Prell, W. L., Niitsuma, N., et al., 1991
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 117

10. MUD TURBIDITES FROM THE OLIGOCENE AND MIOCENE INDUS FAN AT SITES 722 AND 731 ON THE OWEN RIDGE[1]

G. P. Weedon[2] and I. N. McCave[2]

ABSTRACT

The Owen Ridge south of Oman represents oceanic crust that was uplifted by compressional tectonic forces in the early Miocene. Build-out of the Indus Fan led to deposition of a thick sequence of turbidites over the site of the Ridge during the late Oligocene and early Miocene. Early Miocene uplift of the Ridge led to a pelagic cap of nannofossil chalks. Two short sequences of turbidites from the pre- and syn-uplift phases were chosen for detailed grain size analysis.

The upper Oligocene section at Site 731 is composed of thin (centimeter-decimeter scale) graded mud turbidites separated by relatively thick (decimeter-meter scale) intervals of homogeneous, non-bioturbated clayey siltstones. These finer intervals are unusually silt-rich (about 60%) for ungraded material and were probably deposited as undifferentiated muds from a series of turbidity current tails. By contrast, the lower Miocene section at Site 722 is comprised of a sequence of interbedded turbidites and hemipelagic carbonates. Sharp-based silt turbidites are overlain by burrow-mottled marly nannofossil chalks.

The Oligocene sequence may have accumulated in an overbank setting on the middle fan—the local topographic position favoring frequent deposition from turbidity current tails and occasional deposition from the body of a turbidity flow. Uplift of the Ridge in the early Miocene led to pelagic carbonate deposition interrupted only by turbidity currents capable of overcoming a topographic barrier. Further uplift eventually led to entirely pelagic carbonate deposition.

INTRODUCTION AND PALEOCEANOGRAPHIC SETTING

Drilling on the Owen Ridge south of Oman during ODP Leg 117 at Sites 721, 722, and 731 (Fig. 1) penetrated hundreds of meters of turbidites underlying a pelagic cover (Prell, Niitsuma, et al., 1989). The turbidites represent portions of the Indus Fan prior to uplift of the Owen Ridge above the lysocline and level of fan deposition in the early Miocene. The Owen Ridge appears to have been initiated at a transform fault along the proto-Carlsberg spreading ridge. Opening of the Gulf of Aden may have caused compression and uplift of the Ridge (Whitmarsh, 1979; Mountain and Prell, 1987). Currently the Ridge marks a minor plate boundary separating Arabia and India with exceptionally slow rates of dextral strike-slip (Gordon and DeMets, 1989).

Whitmarsh, Weser, et al. (1974) established, via spot coring, the depositional history of the Ridge at DSDP Site 224 (Figs. 1 and 2). Lower Eocene lamprophyre flows are overlain by nannofossil-rich clay and volcanic glass. Upper Eocene nannofossil chalk, silty claystone and sandstone is succeeded by lower Oligocene clayey siltstones and claystones probably deposited close to the lysocline. In the late Oligocene and early Miocene almost barren graded silts and sands (turbidites) were deposited. By the earliest middle Miocene sedimentation rates had dropped, clastic supply to these sites waned, and pelagic nannofossil oozes started accumulating following the uplift of the Ridge.

The present study of a few mud turbidites from the upper Oligocene and the uppermost lower Miocene may provide some insights into the changing nature of sedimentation over the nascent Owen Ridge. It was undertaken to establish the extent to which the barren Oligocene section was of turbidity current origin and to ascertain whether the thick mud turbidites described by Jones (1988) and Jones et al. (in press) from the Madeira Abyssal Plain were present. Grain size investigations were based on Sedigraph X-ray settling tube analysis (Jones et al., 1988). This method allows grain-size distributions spanning fine sand to clay to be analyzed non-destructively from small samples. Size frequency distributions (as opposed to cumulative curves) are especially useful for visualization of grain size populations and permit ready identification of coarsening and fining trends (McCave, 1979). The distributions are displayed with coarser material to the right and they are usefully combined with plots of the percentage of silt (2–63 μm) and the silt/clay ratio.

