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Notes

Hemipelagites: processes, facies and model

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Abstract: Detailed sedimentological studies have been carried out on Pleistocene to Recent sediments from the Makran margin and on Miocene to Recent sediments from the Oman margin of the NW Indian Ocean. In both areas, hemipelagites make up c. 50% of the succession, being closely interbedded with turbidites (Makran) and pelagites (Oman). Their sedimentary features (structure, texture, fabric and composition), bedding style and rates of sedimentation are reported and compared with previous detailed studies of both modern and ancient hemipelagites. A composite facies model is presented. Hemipelagites are fine-grained sediments typically occurring in deep-water settings. They generally comprise an admixture of >10% biogenic pelagic material and >10% terrigenous or volcanigenic material, in which >40% of the terrigenous (volcanigenic) fraction is silt size or greater (i.e. >4 µm). They are deposited by a combination of vertical settling and slow lateral advection. Hemipelagites are mostly thoroughly bioturbated with ichnofossils including *Zoophycos*, *Planolites*, *Chondrites*, *Phycosiphon* and others. They are generally devoid of primary sedimentary structures, except for an organic-rich facies deposited in anoxic conditions which has a distinctive fissile lamination. The submicroscopic fabric is closely packed with subparallel alignment of clays. The grain size is strongly influenced by the composition, although in general the deposits are fine grained (mean size 5–35 µm), and poorly sorted, in some cases with bimodal, trimodal or polymodal grain-size distributions. The composition includes a biogenic fraction that is calcareous and/or siliceous, and a terrigenous fraction dependent on the nature of the supply pathway, i.e. river plumes, aeolian dust, glacial input or volcanoclastic fallout. Chemogenic components (phosphorites, glauconite, ferromanganese nodules) are common in some settings, whereas high organic carbon contents characterize others. Cyclic bedding, typical of climatic forcing, is common although bed boundaries are generally very gradational. Sedimentation rates typically vary from <5 cm/ka to >20 cm/ka and greatly influence development of the different characteristics outlined above. Extremely high rates (>100 cm/ka) occur in zones of hemipelagic sediment focusing, such as slope canyon systems and sediment pathways.

Hemipelagites are fine-grained sediments comprising mixtures of biogenic and terrigenous material that have been deposited by a combination of vertical (pelagic) settling and slow lateral advection. They include muddy oozes, calcareous and siliceous muds or marls, as well as organic-rich, volcanoclastic-rich and glacial-rich muds, and are very widespread in most deep-sea environments, especially those close to continental margins. An estimated 20% of the present-day sea floor is composed of hemipelagites.

Although hemipelagites are widely recognized, the only general facies model to have been proposed so far is that of Stow (1982, 1985a,b, 1986). This is a very rudimentary model that does not fully represent the variety of hemipelagic facies that exist, nor the complex interplay of processes involved in their sedimentation.

The aim of this paper, therefore, is threefold: (1) to report on very detailed studies carried out

on two continental margin systems in the NW Indian Ocean in which contrasting styles of hemipelagic sedimentation are important; (2) to review briefly a number of previous studies on modern and ancient hemipelagites; (3) to present a composite facies model for hemipelagites.

Methods

The detailed studies of hemipelagites from the Makran and Oman margins were carried out by one of us (A. R. Tabrez) as part of a PhD thesis at the University of Southampton. Cores were all described, photographed and X-radiographed, and then subsampled for laboratory analysis. Standard techniques were used throughout (e.g. Tucker 1989) and have been reported more fully by Tabrez (1995).

Grain-size analysis of over 350 samples was carried out using a Malvern 2600 Particle Analyser, with a focal length of 100 mm. Bulk

sediment analysis of dried and powdered samples, followed by clay mineral analysis of the <2 µm fraction, was carried out on 175 samples by X-ray diffraction. A Philips 1730 X-ray Diffractometer was used with Cu radiation and Ni filtering, at 35 mA, 40 kV and 1.7°/min scanning speed. Further compositional studies utilized conventional petrographic techniques on smear slides, grain mounts and washed residues. Sediment fabric was examined and characterized on a limited number of samples (<20) using a JEOL 6400 Scanning Electron Microscope. An additional 300 samples were analysed for both inorganic carbonate and organic carbon–hydrogen–nitrogen using a Carlo Elba EA 1108 Elemental Analyser.

