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

36. ORGANIC PETROLOGY OF NEOGENE SEDIMENTS FROM NORTH INDIAN OCEAN (LEG 117): AMOUNT, TYPE, AND PRESERVATION OF ORGANIC MATTER[1]

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ABSTRACT

Neogene sediments from three areas of the Northern Indian Ocean (Indus Fan, Owen Ridge, Oman Margin, ODP Leg 117) were studied in order to determine the amount, type, and preservation of organic matter as functions of the environments encountered. The work consisted of geochemical analyses on whole sediment (Total Organic Content and Rock Eval pyrolysis) and of petrographic studies on isolated organic matter by optical and scanning electron microscopy. In Indus Fan sediments, organic matter is present in low amounts, mainly as lignaceous fragments. A contrasting situation exists in Oman Margin sediments which are generally rich in amorphous autochtonous organic matter. Owen Ridge, located between Indus fan and Oman Margin areas, shows two phases of organic sedimentation as a consequence of the uplift of the ridge. The older phase (Oligocene to early or middle Miocene) is strongly influenced by detrital supply from the Indus, while the younger phase (middle Miocene to Pleistocene) is characterized by relatively high amounts of autochtonous organic matter.

From a general point of view it appears that high amounts of organic matter are mainly due to good preservation of marine amorphous organic matter, such as in Oman Margin sediments and in upper pelagic levels of Indus Fan and Owen Ridge deposits. Low total organic carbon contents are correlated with low proportions of amorphous material in the total organic matter due to oxidizing conditions. This leads to a relative enrichment in components derived from resistant materials (lignin, chitin, or other resistant biopolymers) such as lignaceous fragments (Indus Fan) and/or fragments from benthic organisms and alveolate microplankton (Oman Margin).

INTRODUCTION

Organic matter content of marine sediments depends on many interrelated factors, such as primary productivity, supply of continental organic matter, oxygenation of bottom water, early diagenetic processes, and sediment accumulation rates. Leg 117 provided interesting examples of different sedimentary environments (Fig. 1) where relationships between those factors can be studied:

1. Indus Fan area (Site 720), dominated by a detrital sedimentation,
2. Owen Ridge area (Sites 721, 722, and 731) where sedimentation was strongly modified in the Miocene because of uplift of the ridge, and
3. Oman Margin area (Sites 723, 724, 725, 726, 727, 729, and 730) where the sediments were probably deposited in an Oxygen Minimum Zone (OMZ), and marine productivity was enhanced by a coastal upwelling regime.

This paper discusses amount and type of organic matter as a function of these environments.

METHODS

Lithology of samples was determined by visual description and observation of smear slides according to the ODP standards.

The Total Organic Carbon content (TOC) was determined using a Carmhograph analyzer device. After elimination of carbonates (HCl 2N), samples are burned at 1100°C under oxidizing conditions (O_2 current). The gas mixture released by combustion goes through a perhydrite filter which removes SO_2, then goes through a NaOH N/250 solution, the conductivity of which is modified by CO_2. Calibration is made using pure $CaCO_3$. Whole samples were analyzed using the Oil Show Analyzer version (OSA) of the Rock Eval (Espitalié et al., 1985a, b, 1986). Only Hydrogen Index (HI) and temperature of S_2 peak maximum (T_{max}) are reported in this paper, as characterizing respectively the hydrocarbon potential of the organic matter and its thermal maturity level.

The petrographic analysis consisted of observations of isolated kerogen in transmitted light microscopy and in Scanning Electron Microscopy (SEM). Qualitative chemical determinations were carried out using an Energy Dispersive Spectrometer (EDS) coupled with SEM. The kerogen was observed at two stages of the isolation procedure. In a first step, the HCl-HF treatment leads to a residue containing organic matter, metallic sulfides (mainly pyrite), and some fine minerals that have survived the acid treatment either because of their association with amorphous matter or because of their mineralogical nature (Ti minerals). This residue was called Total Residue (TR). In a second step, the TR was submitted to additional KOH and HNO_3 treatments, following by a densitometric separation ($d < 2.2$), leading to the Second Residue (SR). This latter is composed almost exclusively of organic matter, sometimes still containing fine pyrite crystals. Generally, pyrite framboids and massive crystals and other minerals are entirely removed during this step. Semiquantitative evaluations that are given in Table 4 are based on the observation of SR in transmitted light microscopy. The general descriptions and comments given in text take into account observation of both TR and SR. The residues are described and evaluated using five categories of components: Amorphous Organic Matter (AOM), Lignaceous Fragments (LF), Undetermined Structured Organic Matter (USOM), benthic and pelagic Marine Microfossils (MM), and Pyrite.

