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4. CLAY MINERALOGY OF SEDIMENTS FROM THE BENGAL FAN[1]

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ABSTRACT

We have measured the relative abundances of smectite, illite, chlorite, and kaolinite in a composite section of the distal Bengal Fan. Two sources of sediment appear to dominate, a smectite-poor, illite-rich source associated with rapid denudation of the Himalayas and a smectite-rich, illite-poor source probably on the continental margin of the Indian sub-continent. Changes in source appear to be related to uplift in the Himalayas and Tibetan Plateau both directly and through the climatic and oceanographic consequences of uplift.

INTRODUCTION

The abundance of the clay size fraction (<2-μm effective settling diameter) of the phyllosilicate minerals in marine sediments contains information on the composition and climate of the terrains from which these minerals were derived. In general, smectite can be interpreted as the product of the weathering of basic igneous rocks. Illite is the product of the weathering of siliceous igneous and high-grade metamorphic rocks, especially the micas in these rocks. Chlorite is relatively unstable to weathering and generally its presence indicates rapid erosion due to uplift or glaciation, particularly of low-grade metamorphic rocks. Kaolinite is a highly leached, cation-deficient mineral indicative of deep weathering either in tropical regions or in locales where erosion rates are low and deep weathering is common. Of course, the re-erosion of sedimentary rocks also contributes to the clay mineral abundances of marine sediments. In this paper we report the results of our measurements of clay mineral abundances and our interpretation of these data, and compare them to the lithostratigraphic interpretations of the shipboard scientific party.

METHODS

Sample Processing

Samples were collected aboard *JOIDES Resolution*, returned to the laboratory, and subjected to a standard treatment (Jackson, 1975; Mehra and Jackson, 1960). Approximately 5 g of sample were added to 50 mL of 1 M Sodium Acetate-Acetic Acid buffer (pH 5) and disaggregated mechanically and ultrasonically. The resulting suspension was digested on a hot plate set at approximately 80°C for 30 min to remove carbonate. Samples occasionally required more buffer to remove carbonate. After this digestion, 5 mL of 30% H_2O_2 were added to remove organic matter. The suspension was digested for an additional 2 to 4 hr on the hot plate and then evaporated to a thin paste. Twenty mL of 0.3 M Sodium Citrate and 5 mL of 1 M Sodium Bicarbonate solution were added. The temperature was brought to 80°C in a water bath and 1 g of $Na_2S_2O_4$ was added. The mixture was stirred constantly for 1 min and occasionally for another 15 min. This treatment dissolved amorphous silica, reduced iron oxides and hydroxides and chelated the dissolved iron. The supernate was decanted. If the sediment remained in suspension, 2 mL of 1 M $MgCl_2$ were added to flocculate the clays. The samples were then ready for size separation.

The treated samples were then suspended in 25 mL of 1 M Calgon (sodium hexametaphosphate) solution and separated by sieving and gravity settling. The 2.0- to 0.2-μm fraction (equivalent settling diameter) was removed by centrifugation. This fraction was dried and preserved for X-ray diffractometry.

Samples were prepared for X-ray diffractometry in 10 mL of 1 M $MgCl_2$. The samples were ultrasonically resuspended and heated overnight on the water bath to saturate the exchangeable sites in the clays with Mg^{2+} ion. The saturated samples were deposited on a 0.45-μm silver membrane filter in a vacuum filtration device (Poppe and Hathaway, 1979). Vacuum filtration was continued until an optically thick coating had been deposited on the entire exposed area of the silver filter. These oriented sample mounts were then dried in a desiccator overnight and stored in the desiccator until X-rayed. After the initial X-ray run the samples were vapor glycolated at 80°C for at least 90 min in a heated metal desiccator containing liquid ethylene glycol. Samples were re-glycolated if more than 5 hr had elasped since their initial treatment.

