P. E., *Am. Mineral.*,1964, **49**, 1281–1289.
14. Reddy, N. P. C., Mohana Rao, K., Pavanputra, A. V. S. and Rao, Ch. M., *Global Climate Due to Natural and Human Activities* (eds Das, S. N. and Thakur, R. S.), Allied Publishers, New Delhi, 1997, pp. 180–200.
15. Fairbridge, R. W., *Sci. Am.*, 1962, **202**, 70–79.
16. Krishnan, M. S., *Geology of India and Burma*, HigginBothams (P) Ltd, Chennai, 1968, p. 536.
17. La Fond, E. C. and La Fond, K. G., *Bull. Natl. Inst. Sci., India*, 1968, **38**, 164–183.
18. Reddy, N. P. C. and Mohana Rao, K., *Indian J. Mar. Sci.*, 1989, **18**, 128–130.
19. Purnachandra Rao, V., *Indian J. Mar. Sci.*, 1991, **20**, 7–12.
20. Goodbred, S. L., Jr. and Kuehl, S. A., *Sediment. Geol.*, 2000, **133**, 227–248.
21. Prell, W. C., Hutson, W. H., Williams, D. F., Be, A. W. H., Geitsenauer, K. and Molfineo, B., *Quat. Res.*, 1980, **14**, 309–336.
22. Ramaswamy, V. and Parthiban, G., *Geol. Surv. India Spec. Publ.*, 1992, **29**, 25–32.
23. Sarin, M. M., Borole, D. V. and Krishnaswami, S., *Proc. Indian Acad. Sci. Part A*, **88**, 131–154.
24. Suresh, N. and Bagati, T. N., *Curr. Sci.*, 1998, **74**, 977–987.
25. Goodbred, S. L. Jr. and Kuehl, S. A., *Geology*, 2000, **28**, 1083–1086.
26. Weber, M. E., Wiedicke, M. H., Kudrass, H. R., Hubscher, C. and Erlenkeuser, H., *Geology*, 1997, **25**, 315–318.

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