RESULTS

Lithology, TOC, and Rock Eval results are presented in Tables 1, 2, and 3, petrographic composition of organic matter

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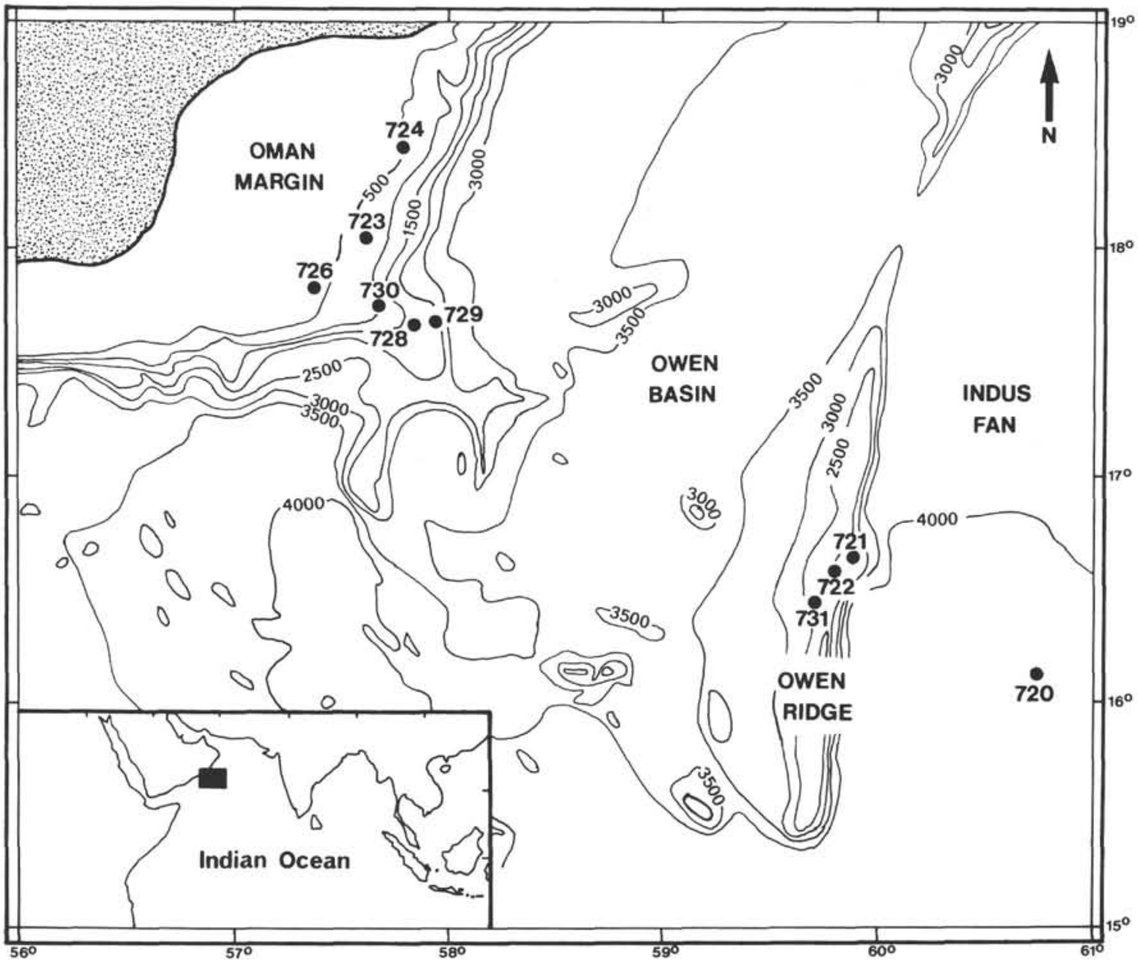

Figure 1. Location of the different Leg 117 sites studied in this paper.

Table 1. Lithology and organic geochemical results of Site 720 samples (Indus Fan).

Sample identification	Depth (mbsf)	Lithology	Unit	Stratigraphic age	TOC	HI	T_{max}
720A-1H-3, 130-132 cm	4.30	Foraminifer-bearing nannofossil ooze	1	Pleistocene	0.12	n.d.	n.d.
702A-2H-7, 5-7 cm	18.45	Foraminifer nannofossil silty clay	2	Pleistocene	0.12	n.d.	n.d.
720A-6X-CC(7-9 cm)	57.20	Foraminifer-bearing nannofossil ooze	2	Pleistocene	0.13	n.d.	n.d.
720A—11X-1, 10-12 cm	96.50	Foraminifer-bearing clayey silt	2	Pleistocene	0.14	n.d.	n.d.
720A-11X-1, 36-38 cm	96.76	Nannofossil ooze	2	Pleistocene	0.11	n.d.	n.d.
720A-24X-1, 106-108 cm	223.06	Calcareous clayey silt	2	Pleistocene	0.11	n.d.	n.d.
720A-30X-3, 71-73	283.51	Calcareous clayey silt	2	Pleistocene	0.54	284	420

(SR) is presented in Table 4. The lithological units and ages are as reported in the hole summaries of Leg 117 (Prell, Niitsuma, et al., 1989).

Total Organic Carbon (TOC)

TOC concentrations of sediments from the Indus Fan (Site 720) and in the Owen area (Sites 721, 722, and 731) are generally low (< 0.5%), except for some samples in which TOC is over 2% (Hole 721A, 80.45 mbsf; Hole 722A, 89.64 mbsf; and Hole 731A, 67.82 mbsf).

This is different from Oman Margin sediments where TOC values are more commonly high (> 2%), mainly at Site 723. These high values correspond to Pleistocene calcareous clayey silts.

Hydrogen Indices (HI) and T_{MAX}

The interpretation of pyrolysis results is difficult when TOC is very low, because of adsorption phenomena by mineral matrix that can lead to depressed HI values and elevated T_{max} values (Espitalié et al., 1985a, b, 1986). Thus, only one sample from Indus Fan gave a possibly reliable result, indicating an immature organic matter (T_{max} = 420°C) with a relatively low hydrocarbon potential (284 mg HC/g TOC).