Makran margin hemipelagites

General setting

The Makran continental margin in the Gulf of Oman (Fig. 1) forms the seaward extremity of an accretionary sediment prism which extends several hundred kilometres inland (Minshull & White 1989). The Makran accretionary complex marks a zone of convergence between oceanic lithosphere of the Arabian plate and continental lithosphere of the Eurasian plate, which has resulted in an irregular stepped slope

morphology of basins and part basins separated by intervening structural highs or ridges that represent the seaward edge of a series of imbricate thrust slices (Fig. 2).

Between the uplifted ridges, the basins are filled with sediment, the amount of infill generally increasing towards the coast. The sediment in the basins is derived partly from reworking of the material of the ridges, and partly from the surrounding land masses of Arabia and the Makran. The complex morphology and active nature of the margin has resulted in a series of channel-like pathways connecting the basins rather than any distinct erosive channels. Both low-density turbidity currents and slow hemipelagic advection are believed to follow these downslope pathways, although hemipelagic dispersion is widespread over the intervening highs as well.

Five piston cores, MKM-468, MKM-469, MKM-470, MKM-471 and MKM-472, were recovered in water depths of between 1325 and 3274 m. They form a single N–S transect along the line of the seismic section described by White (1982) (Figs 1 and 2). They range in length from 5.5 to 14 m and provide a complete late Quaternary–Holocene succession back to about 26 ka (core 469). Tabrez (1995) was able to correlate and date the cores on the basis of lithostratigraphy, oxygen isotope analysis and magnetostratigraphy.

Sediment facies and structures

The principal facies present are closely interbedded fine-grained turbidites and hemipelagites, each making up between 40% and 60% of the cores examined. True pelagites are present only at the deepest site and make up 10–15% of Core 472. Hemipelagite units can be distinguished from the intervening turbidites on the basis of texture, composition, sedimentary structures and colour. The hemipelagites consist of a foraminiferal and nannofossil biogenic fraction, and terrigenous silty clays of similar composition to the turbidites. They are apparently fully homogenized and mottled by bioturbation, although distinct burrow traces are not very common. Sediment colour varies from olive grey to pale grey. The upper parts of hemipelagic units are typically rich in foraminifera and nannofossils, with indistinct bioturbation. The lower bedding contacts with underlying turbidites are gradational whereas the base of overlying turbidites is sharp. No lamination or other primary sedimentary structures are evident. Bed thickness ranges from 5 cm to 50 cm.

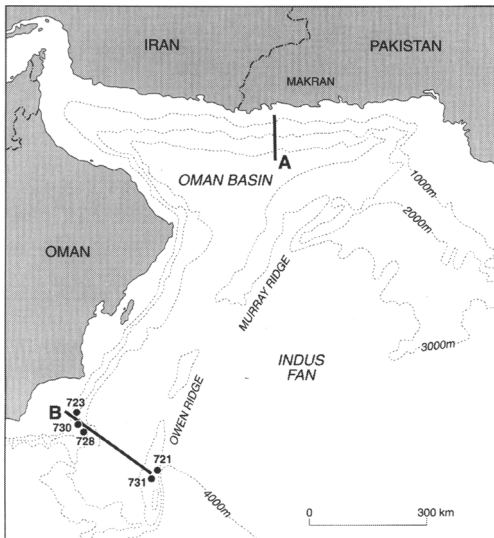


Fig. 1. General setting and bathymetry of the NW Indian Ocean showing line of transect across the Makran margin (line A; see Fig. 2), along which cores MKM-468 – MKM-472 were taken, and transect across the Oman margin (line B; see Fig. 5), along which ODP Leg 117 sites were located.