X-ray Diffractometry

Samples were X-rayed on a Philips-Norelco XRG 3000 X-ray diffractometer using Ni-filtered Cu radiation. A secondary monochromator was used in front of the scintillation detector to remove the copper K-beta peak. Goniometer scans were conducted from 26° to 24° (2θ) at a speed of one fourth degree per minute and from 15° to 3° at a speed of 1°/min. Data output was collected on a paper chart for reduction.

Background lines were drawn under the 17-Å (glycolated smectite), 10-Å (Illite) and 7-Å (Kaolinite + Chlorite) peaks, and areas were measured using a polar planimeter. Planimeter calibrations on standard areas indicate a precision of approximately ± 2%, but errors in estimating backgrounds and in determining the actual shape of the peaks probably lead to precisions of ± 10% of the abundance calculated or ± 5% in absolute abundance, whichever is larger (i.e., an abundance of 90% has an overall precision of ± 9%, an abundance of 30% has an overall precision of ± 5%). We applied the technique employed by Biscaye (1965) using weighted peak areas (1 × smectite, 2 × kaolinite+chlorite and 4 × illite) and calculated the abundances of the clay minerals as a percentage of the total diffracting species. Information on the abundance of non-diffracting, amorphous material in the clay size fraction (cf. Heath and Pisias, 1979) was not collected. The proportions of chlorite and kaolinite

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assignable to the 7-Å peak was calculated from the relative intensities of the kaolinite peak at 3.53 Å (24.87°) and the chlorite peak at 3.58 Å (25.15°). Abundance calculations of this kind have certain intrinsic difficulties (Heath and Pisias, 1979) but the patterns of clay mineral distribution are still accurately reflected and, as long as a consistent method is used, conclusions drawn from the data about sources and their changes are valid.

RESULTS AND DISCUSSION

Results

The results of our analyses are shown in Tables 1 and 2. The data presented are the abundances of smectite, illite, chlorite, and kaolinite in weight percent of the total abundance of these four clay minerals. Data are reported from

Table 1. Clay mineralogy, Holes 717A and 717C.

Core	Section	Interval (cm)	Depth (mbsf)	Smectite (wt%)	Illite (wt%)	Kaolinite (wt%)	Chlorite (wt%)
Hole 717A							
1H	01	60–62	0.7	50	39	6	5
1H	02	15–17	1.7	44	19	20	17
1H	02	115–117	2.7	52	28	10	10
1H	03	60–62	3.7	27	30	13	30
1H	04	15–17	4.7	6	58	18	18
1H	05	60–62	6.7	7	57	9	27
1H	06	115–117	8.7	0	56	13	31
1H	07	15–17	9.2	0	43	17	40
1H	CC	15–17	9.7	0	61	8	31
Hole 717C							
2H	02	15–17	15.2	0	58	32	10
2H	02	115–117	16.2	0	63	27	10
5X	01	13–15	36.6	0	63	25	12
8X	02	15–17	66.7	0	64	21	15
12X	CC	9–11	93.6	0	60	25	15
14X	02	54–56	105.0	0	61	27	12
20X	01	26–29	150.8	0	54	34	12
20X	03	27–30	153.8	0	61	27	12
22X	03	60–62	173.1	35	19	15	31
23X	03	60–62	182.6	59	0	15	26
24X	07	15–17	197.7	39	12	2	47
26X	06	16–18	215.2	25	38	12	25
27X	06	15–17	224.7	15	33	27	25
32X	01	60–62	265.1	4	52	33	11
42X	01	60–63	360.1	5	50	25	20
43X	01	58–60	369.6	31	0	5	64
46X	02	15–17	399.2	0	43	17	40
48X	02	15–17	418.2	30	16	3	51
49X	02	15–17	427.7	28	38	17	17
50X	02	15–17	437.2	42	23	13	22
51X	02	15–17	446.7	43	16	10	31
52X	02	15–17	456.2	22	42	16	20
53X	01	60–62	464.6	3	59	31	7
53X	02	15–18	465.7	31	36	18	15
54X	01	62–64	474.1	25	0	19	56
55X	02	15–17	484.7	26	39	18	17
56X	02	15–17	494.2	22	40	18	20
57X	01	60–62	502.6	42	24	13	21
58X	02	15–17	513.2	26	43	18	13
60X	02	60–62	532.6	75	0	3	22
62X	01	60–62	550.1	7	46	30	17
70X	02	15–17	627.2	6	54	20	20
71X	01	60–62	635.6	0	53	31	16
72X	02	15–17	646.2	0	54	25	21
73X	02	15–17	655.7	4	45	28	23
74X	01	60–62	664.1	0	59	27	14
76X	02	15–17	684.2	0	55	18	27
77X	02	15–17	693.7	19	42	22	17
78X	01	60–62	702.1	25	41	21	13
78X	02	15–17	703.2	37	29	12	22
79X	02	15–17	712.7	23	40	20	17
80X	02	15–17	722.2	3	58	26	13
81X	01	65–67	730.7	0	59	25	16
82X	01	60–62	740.1	3	52	27	18
83X	01	60–62	749.6	0	58	23	19
83X	CC	15–17	750.1	25	42	18	15
84X	01	60–62	759.1	7	56	29	8
84X	01	115–117	759.7	18	44	21	17
85X	01	59–61	768.6	12	49	27	12
85X	02	15–17	769.7	0	59	28	13
86X	01	14–16	777.6	12	43	45	0
88X	CC	15–17	797.7	0	58	31	11
89X	01	16–18	806.2	0	50	50	0
90X	01	60–62	809.8	7	46	40	7
91X	02	15–17	820.4	8	50	28	14