Higher HI values are observed in Owen Ridge sediments, generally ranging from 350 to 450 mg HC/g TOC, and up to 675 for one sample. This latter value as well as the associated T_{max} value (330°C) is doubtful because the sample has a very low TOC value (0.02 %).

Table 2. Lithology and organic geochemical results of Sites 721, 722, and 731 samples (Owen Ridge).

Sample identification	Depth (mbsf)	Lithology	Unit	Stratigraphic age	TOC	HI	T_{max}
721A-1H-4, 70–72 cm	5.20	Marly nannofossil ooze	1	Pleistocene	0.46	458	423
721A-7H-3, 63–65 cm	61.03	Nannofossil ooze	1	Pleistocene	0.34	361	417
721A-7H-6, 64–66 cm	65.54	Nannofossil ooze	1	Pleistocene	1.22	336	424
721A-8H-3, 98–100 cm	70.88	Nannofossil ooze	1	late Pliocene	0.45	357	414
721A-9H-3, 105–107 cm	80.45	Nannofossil ooze	1	late Pliocene	2.15	394	424
721A-9H-4, 105–107 cm	81.95	Nannofossil ooze	1	late Pliocene	0.82	350	422
721B-19X-6, 56–58 cm	180.96	Nannofossil chalk	1	late Miocene	0.39	613	417
712B-22X-2, 140–142 cm	204.90	Nannofossil chalk	1	late Miocene	0.93	355	420
721B-23X-4, 8–10 cm	216.28	Nannofossil chalk	1	late Miocene	0.15	550	420
721B-24X-1, 140–142 cm	222.70	Nannofossil chalk	1	late Miocene	0.75	377	422
721B-25X-5, 90–92 cm	237.40	Nannofossil chalk	1	late Miocene	0.16	n.d.	n.d.
721B-26X-4, 27–29 cm	244.87	Nannofossil chalk	1	late Miocene	0.17	n.d.	n.d.
721B-33X-1, 39–41 cm	308.79	Nannofossil chalk	2b	early or middle Miocene	0.15	392	424
721B-33X-CC(17–19 cm)	311.44	Nannofossil chalk	3	early or middle Miocene	0.14	n.d.	n.d.
721B-34X-2, 90–92 cm	320.40	Nannofossil chalk	3	early Miocene	0.05	n.d.	n.d.
721B-34X-5, 64–66 cm	324.64	Nannofossil chalk	3	early Miocene	0.07	n.d.	n.d.
721B-36X-CC(34–36 cm)	347.00				0.07	n.d.	n.d.
721B-38X-1, 101–103 cm	357.61	Nannofossil chalk	4	early Miocene	0.07	n.d.	n.d.
721B-38X-2, 57–59 cm	358.67	Marly nannofossil ooze	4	early Miocene	0.07	n.d.	n.d.
721B-38X-5, 83–85 cm	363.43	Clayey silt	4	early Miocene	0.10	n.d.	n.d.
721B-44X-2, 87–89 cm	416.87	Nannofossil clayey silt	4	early Miocene	0.35	150	504
721B-44X-5, 10–12 cm	420.60	Clayey silt	4	early Miocene	0.15	n.d.	n.d.
722A-1H-1, 80–82 cm	0.80	Nannofossil ooze	1	Pleistocene	0.84	402	426
722A-5H-4, 24–26 cm	43.34	Nannofossil ooze	1	Pleistocene	0.27	345	420
722A-10X-3, 14–16 cm	89.64	Nannofossil ooze	1	middle Pliocene	3.45	422	423
722A-10X-3, 106–108 cm	90.56	Marly nannofossil ooze	1	middle Pliocene	0.83	300	424
722A-16X-1, 53–55 cm	145.13	Nannofossil ooze	1	early Pliocene	0.30	341	414
722A-16X-4, 22–24 cm	149.32	Nannofossil ooze	1	early Pliocene	1.94	387	423
722B-37X-6, 70–72 cm	351.60	Nannofossil chalk	3	middle Miocene	0.07	300	423
722B-41X-1, 144–146 cm	383.64	Nannofossil chalk	3	middle Miocene	0.07	n.d.	n.d.
722B-43X-2, 105–107 cm	403.95	Marly nannofossil chalk	3	middle Miocene	0.08	n.d.	n.d.
722B-44X-4, 35–37 cm	415.95	Nannofossil-bearing clayey silt	4	middle Miocene	0.08	n.d.	n.d.
722B-44X-4, 75–77 cm	416.35	Siltstone	4	middle Miocene	0.06	n.d.	n.d.
722B-48X-1, 38–40 cm	450.18	Silty claystone	4	early Miocene	0.33	200	439
722B-49X-1, 83–85 cm	460.23	Silty claystone	4	early Miocene	0.10	n.d.	n.d.
722B-52X-5, 43–45 cm	494.63	Silty claystone	4	early Miocene	0.02	675	330
722B-59X-1, 54–56 cm	556.44	Claystone	4	early Miocene	0.10	n.d.	n.d.
731A-6H-2, 100–102 cm	50.30	Marly nannofossil ooze	1a	Pleistocene to Holocene	0.35	217	399
731A-6H-4, 100–102 cm	53.30	Calcitic marly nannofossil ooze	1a	Pleistocene to Holocene	0.97	290	411
731A-8X-1, 82–84 cm	67.82	Nannofossil-bearing calcitic silty clay	1b	late Pliocene	2.80	304	415
731A-30X-2, 83–85 cm	282.23	Calcitic marly nannofossil chalk	3	early to middle Miocene	0.26	242	396
731A-30X-4, 80–82 cm	285.20	Nannofossil chalk	3	early to middle Miocene	0.07	n.d.	n.d.
731A-31X-CC(4–6 cm)	294.40	Marly nannofossil chalk	3	early to middle Miocene	0.02	n.d.	n.d.
731A-31X-CC(36–38 cm)	294.78	Nannofossil-bearing clayey siltstone	3	early to middle Miocene	0.08	n.d.	n.d.
731A-35X-CC(12–14 cm)	331.13	Nannofossil-bearing clayey siltstone	4	early to middle Miocene	0.07	n.d.	n.d.
731B-5X-1, 60–62 cm	448.00	Siltstone	4	early to middle Miocene	0.23	n.d.	n.d.
731C-2R-4, 74–76 cm	507.64	Calcitic silty claystone	4	early Miocene	0.04	n.d.	n.d.