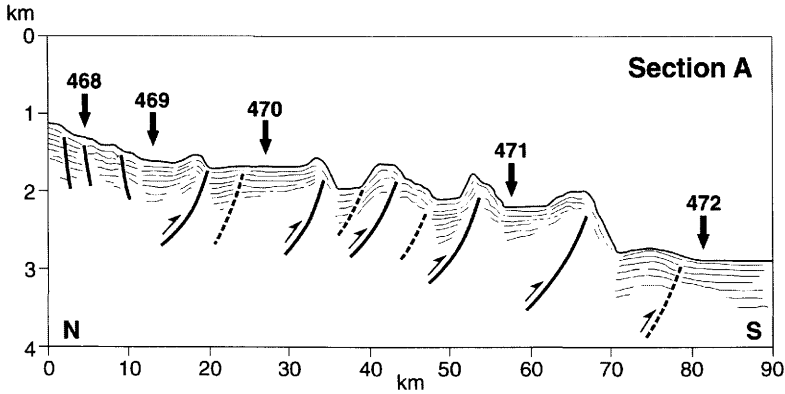


Fig. 2. Line drawing interpretations of seismic profile from White (1982) across the Makran margin, showing locations of core sites MKM-468–MKM-472. Depths are recalculated to below sea level. Location of section A is shown in Fig. 1.

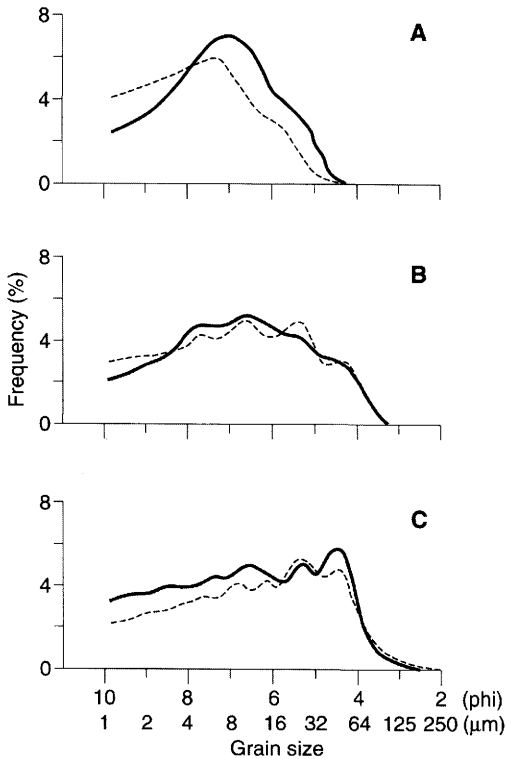


Fig. 3. Selected grain-size distribution smoothed frequency curves from hemipelagites in cores MKM-469 and MKM-472. The three main types of grain-size distribution are illustrated: (a) very fine silt–clay median size, unimodal; (b) fine silt median, irregular or slightly bimodal; (c) fine to medium silt median, irregular to polymodal.

Grain-size characteristics

The median grain size of all hemipelagite samples analysed varies between about 5 μm and 15 μm , and for most of these samples lies within the narrower range of 5–10 μm . The mean grain-size values tend to be slightly higher, typically 7–16 μm , and range up to 27 μm . Sorting is generally very poor. Most samples show slight to moderate positive skewness.

The variation in shape of the grain-size distribution curves is illustrated for cores MKM-469 and MKM-472 (Fig 3a and b). Three types are evident: (1) sediments with a relatively fine median grain size (i.e. 5–8 μm), which present a unimodal distribution with a peak between 5 and 8 μm ; (2) sediments with coarser median grain size (8–15 μm) with either bimodal or less regular distributions; (3) sediments with a median grain size up to about 20 μm and a polymodal distribution in which individual peaks are more or less distinct from the background curve at values of about 5, 10, 30 and 40 μm . In all three cases, the apparent ‘peak’ at 0.5 μm is due to summation of all the finer grain sizes as the lower limit of grain-size measurement was 0.5 μm .