SAMPLES FROM HOLE 731C

Thirty three samples spanning 2.6 m were collected from Core 117-731C-9W (upper Oligocene) at about 691 meters below seafloor (mbsf) (Fig. 2). An irregular sampling pattern was designed to provide a suite of specimens reflecting the full range of grain size variations. The dominant lithotypes are siltstone and clayey siltstone arranged in sharp-based fining-upward sequences a few decimeters thick. The siltstone is dark gray (10YR 4/1) with mainly plane laminations. At some levels (not sampled) rare ripple cross-lamination and low angle cross-stratification is present. The dark gray (10YR 4/1) clayey siltstone exhibits a predominantly homogeneous fabric with faint horizontal banding. The homogeneity of the clayey siltstone is not due to bioturbation (contrary to the shipboard descriptions), as layering is present and the contacts between homogeneous and laminated sediment are extremely sharp and lack burrow mottling (Fig. 6 of Site 731 chapter in Prell, Niitsuma, et al., 1989). Occasionally small slump folds and dewatering structures are present. At some levels sandstone beds of a few centimeters to decimeters occur. These have sharp bases and grade up into clayey siltstone or have sharp tops and bottoms. These coarser sequences have not been examined here. Shipboard determinations demonstrated carbonate contents of about 5%. This carbonate is detrital, the sequence being essentially barren of microfossils, probably reflecting deposition below the lysocline. The proportion of the other main components, quartz and clay minerals, is a function of bulk grain size.

---

[1] Prell, W. L., Niitsuma, N., et al., 1991. *Proc. ODP, Sci. Results,* 117: College Station, TX (Ocean Drilling Program).

[2] Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, United Kingdom.

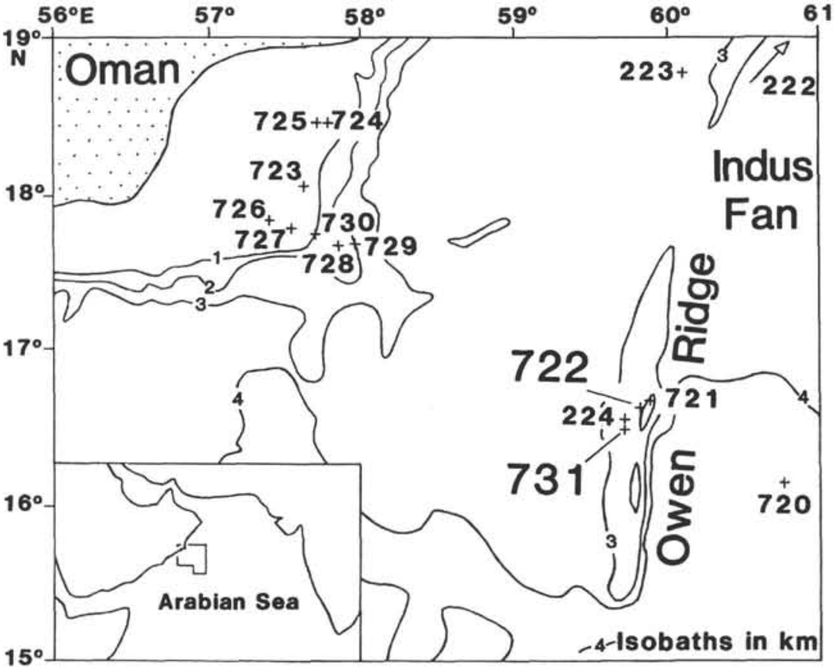

Figure 1. Location map of ODP Sites 722 and 731.