Table 3. Lithology and organic geochemical results of Sites 723, 724, 726, 728, 729, and 730 samples (Oman Ridge).

Sample identification	Depth (mbsf)	Lithology	Unit	Stratigraphic age	TOC	HI	T_{max}
724A-1H-2, 122–124 cm	2.72	Calcareous clayey silt	1	Pleistocene	0.64	260	410
723A-1H-3, 0–2 cm	3.00	Calcareous clayey silt	1	Pleistocene	2.51	375	416
724A-4H-2, 71–73 cm	27.61	Calcareous clayey silt	1	Pleistocene	2.21	390	416
729A-4R-5, 0–2 cm	28.30	Nannofossil-bearing marly limestone	1 to 2	Eocene to Pleistocene	0.91	268	412
724A-4H-3, 71–73 cm	29.11	Calcareous clayey silt	1	Pleistocene	0.44	173	399
729A-4R-5, 85–87 cm	29.15	Nannofossil-bearing limestone	2	Eocene to Pleistocene	0.04	n.d.	n.d.
726A-4H-5, 20–22 cm	31.60	Foraminifer-bearing nannofossil ooze	1a	Pleistocene	0.34	560	394
726A-5H-1, 86–88 cm	35.76	Calcareous clayey silt	1b	Pleistocene	2.90	393	415
730A-5H-4, 109–111 cm	42.39	Diatomaceous silty clay		late Miocene	3.09	397	418
730A-5H-6, 109–111 cm	45.39	Diatomaceous marly nannofossil ooze		late Miocene	1.32	401	412
730A-7H-2, 130–132 cm	58.60	Diatomaceous silty clay		late Miocene	4.58	410	415
728A-16X-2, 30–32 cm	145.30	Marly nannofossil ooze		Pliocene	2.77	323	412
723A-25X-6, 25–27 cm	237.85	Calcareous clayey silt	1	Pleistocene	3.92	431	406
730A-26X-2, 40–42 cm	241.50	Marly nannofossil chalk		middle Miocene	0.31	315	406
730A-26X-5, 40–42 cm	246.00	Calcareous clayey silt		middle Miocene	0.94	304	406
728A-27X-4, 67–69 cm	254.97	Marly nannofossil ooze		Miocene	0.83	313	414
723A-28X-1, 86–88 cm	259.96	Calcareous clayey silt	1	Pleistocene	4.31	400	409
723A-29X-1, 57–59 cm	269.27	Calcareous clayey silt	1	Pleistocene	3.41	322	411
723A-33X-3, 65–67 cm	310.75	Marly nannofossil ooze	1	Pleistocene	5.17	430	407
723A-36X-4, 45–47 cm	331.25	Calcareous clayey silt	1	Pleistocene	4.69	448	409

Table 4. Optical evaluation of the petrographic composition of organic matter (transmitted light microscopy).

Sample identification	Depth (mbsf)	AOM	LF	USOM	MM
720A-1H-3, 130–132 cm	4.30	25	25	40	—
720A-11X-1, 10–12 cm	96.50	10	80	—	—
720A-24X-1, 106–108 cm	223.06	5	90	—	—
721A-1H-4, 70–72 cm	5.20	95	3	2	—
721A-9H-3, 105–107 cm	80.45	85	5	10	—
721B-22X-2, 140–142 cm	204.90	95	trace	2–5	—
721B-34X-5, 64–66 cm	324.64	—	trace	trace	—
721B-36X-CC (34–36 cm)	347.00	—	—	trace	—
721B-38X-2, 57–59 cm	358.67	—	—	—	—
722A-10X-3, 14–16 cm	89.64	98	trace	2	—
722B-49X-1, 83–85 cm	460.23	—	—	trace	—
723A-1H-3, 0–2 cm	3.00	70	trace	30	—
723A-25X-6, 25–27 cm	237.85	99	trace	trace	—
723A-28X-1, 86–88 cm	259.96	99	trace	trace	—
723A-29X-1, 57–59 cm	269.27	99	trace	trace	—
723A-33X-3, 65–67 cm	310.75	99	trace	trace	trace
723A-36X-4, 45–47 cm	331.25	99	trace	trace	—
724A-4H-2, 71–73 cm	27.61	96	2	2	—
724A-4H-3, 71–73 cm	29.11	97	trace	2	trace
726A-4H-5, 20–22 cm	31.60	97	trace	trace	—
726A-5H-1, 86–88 cm	35.76	97	2	—	—
729A-4R-5, 0–2 cm	28.30	60	trace	40	trace
729A-4R-5, 85–87 cm	29.15	—	—	—	—
730A-5H-4, 109–111 cm	42.39	80	—	20	trace
730A-5H-6, 109–111 cm	45.39	80	—	20	trace
730A-26X-2, 40–42 cm	241.50	80	—	20	trace
730A-26X-5, 40–42 cm	246.00	80	—	20	trace