The vertical variation of grain-size properties, for hemipelagites analysed throughout each of the five cored intervals, is extremely interesting. This is most clearly illustrated by median grain-size variation shown in Fig. 4. Three features are noteworthy. First, there is a zone of minimum grain size between 2 and 3 m depth in cores MKM-468, -469 and -470, and between 7 and 10 m in cores MKM-471 and -472. The median grain size shows a general decrease up to this level from the base of the cores and then an increase upwards from this minimum zone.

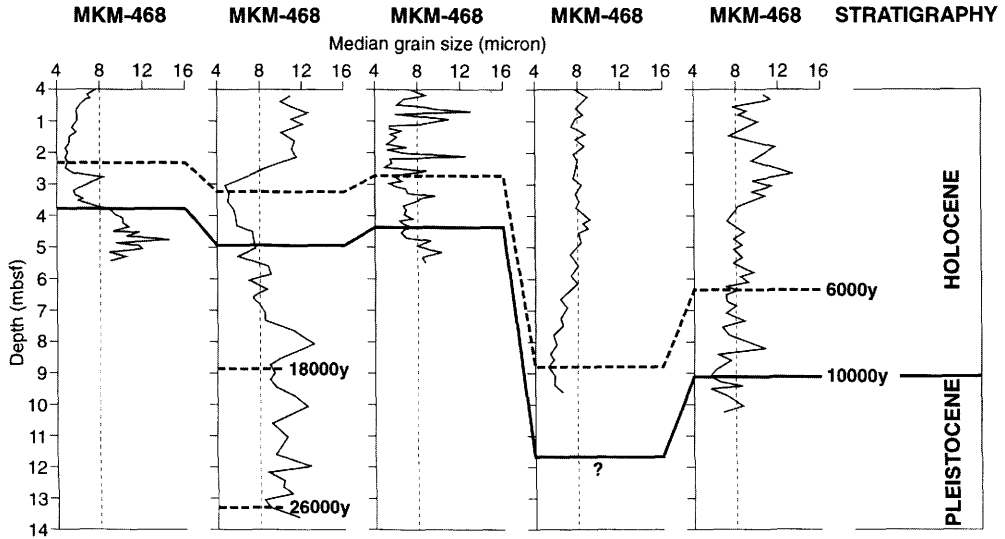


Fig. 4. Plots of median grain size v. depth for all Makran margin cores. Depths in metres below sea floor (mbsf). The grain-size low apparent in most cores is shown correlated with a dashed line and has been dated at around 6000 a BP. The Holocene–Pleistocene boundary was determined principally from oxygen isotope analysis of foraminifera from cores MKM-469 and MKM-472, as were the other ages indicated on the longer section of MKM-469. (See Tabrez (1995) for full details.)

Second, there is a small-scale oscillation or cyclicity of median grain size evident on a vertical scale of 0.2–1.0 m. Third, this oscillation is particularly marked, with variation in median grain size of 4–6 μm , only at certain horizons in each of the cores. The uppermost 2.5 m of section in core MKM-468 does not show this cyclicity.

If the grain-size oscillation is smoothed, then the average values for median or mean grain size might be expected to show some consistent variation with distance from shore. The innermost (i.e. shoreward) sites, MKM-468 and -469, both show smoothed average values between 5 and 11 μm ; the two slope basin sites, MKM-470 and -471, show average values of 6–8 μm ; and

the abyssal plain site, MKM-472, values of 7–10 μm . No clearcut pattern is evident.

Composition

The composition of both hemipelagites and turbidites, based on smear-slide analysis of over 100 samples, is shown in Table 1. The main components of hemipelagites typically include 60–80% terrigenous material (quartz, feldspars and clays being dominant) and 20–40% biogenic material (mainly nannofossils). The main terrigenous components of the interbedded turbidites are very similar to those of the hemipelagites, but the biogenic fraction is notably less. Non-specific calcite, which could be

Table 1. Composition of Makran margin sediments; per cent estimates from smear slides

	Hemipelagites	Turbidites
Quartz	15–40	30–40
Feldspar	1–10	10–15
Non-specific calcite	5–25	15–20
Dolomite	1–3	<1
Opaques	<1	<1
Terrigenous silt and clay	20–30	20–30
Nannofossils	20–50	1–5
Foraminifera	<5	<2
Other biogenic material	<5	<1

derived from land or from fragmented biogenic material, is a significant component of both facies. Generally, there is very uniform composition between sites, but there are marked vertical changes in hemipelagite composition coincident with grain-size change. There is a decrease in terrigenous and increase in nanofossil content coincident with finer grain size.