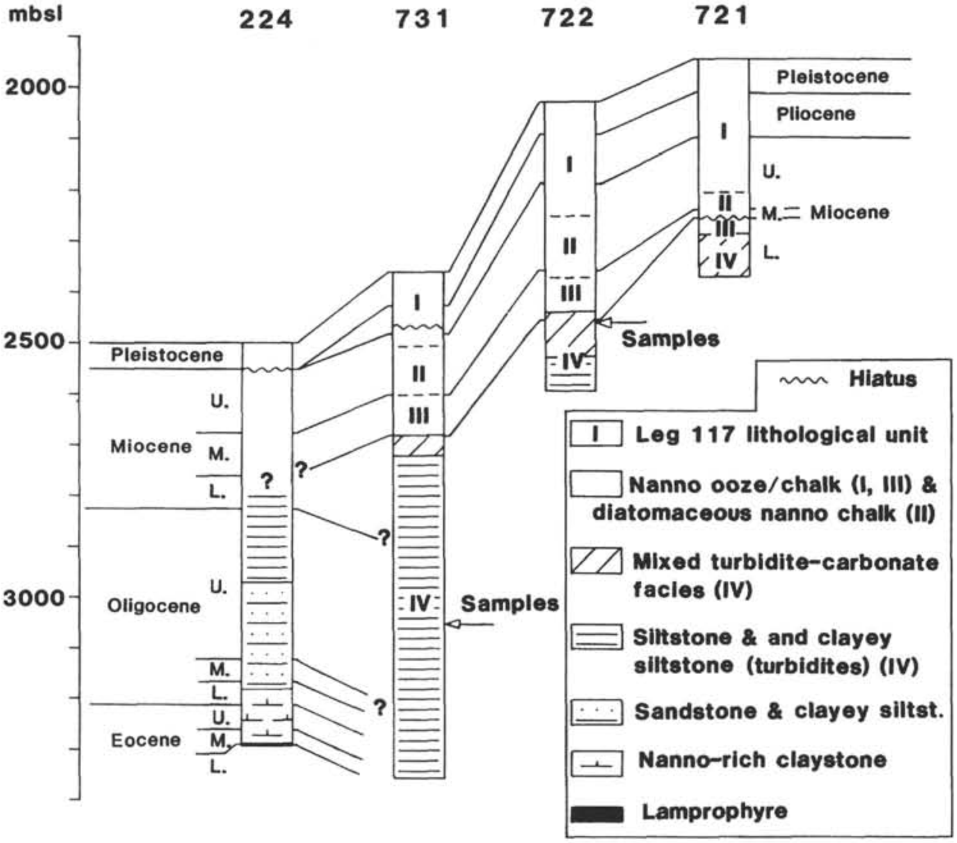

Figure 2. Lithostratigraphy for four sites on the Owen Ridge. The location of the sampling is indicated. Tie lines are based on biostratigraphy.

The sequence analyzed has been divided into fining-upward units A to E on the basis of the silt percentages and silt/clay ratios (Fig. 3). In the cases of units B to E a relatively coarse base of 5–20 cm thickness with 70% to 85% silt is overlain by clayey siltstone intervals of 15–100 cm with about 60% silt. Unit A, however, has an exceptionally coarse base (up to 96% silt; Table 1) which is much thicker than the coarse components of the other packages; yet the finer top is just 10 cm thick.

In terms of grain-size distributions a clear pattern emerges. The base of each package is defined by a distribution dominated by a single modal peak which is usually very narrow indicating extremely good sorting. From the base of each package the mode shows an orderly migration towards finer grain sizes (normal grading). The one exception to this occurs at the base of unit C which is reverse graded. The grain size distributions of the basal coarse units (siltstones) do not contain modal peaks that are present in the underlying finer material. Thus there is no evidence for erosion of the underlying sediment (cf. McCave, 1979). The finer (clayey siltstone) part of each package is less well-sorted as shown by a broad fine- and medium-silt mode. In the thicker examples of these fine intervals there is no evidence for grading (units C and D). All of this poorly-sorted material