AOM = Amorphous Organic Matter, LF = Lignaceous fragments, USOM = Undetermined Structured Organic Matter (alveolate microplankton, membranous fragments, and other incertae sedis), MM = Marine Microfossils (microplankton and microbenthos).

In Oman margin cores, almost all the samples show values higher than 300 mg HC/g TOC with a maximum at 448 if only the samples with TOC over 1% are considered. As for Indus Fan and Owen Ridge sediments, T_{max} ranging from 406° to 418°C (samples with TOC over 1%) indicate a low thermal maturation level.

Petrographic Analysis of Kerogen

Due to very low TOC, only three samples from Indus fan gave enough residue to be optically studied. Terrestrial organic matter (lignaceous fragments, spores and pollen; Pl. 1, Figs. 1–4) is the main organic component for samples from Unit 2 (Site 720). It is associated with a minor amount of amorphous organic matter and with abundant pyrite microcrystals or epigenized pyrite from lignaceous fragments. Some of the lignaceous fragments are fusinized (transformed in fusinite particles by early oxidation, mainly before deposition).

The sample from Unit 1 of Site 720, located near the top of the sedimentary column (4.3 mbsf), reveals a more marine organic composition according to the lithology of this unit (mainly foraminifer bearing nannofossils oozes). This composition is characterized by a higher proportion of amorphous organic matter than in deeper samples and by the presence of dinoflagellates, while 40% of the residue occurs as structured marine organic matter, mainly comprised of alveolate microplankton, membrane fragments, and some incertae sedis. As they are not precisely determined, we called them USOM. Amorphous organic matter is predominant (85%–98%) in the total residues from Owen Ridge upper sediments. No benthic and pelagic organic microfossils were observed. However, some radiolarian tests, totally transformed in pyrite, are present in total residues, but not in second residues. Therefore, they do not appear in the quantitative evaluation (Table 4). The recovery of organic residues from Owen Ridge lower sediments is too poor to allow their optical study.

The predominance of amorphous organic matter is the main character of residues from the Oman Margin samples (Pl. I, Figs. 5, 6). In many cases, the residue is almost totally composed of AOM. Nevertheless, the optical aspect of this component is not the same for all the sites. Indeed, AOM appears well aggregated (flaky), yellow-brown, and granular textured in residues from more seaward and deeper Sites 723, 729, and 730, while it appears disseminated and grey-brown in residues from more landward Sites 724 and 726.

Marine microfossils are rare at Sites 723, 724, and 726 and more frequent at Sites 729 and 730 (dinoflagellates, chitinous microforaminifers, scolecodonts, and epiderm fragments; Pl. 2, Figs. 3–7). This is probably due to the fact that these latter are further away from the continent than the others.

Undetermined structured organic matter is abundant in Miocene samples at Sites 729 and 730 (20%–40%), and in the uppermost Pleistocene sample of Site 723 (30%). In this sample, USOM mainly occurs as brown alveolate particles (Pl. 2, Figs. 1, 2), characterized as microplankton by Caratini et al., (1978). Pyrite is rare, showing sometimes dodecahedric crystals in SEM investigations. However, although rare in total residues, pyrite exists in whole sediment.

DISCUSSION—AMOUNT, TYPE, AND PRESERVATION OF ORGANIC MATTER

Indus Fan (Site 720)

Any generalization for the Indus Fan Pleistocene sediments is limited because of the small number of the samples in our study. Some trends can be noticed. Organic matter is mainly terrestrial (lignaceous fragments), in agreement with the predominant sedimentary supply of sediments, and occurs in very small amounts. These low amounts cannot be explained by dilution of continental organic matter by the mineral matrix because they have probably the same origin (mainly Indus River). Their relative proportions should be initially determined in the suspended matter of Indus River. However, low amounts of marine organic matter relative to continental organic matter are probably a consequence of the dilution by the continental organic input.

Other phenomena can also occur such as organic matter oxidation during transportation and/or early diagenetic processes, as showed by the occurrence of fusinite particles and lignaceous fragments transformed in pyrite. Intense epigenization of lignaceous fragments in pyrite suggests that a significant part of the deposited organic matter has been removed by bacterial sulfate-reducing activity and were thus not or poorly oxidized (fusinized) during transportation.