Table 2. Clay mineralogy, Hole 718C.

Core	Section	Interval (cm)	Depth (mbsf)	Smectite (wt%)	Illite (wt%)	Kaolinite (wt%)	Chlorite (wt%)
37X	01	50–52	351.8	0	50	29	21
38X	01	52–54	361.3	0	56	24	20
40X	01	34–36	380.1	40	28	10	22
41X	02	30–32	391.1	6	48	29	17
42X	01	48–50	399.3	8	50	26	16
43X	01	24–26	408.5	5	50	31	14
44X	01	60–62	418.4	16	44	25	15
45X	01	14–16	427.4	11	40	30	19
46X	01	27–29	437.1	17	42	25	16
47X	01	33–35	446.6	14	45	24	17
48X	01	7–9	455.9	10	48	26	16
49X	01	15–17	465.5	10	48	18	24
50X	01	31–33	475.1	12	40	32	16
51X	01	48–50	484.8	8	45	24	23
52X	01	23–25	494.0	7	52	23	18
53X	01	25–27	503.6	6	50	31	13
54X	01	40–43	513.2	24	37	9	30
55X	01	5–7	522.4	4	45	31	20
56X	01	31–33	532.1	2	46	35	17
57X	01	30–32	541.6	2	43	30	25
58X	01	10–12	550.9	0	44	31	25
59X	01	30–32	560.6	11	47	24	18
60X	01	23–25	570.0	7	44	32	17
61X	01	31–33	579.6	9	39	32	20
62X	01	30–32	589.1	5	50	25	20
63X	01	30–32	598.6	0	43	32	25
64X	01	30–32	608.1	13	47	21	19
65X	01	26–28	617.6	17	46	18	19
66X	01	31–33	627.1	0	61	22	17
67X	01	31–33	636.6	2	49	36	13
68X	01	13–15	645.9	4	49	28	19
69X	01	29–31	655.6	0	43	33	24
70X	01	27–29	665.1	0	41	38	21
71X	01	32–34	674.7	8	45	22	25
72X	01	29–31	684.1	13	42	21	24
73X	01	29–31	693.6	6	44	25	25
74X	01	29–31	703.1	4	45	27	24
77X	01	29–31	731.6	13	40	21	26
78X	01	33–35	741.1	23	30	2	45
79X	01	27–29	750.6	3	50	23	24
81X	01	31–33	769.6	4	48	28	19
82X	01	29–31	779.1	4	53	24	19
83X	01	29–31	788.6	0	53	31	16
84X	01	34–36	798.2	3	55	26	16
85X	01	29–31	807.6	3	52	25	20
86X	01	24–26	817.0	0	40	30	30
87X	01	29–31	826.6	33	14	0	53
88X	01	23–25	836.0	3	47	24	26
89X	01	27–29	845.6	16	36	14	34
90X	01	16–18	855.0	0	49	39	12
91X	01	22–24	864.5	0	55	24	21
93X	01	28–30	878.3	0	56	25	19
94X	01	24–26	887.8	42	19	1	38
95X	01	28–30	897.3	5	46	24	25
96X	01	22–24	906.7	0	54	27	19
97X	01	27–29	916.3	2	48	26	24