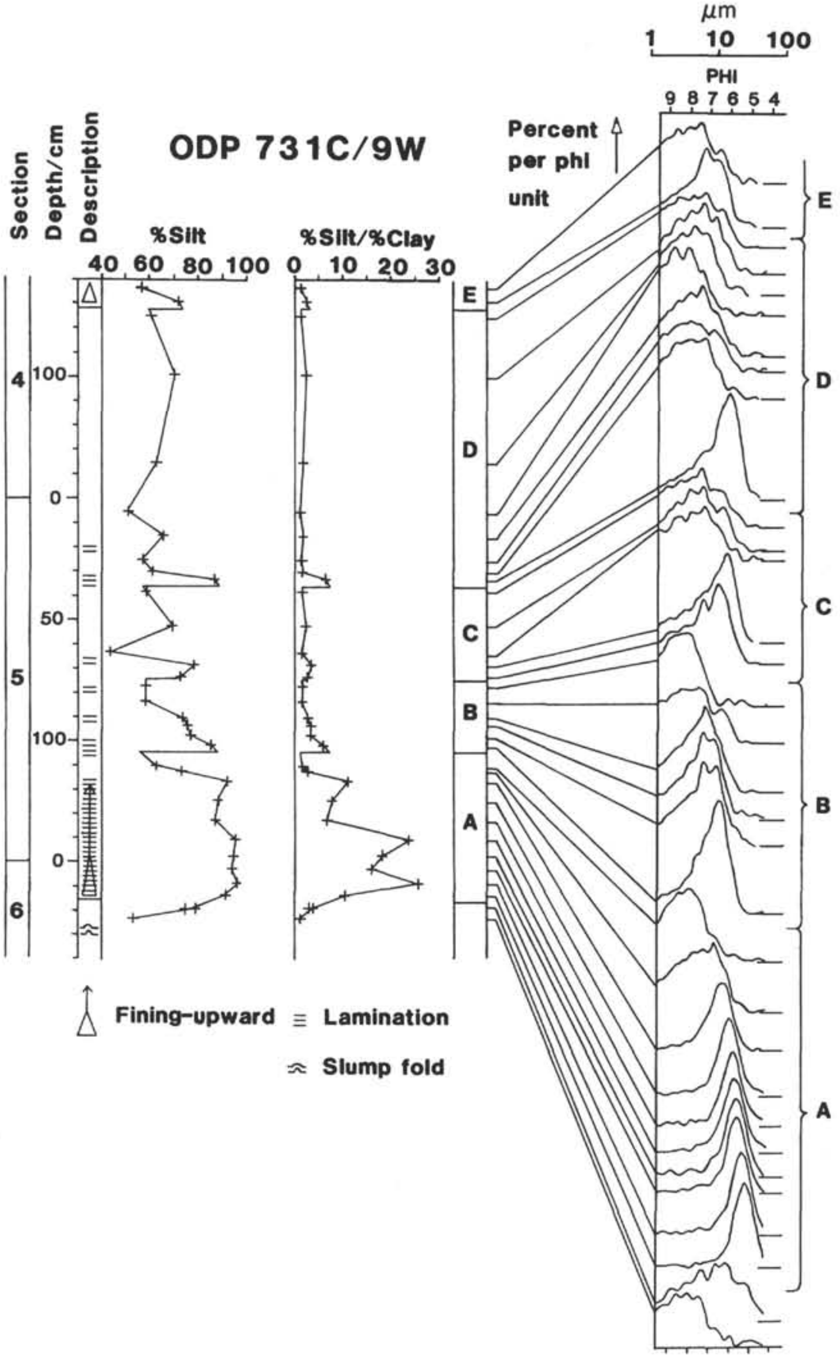

Figure 3. Grain size data for late Oligocene sediments from Site 731. Individual fining-upward units are labelled A to E.

Table 1. Grain size data for the upper Oligocene section, Hole 731C.

Core, section, interval (cm)	Depth (mbsf)	Median/phi	%Silt	%Silt/%clay	Unit
9W-4, 63–64	690.73	8.62	56.8	1.31	E
9W-4, 69–70	690.79	7.66	72.0	2.59	E
9W-4, 75–76	690.85	8.44	60.5	1.53	D
9W-4, 95–96	691.05	8.01	70.1	2.34	D
9W-4, 135–136	691.45	8.39	63.1	1.70	D
9W-5, 5–6	691.65	8.91	50.8	1.02	D
9W-5, 15–16	691.75	8.20	65.9	1.95	D
9W-5, 25–26	691.85	8.60	56.7	1.31	D
9W-5, 30–31	691.90	8.45	61.3	1.59	D
9W-5, 33–34	691.93	6.55	86.5	6.58	D
9W-5, 38–39	691.98	8.48	58.4	1.41	C
9W-5, 52–53	692.12	8.00	69.9	2.37	C
9W-5, 63-64	692.23	8.60	43.7	1.27	C
9W-5, 68–69	692.28	7.10	78.1	3.60	C
9W-5, 73–74	692.33	7.48	72.8	2.70	C
9W-5, 77–78	692.37	8.64	58.4	1.43	B
9W-5, 83–84	692.43	8.56	58.4	1.39	B
9W-5, 90–91	692.50	7.80	73.5	2.79	B
9W-5, 93–94	692.53	7.58	75.7	3.12	B
9W-5, 97–98	692.57	7.46	77.2	3.43	B
9W-5, 101–102	692.61	6.96	85.6	6.00	B
9W-5, 110–111	692.70	8.48	62.7	1.68	A
9W-5, 112–113	692.72	7.81	73.3	2.75	A
9W-5, 116–117	692.76	6.50	91.9	12.10	A
9W-5, 124–125	692.84	6.05	88.3	7.83	A
9W-5, 132–133	692.92	5.87	86.6	6.69	A
9W-5, 140–141	693.00	5.79	95.0	23.80	A
9W-5, 147–148	693.07	5.69	94.3	18.10	A
9W-6, 2–3	693.12	5.69	93.8	15.90	A
9W-6, 8–9	693.18	5.39	96.0	25.60	A
9W-6, 13–14	693.23	5.30	91.2	10.50	A
9W-6, 19–20	693.29	7.26	74.7	2.99	—
*9W-6, 19–20	693.29	7.16	79.0	3.84	—
9W-6, 23–24	693.33	8.73	53.7	1.16	—