Owen Ridge (Sites 721, 722, and 731)

Our results identify two phases of sedimentation of the organic matter in the Owen Ridge area. The older phase (early to middle Miocene) is characterized by very small amounts of organic carbon, often < 0.1%. These low TOC concentrations prevent determination of the petrographic type of organic matter. The younger phase (early Pliocene to Pleistocene) is characterized by relatively high TOC (up to 3.45%) and HI (350–450 mg HC/g TOC) and by a predominance of amorphous organic matter, which indicates a probable marine origin. These two phases correspond to lithostratigraphic units where a hemipelagic to pelagic series (middle Miocene to Pleistocene) follows a more detrital series (Oligocene to early or middle Miocene). In both types, sediments are weakly to moderately bioturbated, suggesting that the activity of benthic organisms is not an important factor in the TOC control. We assume that, during the older phase, the autochthonous marine organic matter was strongly diluted by Indus sediments. Indeed, according to the most active stage of the Himalayan uplift, the sedimentation rates of the Indus Fan were very high during this period (Whitmarsh, Weser, et al., 1974). During the younger phase, the Owen Ridge would have constituted a topographic obstacle for the Indus sediments (Stewart et al., 1965), so that calcareous pelagic sediments accumulated with relatively high amounts of marine organic matter. This does not preclude changes in the oceanic surface conditions and productivity as complementary factors in the control of both TOC and organic matter type.

Rock Eval results of Site 731 upper units show lower hydrogen indices than the other sites of Owen Ridge area (Table 2). In both cases, the organic matter is mainly amorphous. The HI difference may indicate that the Site 731 organic content has undergone more alteration than the other sites. The nature and origin of this alteration have not been identified, but could be related to the deeper location of Site 731 at the base of the ridge. Reimers and Suess (1983), studying fluctuations in the cycling of organic matter off Central Peru, proposed that elemental composition of kerogen could depend on the time that detrital particles are exposed to the bottom waters. Our hypothesis is consistent with the low accumulation rates of Site 731 upper sediments, due to the lack of turbidites, and to more oxidizing deep bottom waters.

Oman Margin (Sites 723, 724, 726, 728, 729, and 730)

The organic facies in the Oman Margin sediments have a strong dominance of amorphous organic matter with high HI, indicating a probable marine autochthonous origin. This observation, in conjunction with relatively high TOC, is consistent with the fact that sediments were deposited under a zone of enhanced surface productivity, due to a coastal upwelling regime, and that seafloor areas were probably within a depleted oxygen zone (Prell, Niitsuma, et al., 1989; Summerhayes, 1983). In addition, sediments received only a small continental contribution from the nearby dry Arabian coasts as seen either by the general lithology (mainly pelagic to hemipelagic facies) and by organic facies (no or very few lignaceous fragments). Does the amount, type, and preservation of organic matter reveal changes in environmental conditions that occurred during Neogene times? Some trends can be noticed, but the limited number of samples per site does not allow a reconstitution of the sequence of the events.

The lowest TOC values are mostly associated with bioturbated (Sites 728 and 730) or shell-bearing levels (Sites 724 and 729), whereas highest values are mainly associated with homogeneous or laminated levels (Sites 723). The activity of benthic organisms, as an indicator of the oxygenation of bottom waters, seems to control closely the concentration of organic matter. However, large variations in TOC values occur within bioturbated levels, such as in levels described as "weakly bioturbated" where TOC range from 0.34% to 4.58% (Sites 730, 724, and 726). The existence of high TOC in some bioturbated levels means that the supply of organic matter to the bottom was much greater than that which could be removed by benthic and bacterial activities. Hence, preservation was enhanced. For example, high-TOC episodes can be obtained at the beginning of intense short-term production increases due to upwelling regime (Summerhayes, 1983) by rapid sinking of fecal pellets, while bottom waters were still oxygenated.

Whatever the intensity of bioturbation may be, the organic facies is strongly dominated by amorphous organic matter occurrence (undetermined structured organic matter, although sometimes abundant, does not correlate with the intensity of bioturbation). This suggests that the loss of structure is due to very early bacterial activity within the sedimentary column, thus acting as a second control for concentration of organic matter. The occurrence of well-preserved USOM together with dominant non-structured organic matter would be due to the nature of material (for example, chitinous fragments), rather than to changes in early diagenetic processes. Indeed, in addition to its morphological preservation, USOM does not appear to be associated with pyrite (Pl. 2, Figs. 1, 2). "Alveolate" microplankton that was observed in some samples could be made of a resistant biopolymer such as PRB (Polymére Résistant de Botryococcus, Berkaloff et al., 1983) in planktonic algae, that has not been affected by chemical or bacterial effects. Other optical and SEM studies on marine sediments (unpublished) reveal that lower TOC levels contain higher amounts of benthic and pelagic forms of organic matter relatively to amorphous organic matter, that is consistent with a better resistance of the undetermined structured organic matter and some of the marine organic microfossils to oxidation processes.

Based on organic petrographic compositions, some regional trends have been observed in the Oman Margin sediments. Sites 728, 729, and 730 located away from the continent have an organic carbon content generally lower than those situated nearer the coast (Sites 723, 724, and 726), regardless of the age of sediments. Moreover they have a higher contribution of benthic and pelagic forms of organic matter relative to amorphous fraction than the others. If the OMZ extension has changed little during Neogene times, this difference could be related to the present location of the sites. Thus, Sites 728, 729, and 730 sediments would have been subjected to more oxidizing conditions due to their depth. On the other hand, shallower more organic-rich sediments (Sites 723, 724, and 726), which contain greater organic content variations, could result from weak OMZ fluctuations prevailing only on the continental margin.

CONCLUSION

The petrographic and geochemical results obtained from North Indian Ocean sediments, as representing different open ocean sedimentation environments, allow the following conclusions.