the entire section recovered from Holes 717A and 717C and from the part of Hole 718C below 350 meters below sea floor. The age of the sediment at 350 mbsf in Hole 718C is approximately the same as the age of the sediments at the bottom of Hole 717C, and the section from Hole 718C below 350 mbsf is, in effect, a continuation of Hole 717C. The combined data set represents a continuous section of the distal Bengal Fan back to approximately 17 m.y. BP. Figures 1 and 2 show the abundances of smectite, illite, chlorite, and kaolinite vs. depth for Holes 717C and 718C, respectively.

Discussion

Several workers have studied the Holocene sediments of the region. Gorbunova (1966) found high abundances of smectite and low kaolinite and illite in the surface sediments of the western Bay of Bengal. Kolla and Biscaye (1973) distinguished five sedimentary provinces in the eastern Indian Ocean. In particular they determined that the smectite-rich surface sediments of the western part of the region belonged to their Deccan Province, a smectite-rich region with illite <20% and chlorite and kaolinite both around 15%. They attributed the high smectite abundance to the weathering of the Deccan Traps and transport to the Bay of Bengal by the peninsular rivers, especially the Krishna and the Godavari. Kolla et al. (1976) found the same distribution pattern. Sites 717 and 718 are close to the boundary between the Deccan Province and the Ganges Province of Kolla and Biscaye in which Illite exceeds 25% and may be as high as 70%.

Bouquillon et al. (1989) studied a number of cores from the region and analyzed clays from DSDP Site 218. They divide