* = Repeated sample.

would have been carried in suspension, within a thin near-bed layer. The inversely graded layer of unit C would have had an origin in changing flow conditions. The fine grain size of the silt would have put it in a viscous shear regime rather than an inertial one. Thus the dynamic method of generating the inverse grading found in sandy turbidites would not have occurred here (Jones, 1988).

DISCUSSION

There is a great deal of similarity in the overall nature of this sequence to that described from the middle Miocene to upper Pliocene sediments of the Leg 23 Indus Fan site (DSDP Site 222, Whitmarsh, Weser, et al., 1974). In both cases the sediments are dominated by homogeneous, ungraded grey clayey siltstone units that are tens of centimeters to meters thick. Interbedded with these are beds of siltstone or sometimes sandstone that are typically around 10 cm thick. Some of the coarser horizons at Site 222 were analyzed mineralogically and for grain size by Jipa and Kidd (1974). Their observations are entirely consistent with the graded siltstone parts of the analyzed sequence being composed of mud turbidites. Judging from the grain sizes and dominance of plane lamination these may represent the D division of the ideal Bouma sequence. However, two problems remain: what is the origin of the dominant, exceptionally silt-rich clayey siltstones and what does the anomalous nature of fining-upward unit A indicate?

Excluding unit A, the homogeneity and thickness of the clayey siltstone relative to the coarser bases suggests that this material was not deposited rapidly from a single turbidity current. To explain the high silt content, Jipa and Kidd (1974) favored sedimentation from low velocity, semipermanent bottom turbid flows, or (much less probably) intermediate-water suspended turbid flows. Added to this they envisaged some material supplied from eolian input. The semipermanence of such supply was postulated to account for the lack of typically pelagic intervals; though as deposition was near or below the carbonate compensation depth, it is unlikely that pelagic intervals could be identified without very detailed examination (O'Brien et al., 1980).

Their turbid flows were envisaged as low density in nature, yet it is now known that such flows produce alternating sorted silt and mud laminae (Stow and Bowen, 1980). It is unlikely that there was any surface transport from the Indus plume because aggregation would send such material to the bottom much closer to source (Eisma, 1984). An eolian mechanism is possible as this material is fine silt with a modal size of from 4 to 8 μm. In a dispersed state it would have had a sinking speed of 0.8 to 3.2 m/d or 300 to 1200 m/y. Clearly, aggregation would have enhanced that sinking rate (McCave, 1975, 1984).

However, several observations appear to rule out a predominantly eolian origin for the clayey siltstones. For example, an eolian mechanism would imply that the clayey siltstone is hemipelagic, yet it lacks evidence for bioturbation. The clay mineralogy of Unit IV is characterized by high crystallinity chlorite and a lack of kaolinite—indicating an Indus Fan rather than an Oman Margin provenance (Prell, Niitsuma, et al., 1989). Additionally, the wind-transported clay mineral palygorskite, derived from the Arabian Peninsula and Somalia, was identified in Units I and II, but it is absent from Unit IV.