1. High amounts of organic matter are mainly due to a good preservation of amorphous marine organic matter, such as in Oman Margin sediments and in upper pelagic levels of Indus Fan and Owen Ridge deposits.
2. In contrast, low amounts of organic matter are correlated with low relative amounts of this amorphous organic matter, thus leading to a relative enrichment in lignaceous fragments (Indus Fan) and marine figured organic matter (Oman Margin).
3. The petrographic components of lowest TOC levels are made of resistant materials (lignin for lignaceous fragments, chitin, or other polymers for benthic clasts and "alveolate" microplankton).
4. Indus Fan autochthonous organic content is mainly controlled by dilution due to the detrital input. Some oxidation of continental organic material should occur probably before deposition, but the high amount of pyritized fragments suggests that hydrolyzable organic matter was well preserved permitting the sulfate-reducing activity to take place.
5. The whole Oman Margin organic content is autochthonous and lowest TOC levels are characterized by lowest marine amorphous organic matter concentrations. In this case, the marine microfossils and the undetermined structured organic matter represent a residual organic matter.

ACKNOWLEDGMENTS

We are indebted to Ocean Drilling Program for providing samples. Technical assistance by Françoise Champion (petrographic preparation) and Jean Simonato (SEM) is gratefully acknowledged.

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Date of initial receipt: 13 February 1990
Date of acceptance: 21 March 1990
Ms 117B-191

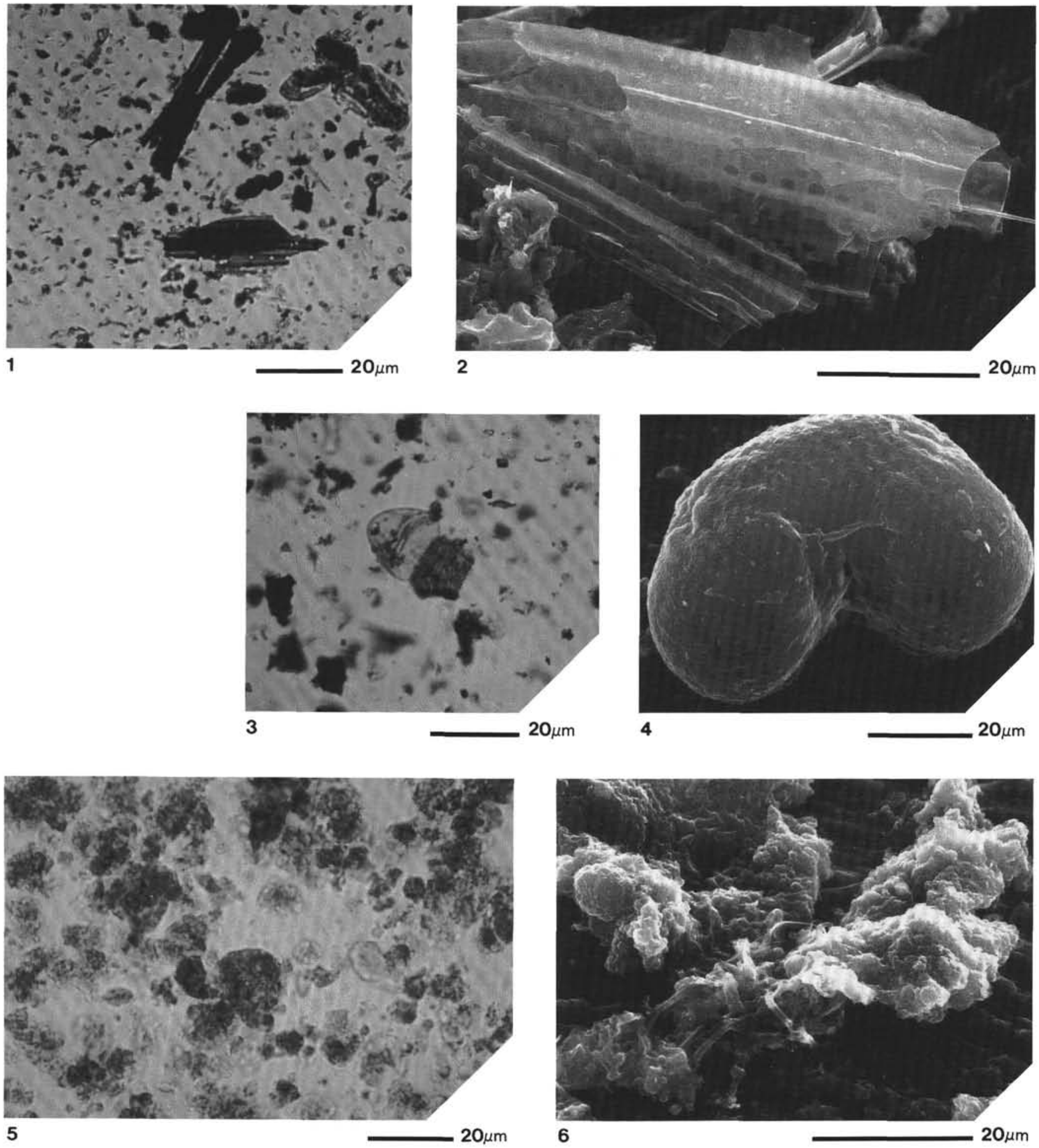

Plate 1. Organic components from North Indian Ocean sediments. **1.** Transmitted light view showing lignaceous fragments: Indus Fan sediment. 720A-24X-1, 106–108 cm. **2.** SEM observation of the same material, showing typical cellular structure: Indus Fan sediment. 720A-24X-1, 104–108 cm. **3.** Transmitted light view of a palynomorph: Indus Fan sediment. 720A-11X-1, 10–12 cm. **4.** SEM view of a gymnosperm pollen: Indus Fan sediment. 720A-1H-1, 130–132 cm. **5.** Transmitted light view of amorphous organic matter: Oman Margin sediment. 723A-28X-1, 86–88 cm. **6.** SEM view of amorphous organic matter and dinoflagellate. Oman Margin sediment: 724A-4H-3, 71–73 cm.