The clay mineral assemblage identified by X-ray diffraction (XRD) analysis includes illite, kaolinite, chlorite and a small amount of smectite. There is no apparent change in this mineralogy either within or between cores, and there is only very slight variation in the relative amounts of these clays recorded between samples, although this shows no consistent pattern and is well within the bounds of analytical error. A sample from a mud volcano present in the Makran coastal region was also analysed and revealed exactly the same clay mineralogy.

Organic carbon contents in all facies are low, ranging from 0.06 to 1.33%. The higher values are found in hemipelagites from core MKM-468. Other sites of mid-slope basins and the abyssal plain show lower values. The CaCO_3 content is in the range of 15–20%, with lower values from the slope region and higher values in hemipelagites of cores 468 and 472.

Oman margin hemipelagites

General setting

The Oman margin is a complex, stepped divergent margin directly off the narrow Oman shelf (Fig. 5). The Owen Ridge originally formed as a component of the Oman slope-apron system but is now separated from it by the narrow oceanic Oman Basin. Superficially, the morphology of this margin is similar to that of the Makran margin and comprises a series of slope basins and partial basins separated by structural highs (Figs 1 and 5). These latter are remnant highs from the rift break-up of the margin rather than thrust slices, and tectonic activity has remained very low during at least the Neogene (White & Loudon 1982; Minishull *et al.* 1992).

The Oman outer shelf and upper slope is currently a region affected by seasonal (monsoon-induced) upwelling and associated high primary productivity. An expanded oxygen-minimum zone within the water column has periodically been well developed and has impinged on the sea floor in the upper-slope region (Fig. 5), thereby affecting the activity of macrobenthos and the preservation of organic carbon in the sediments.