Unfortunately the lack of microfossils in the turbidite part of lithological Unit IV precludes estimation of sedimentation rates. Biostratigraphic information indicates rates of around 24-61 m/m.y. for the overlying mixed turbidite-carbonate division of Unit IV and of 8–30 m/m.y. for the pelagic Unit III (Prell, Niitsuma, et al., 1989). The transition from the turbidite to the mixed turbidite-carbonate facies of Unit IV involved replacement of the dominant clayey siltstone by pelagic carbonates. If the clayey siltstones were of a mainly eolian origin, this transition would imply a major shift in wind direction or a rapid change in regional climate. However, the contact between these divisions of Unit IV as well as between Units IV and III are apparently diachronous over distances of just tens of kilometers (Fig. 2). This observation is incompatible with an eolian model for the origin of the clayey siltstones and their replacement by pelagic carbonates.

An alternative way of producing thick units of ungraded mud is from sluggish flows of fluid mud which are ponded and stop on flat abyssal plains (McCave and Jones, 1988). This fails to account for the presence of faint, horizontal banding within the silty claystones such as observed in the lower half of Section 117-731C-9W-4. Also the setting is not thought to have been flat, though the paleotopography is not well-known. Instead it is suggested that each silty claystone horizon represents a succession of turbidity current tails which left no visible evidence for individual events. This model requires that the material in the turbidity current tails had an unusually high proportion of silt. The lack of clay might have resulted from a combination of relief and climatic factors acting in the Himalayan source region. Another possibility is that the site of deposition was close to the main flow path.

As far as fining-upward unit A is concerned it is notable that despite the relatively thick and coarse basal layer, the overlying clayey siltstone layer is relatively thin. Surprisingly the modal peaks in the graded base of this unit span the same range of grain sizes as the other packages, but there appears to be sorting throughout. Most features of unit A, in particular the good sorting throughout its thickness, are consistent with deposition from a classical, but very silt-rich turbidity current. It presumably represents deposition from the path of the main turbidity current. Examination of many more mud turbidites will be required to determine just how exceptional or otherwise this unit really is.

SAMPLES FROM HOLE 722B

Eleven samples spanning 1.11 m were obtained from Core 722B- 46X (uppermost lower Miocene) at about 430 mbsf (Fig. 2). The samples were taken from the top part of Unit IV composed of sharp-based fining upward clastic units of a few decimeters that are overlain by pelagic or hemipelagic marly nannofossil chalks. This part of the section on the Owen Ridge represents an 86 m thick transitional facies at Site 722 which is underlain by the turbidite-dominated facies described earlier, and overlain by pelagic sediments.

The olive gray (5Y 4/3) siltstone sampled has a sharp base with a few centimeters of plane laminations succeeded by wavy, contorted laminations possibly disturbed by drilling (Fig. 4). This siltstone bed is unusually thick for this part of Unit IV. Shipboard analysis showed that such siltstones contain about 5% calcium carbonate which smear slides show to be predominately detrital calcite mixed with quartz and clay. Overlying the siltstone at 50 cm (Fig. 4) is dark grayish brown (10YR 4/3), bioturbated marly nannofossil chalk. This is dominated volumetrically by nannofossils according to smear slide examination, but limited shipboard chemical analysis indicates only about 25% $CaCO_3$ in such sediment. Other components include quartz, clay, and detrital calcite.

The results of the Sedigraph analyses are illustrated in Figure 4; a simple fining-upward sequence is observed. As with the Oligocene sediments at Site 731C, there is no indication of entrainment of underlying hemipelagic sediment or of a basal sandy layer. The change in sediment color corresponds to a transition from grain-size distributions with a well-defined single modal peak to distributions with multiple peaks. Above the transition in sediment type there is less than 50% silt (Table 2). The transition in sediment type thus corresponds to the burrowed top pelagic or hemipelagic cap to the turbidite.

Table 2. Grain size data for the uppermost lower Miocene section, Hole 722B.