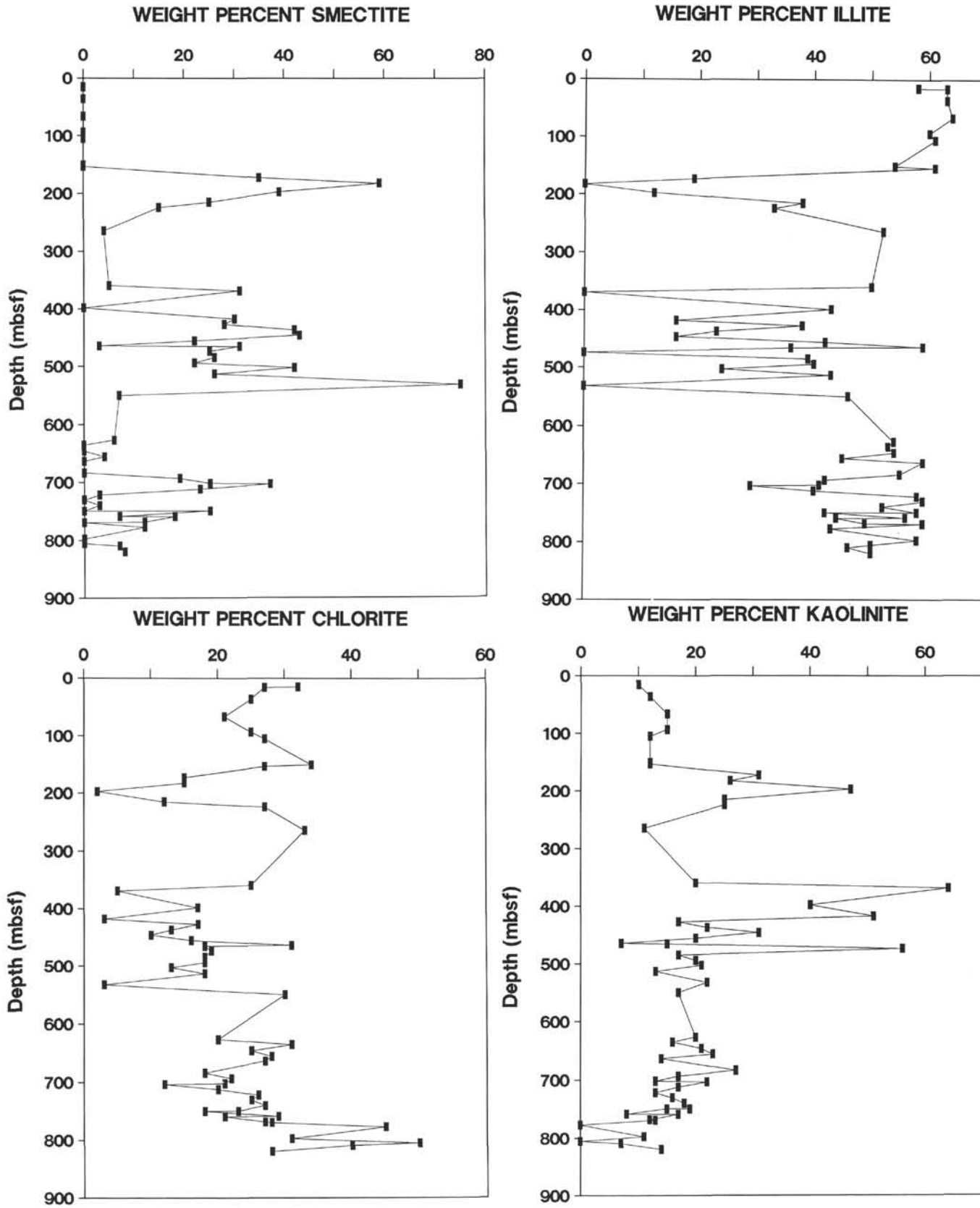

Figure 1. Graphs of clay mineralogy, Hole 717C.