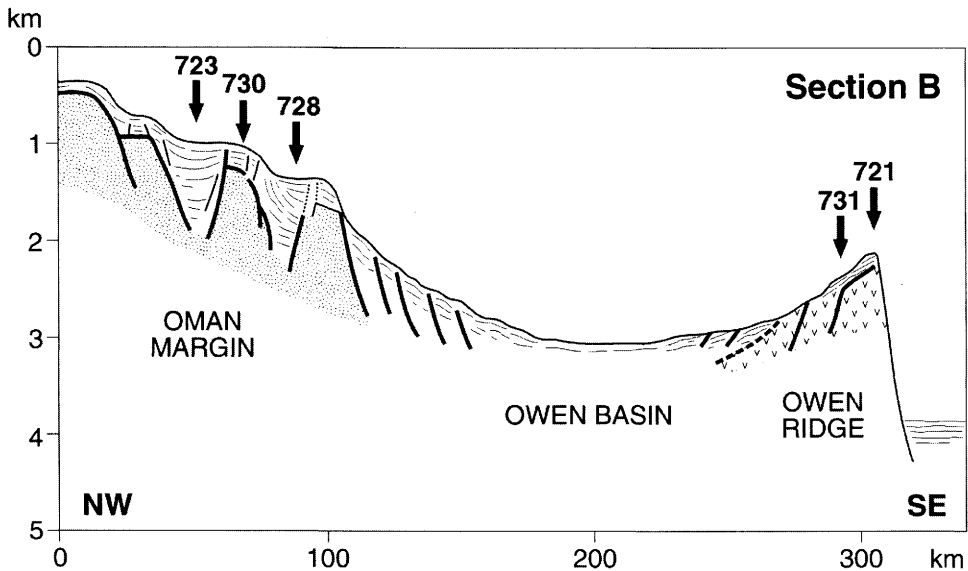
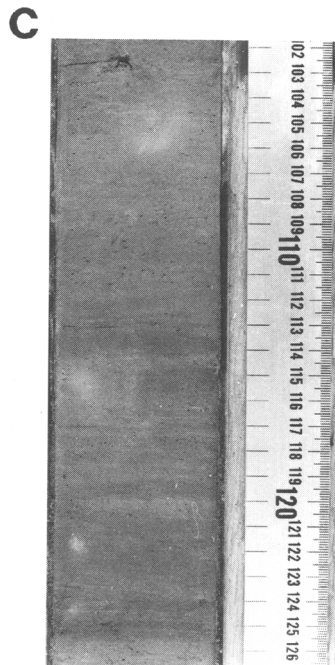
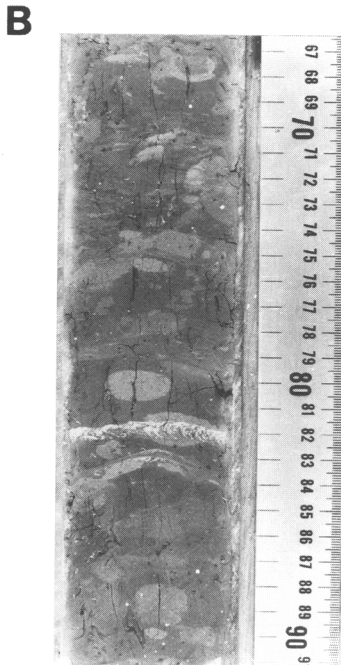
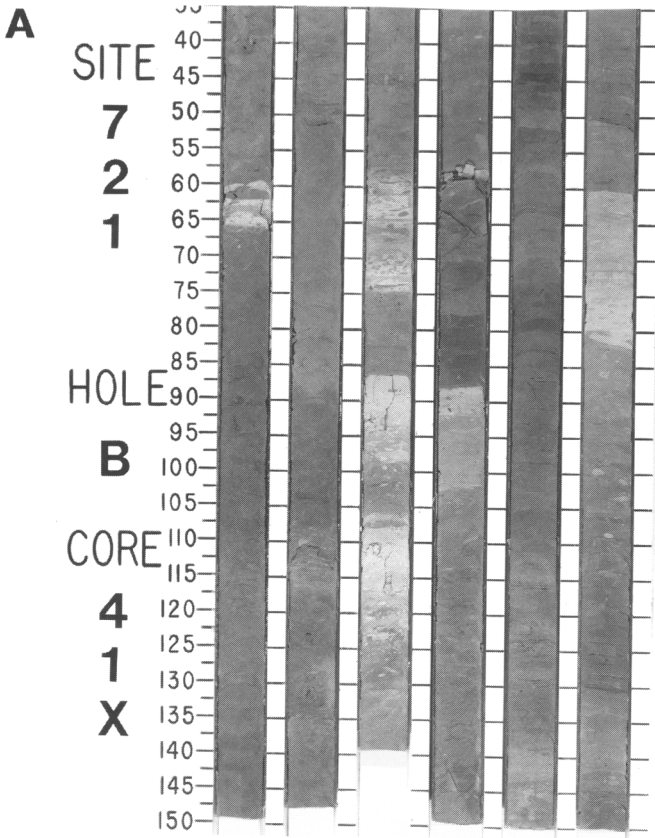


Fig. 5. Line drawing interpretation of seismic profiles from ODP Leg 117 showing a transect across the Oman margin and Owen Ridge. Locations of sites used for this study are shown. Location of section B is shown in Fig. 1.



This study has utilized existing cores from Ocean Drilling Program (ODP) Leg 117, drilled along a cross-margin slope transect similar to that across the Makran margin (Prell *et al.* 1989). Five sites were selected for detailed study, including three sites (723, 728 and 730) from the Oman margin, and two sites (721 and 731) from the Owen Ridge (Figs 1 and 5). Selection was based on site distribution, good core recovery and on the occurrence of a range of different facies. Core sections from each of these sites have been redescribed by one of the authors (A. R. Tabrez) at the ODP core repository, College Station, Texas, and c. 500 samples were taken for subsequent analysis. Smear slides were also made where the required amount of sample was not available. The age of the succession has been determined by detailed micropalaeontological studies as early Miocene to Recent (Prell *et al.* 1989).