Core, section, interval (cm)	Depth (mbsf)	Median/phi	%Silt	%Silt/%clay
46X-1, 2–3	430.52	7.71	65.1	1.91
46X-1, 10–11	430.60	—	33.0	0.49
46X-1, 20–21	430.70	—	28.8	0.40
46X-1, 30–32	430.80	9.76	37.6	0.60
46X-1, 40–41	430.90	—	30.7	0.44
46X-1, 47–49	430.97	9.60	41.4	0.70
46X-1, 55–57	431.05	8.41	53.9	1.16
46X-1, 70–72	431.20	7.21	64.5	1.82
46X-1, 88–90	431.38	6.98	66.9	2.03
46X-1, 108–110	431.58	5.83	89.2	8.38
46X-1, 113–115	431.63	9.23	45.8	0.84

The major break in character of the grain size distribution is between the samples at 47–49 and 55–57 cm (Fig. 4). However, the bioturbation is apparent down to about 67 cm, well into the graded top of the turbidite. This suggests burrowing to over 10 cm below the sediment surface. The simple percentage of silt is somewhat misleading as it suggests grading continuously up to 40 cm, but the visual aspect of the core with color change and burrowing shows it clearly to be hemipelagic at this level.

CONCLUSIONS

The upper Oligocene and lower Miocene turbidites described here represent "episode I" in the development of the Indus Fan (Kolla and Coumes, 1987). The upper Oligocene material includes thin, well-defined graded mud turbidites (Bouma D and E divisions). These are separated by much thicker sequences of homogeneous, non-bioturbated and ungraded clayey siltstones that are barren of microfossils. Each clayey siltstone sequence was probably deposited from many turbidity current tails (Bouma division E). The exceptionally high silt content of the silty claystones may reflect a lack of clay in the Himalayan source region due to relief and/or climatic factors, or proximity to the path of the main flow. The lower Miocene mixed turbidite-carbonate fa-

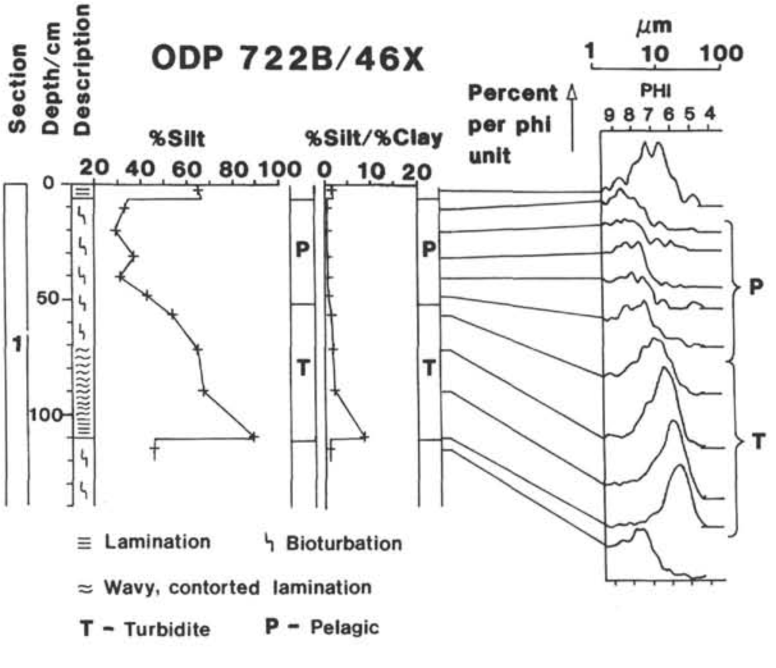

Figure 4. Grain size data for lower Miocene sediments from Site 722.

cies is composed of sharp-based graded mud turbidites (Bouma divisions D and E) overlain by burrowed hemipelagic marly nannofossil chalks.

The change from the turbidite to the mixed turbidite-carbonate facies of Unit IV involved (1) a diachronous transition over a distance of a few tens of kilometers between sites (Fig. 2), (2) a change to preservation of substantial volumes of pelagic nannofossil carbonate, and (3) a change from predominant deposition from frequent turbidite current tails to intermittent deposition from turbidity current main flows. The first two points are easily accounted for by tilting and uplift of the Owen Ridge through the lysocline (Prell, Niitsuma, et al., 1989). The third point is presumably also related to the uplift. Kolla and Coumes (1987) showed that sedimentation on the lower part of the Indus Fan is dominated currently by unchannelized turbidity currents. Middle fan deposition (currently at 3500–4000 mbsl), however, is characterized by channelized turbidity currents with overbank deposition beyond levees. Thus the predominantly clayey siltstone lower Oligocene sequence described here may have accumulated in an overbank setting somewhere on the middle fan. Elevation of the Ridge site during the early Miocene would have then blocked deposition from relatively low-level turbidity current tails, but permitted intermittent deposition from major turbidity currents that could rise up over a small, but growing, topographic barrier.