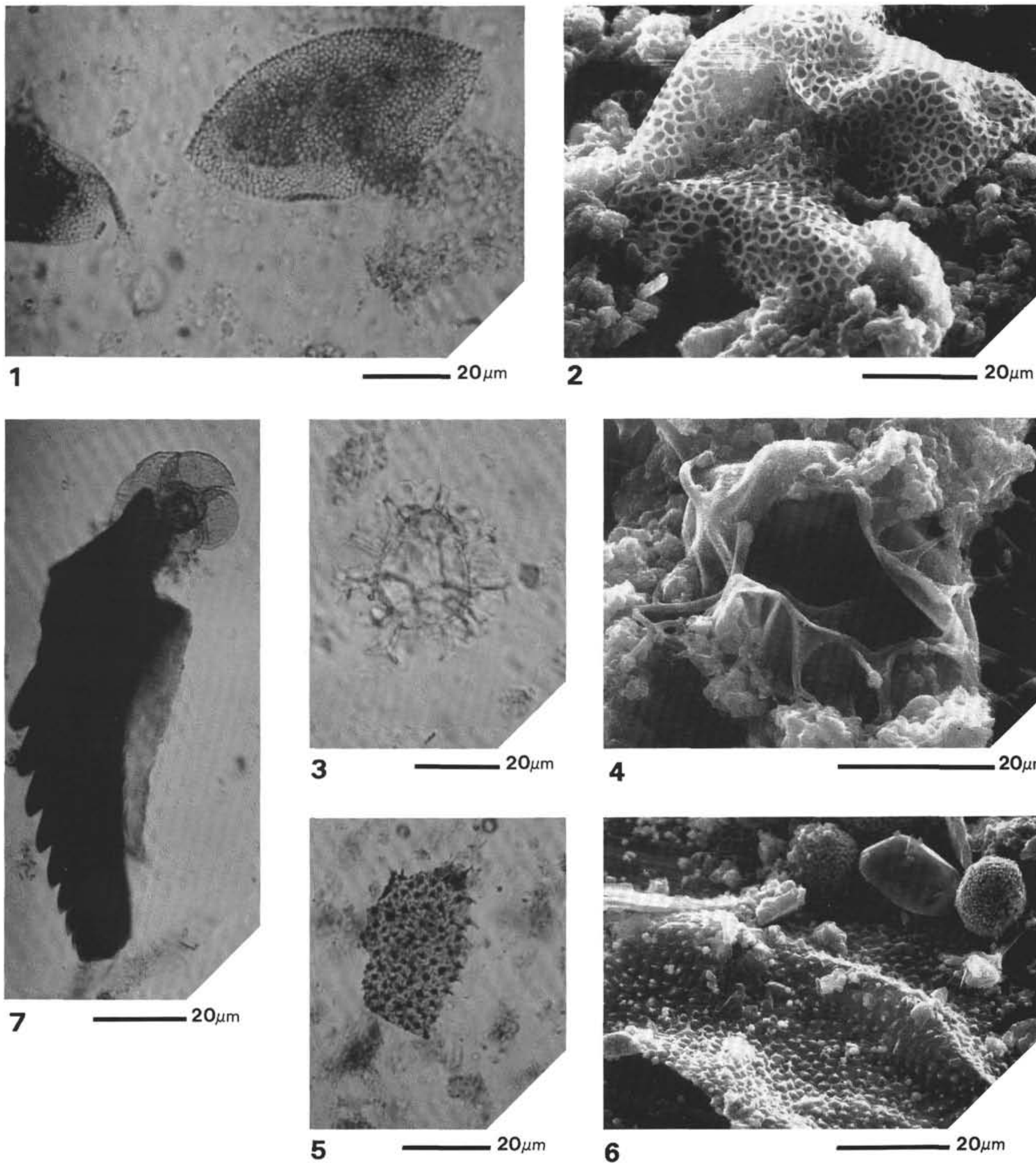

Plate 2. Marine formed organic matter from Oman Margin and upper Indus Fan sediments. **1.** Transmitted light view of "alveolate" microplankton associated with amorphous organic matter: Oman Margin sediment. 723A-1H-3, 0–2 cm. **2.** SEM observation of the same sample. **3.** Dinoflagellate in transmitted light microscopy. 723A-1H-3, 0–2 cm. **4.** SEM view of dinoflagellate associated with amorphous organic matter. 724A-4H-2, 71–73 cm. **5.** Transmitted light view of an epiderm fragment, 730A-26X-2, 40–42 cm. **6.** SEM view of an epiderm fragment, 720A-1H-3, 130–132 cm. **7.** Transmitted light view of scolecodont and microforaminifer. 730A-26X-2, 40–42 cm.