Sediment facies and structures

Hemipelagites and pelagites are the dominant facies on this margin, generally occurring as alternating layers of light, carbonate-rich intervals and darker, clay- and organic-rich intervals (Fig. 6). The lithological units described by Prell *et al.* (1989) are calcareous ooze and clayey silts, which were deposited under the influence of monsoonal-induced upwelling and the related oxygen minimum zone. Each of the selected sites shows a particular variation in lithology that reflects the different settings as well as oceanographic conditions. The upwelling conditions have led to a rather more varied suite of hemipelagite facies and structures than observed on the Makran margin. These fall into three main facies groups: (1) laminated oozes–muddy oozes with faint to well-defined parallel lamination (millimetre to centimetre scale) and minor, small-scale bioturbation (Fig. 6a); (2) bioturbated oozes–muddy oozes with moderate to intense bioturbation; distinct burrow types including *Chondrites*, *Planolites*, *Zoophycos* and *Trichichnus* can be recognized together with a well-developed three-tier ichnofossil distribution in some cases (Fig. 6c); (3) chaotic oozes–muddy oozes in which the original laminated or bioturbated structure has been modified by slumping (Fig. 6b).

There is a complete gradation from intensely bioturbated to well-laminated facies as well as

from pure calcareous ooze (pelagite) to muddy ooze (hemipelagite). The laminated facies are less widespread than the bioturbated facies, and are best interpreted as the result of partial to complete suppression of a burrowing macrobenthos under low oxygen or anoxic bottom waters and a stratified water column. Both facies groups may be resedimented downslope via slumps and slides or turbidity currents.

Grain-size characteristics

Grain-size analysis of selected samples from different facies of the upper basin, lower basin and inter-basinal sites has been carried out. Each sample has been analysed twice to investigate different grain-size components; first, bulk samples were analysed to determine the overall grain-size distribution; second, the same samples were analysed after the removal of carbonate. In general, median values for bulk samples range between 5 and 31 μm , and mean values of the same samples are in the range of 13–47 μm . Sorting is moderate to poor. Removal of carbonate has different effects on different samples in that the median or mean size may be significantly decreased, remain about the same, or be increased. This clearly depends on the composition of the original sample: where nannofossils are the dominant carbonate component then dissolution tends to increase the mean size, whereas where foraminifers and/or coarse detrital carbonate are significant then the mean size may decrease on dissolution.

The different facies groups tend to show characteristic size distribution patterns as follows (Fig. 7):

(1) Unimodal distribution with long fine tail: very fine-grained input of nannofossils and fine clay, the latter probably from aeolian–fluvial suspension; typical of the laminated facies group.

(2) Unimodal or bimodal distribution or no distinct mode with broad spread of sizes, poorly sorted: input of nannofossils together with terrigenous material of probable aeolian and fluvial derivation; typical of the bioturbated facies group.

(3) Polymodal distribution, more or less distinctly peaked: input of nannofossils, mixed biogenic and terrigenous fraction with some foraminifera, probably reflecting greater influence of direct fluvial or reworked shelf input at lowered sea level; typical of slump facies group.

Fig. 6. Photographs of Oman margin cores showing typical hemipelagite facies. (a) Owen Ridge Site 721B, Core 41X, parts of Sections 1–6, depth scale in centimetres. (b) Detail of bioturbated ooze from Margin Site 728A, Core 29X, Section 1, scale in centimetres. (c) Detail of laminated ooze from Margin Site 723B, Core 4H, Section 2, scale in centimetres.