ACKNOWLEDGMENTS

Gillian Foreman is thanked for her help with the Sedigraph analyses. G.P.W. thanks the NERC for a Research Fellowship and Warren Prell and Nobu Niitsuma for the opportunity to participate on Leg 117. He also extends his thanks to the other shipboard sedimentologists, particularly Werner Ricken, David Anderson, and David Murray.

REFERENCES

Eisma, D., 1984. Dispersal of Zaire River suspended matter in the estuary and the Angola Basin. *Neth. J. Sea Res.,* 17:385–411.

Gordon, R. G., and DeMets, C., 1987. Present-day motion along the Owen Fracture Zone and Dalrymple Trough in the Arabian Sea. *J. Geophys. Res.,* 94:5560–5570.

Jipa, D., and Kidd, R. B., 1974. Sedimentation of coarser grained interbeds in the Arabian Sea and sedimentation processes of the Indus Cone. *In* Whitmarsh, R. B., Weser, O. E., et al., *Init. Repts. DSDP,* 23: Washington (U.S. Govt. Printing Office), 471–495.

Jones, K.P.N., 1988. Studies of fine-grained, deep-sea sediments [Ph.D. thesis]. Univ. of Cambridge, U.K.

Jones, K.P.N., McCave, I. N., and Patel, P. D., 1988. A computer-interfaced Sedigraph for modal size analysis of fine-grained sediment. *Sedimentology,* 35:163–172.

Jones, K.P.N., McCave, I. N., and Weaver, P.P.E., in press. Thick mud turbidites from the Madeira Abyssal Plain. *Mar. Geol.* (submitted).

Kolla, V., and Coumes, F., 1987. Morphology, internal structure, seismic stratigraphy, and sedimentation of Indus Fan. *AAPG Bull.,* 71: 650–677.

McCave, I. N., 1975. Vertical flux of particles in the ocean. *Deep-Sea Res. Oceanogr. Abstr.,* 22:491–502.

________, 1979. Diagnosis of turbidites at Sites 386 and 387 by particle-counter size analysis of the silt (2-40 μm) fraction. *In* Tucholke, B. E., Vogt, P. R., et al., *Init. Repts. DSDP,* 43: Washington (U.S. Govt. Printing Office), 395–405.

________, 1984. Size spectra and aggregation of suspended particles in the deep ocean. *Deep-Sea Res. Part A,* 31:329–352.

McCave, I. N., and Jones, K.P.N., 1988. Deposition of ungraded muds from high-density non-turbulent turbidity currents. *Nature,* 333: 250–252.

Mountain, G., and Prell, W. L., 1987. Leg 117 ODP site survey: a revised history of Owen Basin. *Eos,* 68:424.

O'Brien, N. R., Nakazawa, K., and Tokuhashi, S., 1980. Use of clay fabric to distinguish turbidite and hemipelagic siltstone and silts. *Sedimentology,* 27:47–61.

Prell, W. L., Niitsuma, N., et al., 1989. *Proc. ODP, Init. Repts.,* 117: College Station, TX (Ocean Drilling Program).

Stow, D. V., and Bowen, A. J., 1980. A physical model for the transport and sorting of fine-grained sediment by turbidity currents. *Sedimentology,* 27:31–46.

Whitmarsh, R. B., 1979. The Owen Basin off the southeast margin of Arabia and the evolution of the Owen Fracture Zone. *Geophys. J. R. Astron. Soc.,* 58:441–470.

Whitmarsh, R. B., Weser, O. E., Ross, D. A., et al., 1974. *Init. Repts. DSDP,* 23: Washington (U.S. Govt. Printing Office).

Date of initial receipt: 19 July 1989
Date of acceptance: 13 April 1990
Ms 117B-140