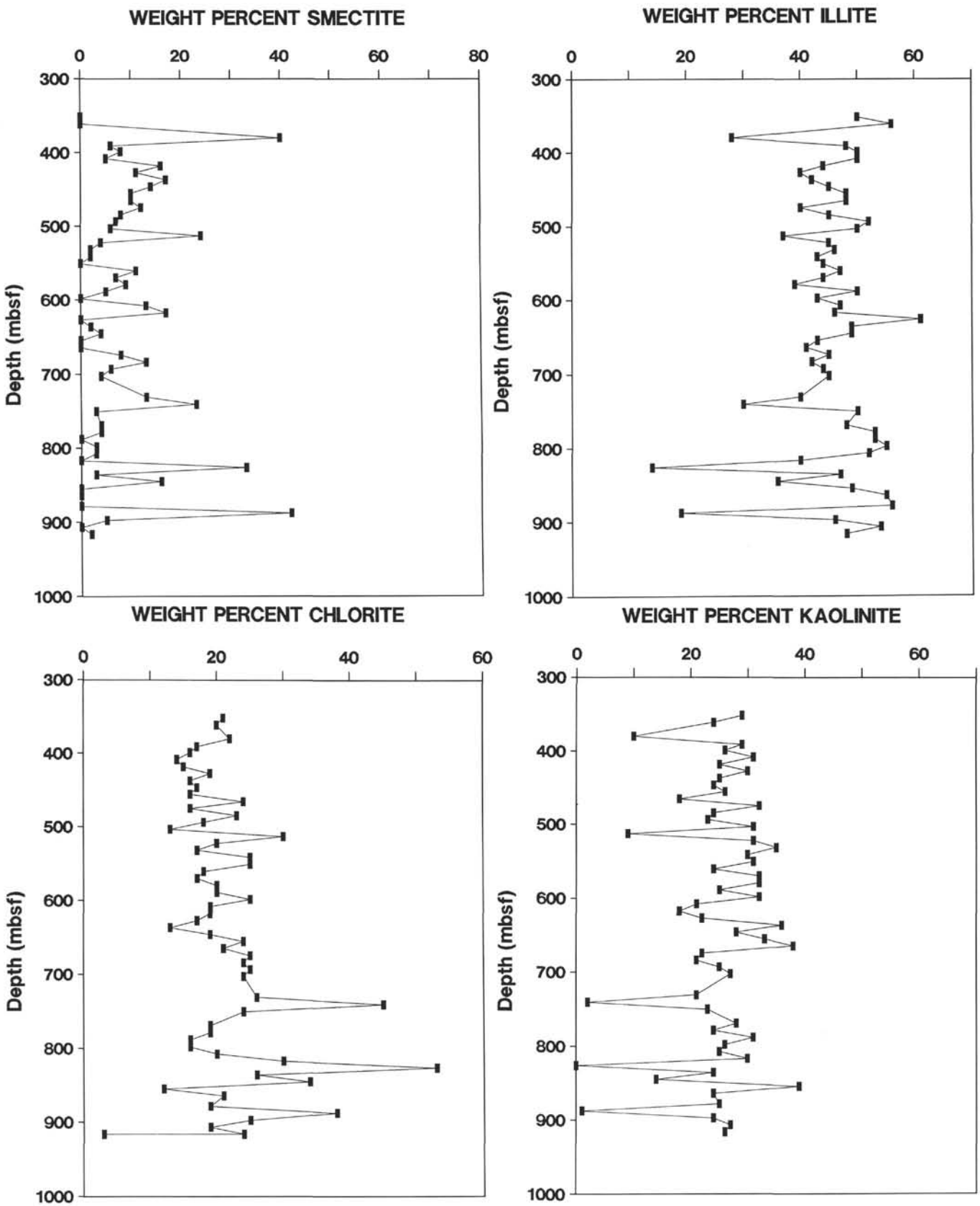

Figure 2. Graphs of clay mineralogy, Hole 718C.

their Ganges Delta assemblage into proximal, medial, and distal assemblages. Sites 717 and 718 appear to lie within their medial assemblage region. These workers find a distinct difference between the clay mineralogy of biogenic (high smectite) and clastic (high illite) assemblages in this region. Their sample locations are, for the most part, from the eastern half of the Bengal Fan and may not have adequately sampled the Deccan Province of Kolla and Biscaye (1973), which is restricted to the western side of the fan, apparently by bottom-current activity (Kolla et al., 1976).

At Site 717 five lithostratigraphic units have been identified. Unit I (0–5.5 mbsf), consists of interbedded structureless muds, organic-poor mud turbidite and calcareous clays. The clay mineral abundances generally conform to the description of the Deccan Province by Kolla and Biscaye (1973) in the upper portion, but below section 3 (approx. 4.5 mbsf) smectite is absent and the clay mineralogy is more like their Ganges Province description. This change in mineralogy takes place somewhat above the unit boundary assigned by the shipboard scientific party. It seems unlikely that this distribution pattern represents an alteration of the biogenic and clastic assemblages of Bouquillon et al., (1989) but even in the relatively high-resolution study reported here Hole 717A is only sampled at roughly 1-m intervals and this sampling rate may not be able to resolve such a distribution.

Unit II (5.5 to 152 mbsf), consisting mostly of silt and silt-mud turbidites, has a highly silicic character. Smectite is undetectable in all samples and illite is abundant (ca. 60%). Chlorite is common in this interval and kaolinite is low. Maximum quartz grain size (Cochran, Stow et al., 1989, p. 54) is high, averaging around 300 μm. The mineralogical complexion of these sediments strongly resembles the Ganges Province sediments of Kolla and Biscaye (1973). Preliminary age data suggest that the base of this interval is less than 0.93 Ma (Cochran, Stow et al., 1989, p. 57) and we suggest that this interval correlates with the recent uplift of the Tibetan Plateau and the associated onset of severe continental glaciation (Ruddiman and Kutzbach, 1989). The age of this transition is estimated to be between 0.7 and 0.9 Ma by various authors (Ruddiman, pers. comm.; Prell, 1982; Pisias and Moore, 1981) and an accurate determination of the age of the base of Unit II for comparison to isotope records would be extremely useful. Alternatively, this unit may reflect a change in the distribution pattern of the Bengal Fan that supplied this material but is unlikely to have been the source of the sediments in the upper parts of Unit I.

Unit III (152–303 mbsf) contains biogenic mud turbidites near its top that decrease in abundance downward through the unit. This distribution is strongly reflected in the clay mineralogy, which undergoes a marked increase in smectite abundance at the top followed by a steady decrease to levels below 10% near the base of the unit. Maximum quartz grain size is low, averaging less than 100 μm. Illite shows a sharp decrease at the top followed by a steady increase with depth. This clearly suggests that the source of the biogenic mud turbidites is much richer in smectite than the source of Unit II. This unit appears to mark a return of Deccan Province sediments. The age of the base of Unit III is approximately 3 Ma. Further detailed study may demonstrate a link between the onset of the deposition of smectite-rich biogenic mud turbidites and the onset of continental glaciation around 2.4 Ma (Zimmerman et al., 1984). Prell (1982) estimates a change of sea level from around −62 m in the early Quaternary to around −95 m in the late Quaternary and draws the inference that the early Quaternary lowering should have affected only the inner to middle shelf regions whereas the late Quaternary low stand should have affected the entire shelf and shelf break region. It would be enlightening to know whether or not the onset of continental glaciation was slow enough to have led to the gradual change in clay mineralogy in Unit III. Regardless of the immediate causes of this alteration of sediment sources, this unit represents a gradual shift from a strong influence of Ganges Province sediments in the lower part to an abundance of Deccan Province sediments in the upper part.

Unit IV (303–533 mbsf) is composed of silty to muddy turbidites. Smectite is moderately abundant, illite varies between very low values and moderate levels around 40% and the maximum quartz grain size is also low, averaging less than 100 μm. This unit bears a notable resemblance to the upper, smectite-rich portions of Unit III and presumably derives from the same source. The admixture of material from siliceous sources is variable but relatively small. The absence of biogenic turbidites from this section suggests that these sediments may have been delivered directly to the Bengal Fan, bypassing the shelf environment.

Unit V (533–828 mbsf) is a monotonous sequence of silty to muddy turbidites. It is continued in Hole 718C where it is also designated as Unit V with the same description. The entire sequence from 533 mbsf in Hole 717C to the bottom of Hole 718C has a common mineralogical character. Smectite is generally low (<15%) and illite high (45% to 50%). Chlorite and kaolinite are moderately abundant and the maximum quartz grain size is quite high throughout, averaging around 300 μm. The high-smectite, fine-quartz Deccan source represented in Units I, III, and IV is poorly represented in this unit. A continuous supply of material, presumably from the Ganges-Brahmaputra system, dominates throughout.

CONCLUSIONS

We conclude from our study of the mineralogy of the clay size fraction of sediments from Sites 717 and 718 in the distal Bengal Fan that:

1. Unit I in Hole 717A represents a source of sediment derived from the weathering of basic igneous rocks, probably from the Indian Penninsula.
2. Unit II in Hole 717C represents the denudation of the Himalayan massif during an episode of rapid uplift and severe continental glaciation.
3. Unit III in Hole 717C is probably not derived from the Himalayan uplift but from the redistribution of sediments from the Indian continental margin during the early Quaternary lowering of sea level.
4. Unit IV in Hole 717C is derived from much the same source as Unit III although the absence of abundant biogenic turbidites may reflect bypassing of the shelf environment and direct deposition into the Bay of Bengal.
5. Unit V in Hole 717C and its continuation in Hole 718C represent denudation of the Himalayan massif continuing back in time to the age of the oldest sediments recovered on Leg 116.

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