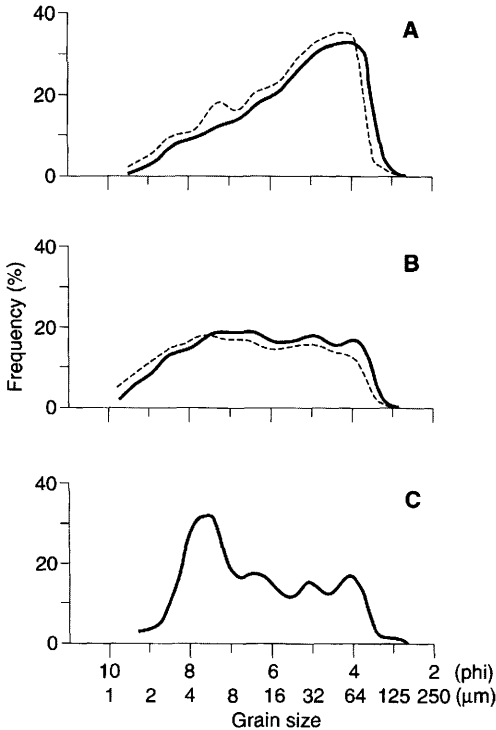


Fig. 7. Selected grain-size distribution smoothed frequency curves from the Oman margin hemipelagites. (a) Unimodal distribution typical of laminated facies; (b) irregular very poorly sorted distribution typical of bioturbated facies; (c) polymodal to irregular distribution typical of some bioturbated facies and of slump facies.

Composition

The principal components of the hemipelagic facies are shown in Table 2. There is a mixed terrigenous and biogenic composition, together with a relatively large broken calcite fraction (up to 20%), which may be fragmented biogenic material or terrigenous debris, or a mixture of both. Separation of the clay fraction and XRD

Table 2. Composition of Oman margin hemipelagic sediments; per cent estimates from smear slides

Quartz	10–15
Feldspar	2–5
Non-specific calcite	5–20
Dolomite	2–5
Opaques	<1
Silt-clay	20–30
Nannofossils	20–50
Foraminifera	<5–25
Diatoms	0–20

analysis shows a clay composition dominated by illite and chlorite, with variable amounts of palygorskite, smectite and mixed layer species.

Organic carbon contents (TOC; total organic carbon) vary widely both between sites on the margin and as a function of sedimentary facies. The highest TOC concentrations (*c.* 7%) occur in sporadic intervals at Site 723B, whereas the average organic carbon content for the laminated facies is 2–3% and for the bioturbated facies is <1%. The Owen Ridge sediments are moderately rich in organic matter, with organic carbon concentrations averaging 0.9–1.2% in the pelagic–hemipelagic sediments. The underlying turbidites typically contain <0.2% organic carbon.

CaCO₃ concentrations range from 36 to 94%. Comparatively higher percentages are noted in the distal slope basin. Most of the bioturbated facies show >70% CaCO₃, whereas the laminated and organic carbon rich facies show <70% CaCO₃.

Microfabric

Thirty samples were selected for microfabric studies using scanning electron microscopy (SEM) from representative facies at each core site. Some of the important features of sediment fabric are illustrated in Fig. 8. However, lack of resolution at these very fine grain sizes, even using high-power SEM backscatter images, precluded the obtaining of definitive results. Preliminary transmission electron microscopic studies were more promising, although this work is still in progress.

The following general observations and interpretations can be made:

(1) Randomly oriented particles in the laminated facies suggest deposition, in part, as flocs and at relatively high rates of sedimentation. Some intervals within the laminated facies show better orientation, suggesting periods of lower rates of sedimentation.

(2) Relatively more preferred orientation of fabric in the bioturbated facies suggests fewer flocs and lower rates of sedimentation. Areas with more random particle arrangements are interpreted to result from bioturbation.

(3) The preferred orientation observed in some slump horizons may result from particle reorientation by within-sediment slippage during downslope slide movement.

(4) In general, studies of the clay microfabric of these sediments are compatible with pelagic–hemipelagic settling of organic aggregates, clay flocs and silt particles (Bennett *et al.* 1991; O'Brien *et al.* 1980; Reynolds & Gorsline 1991).

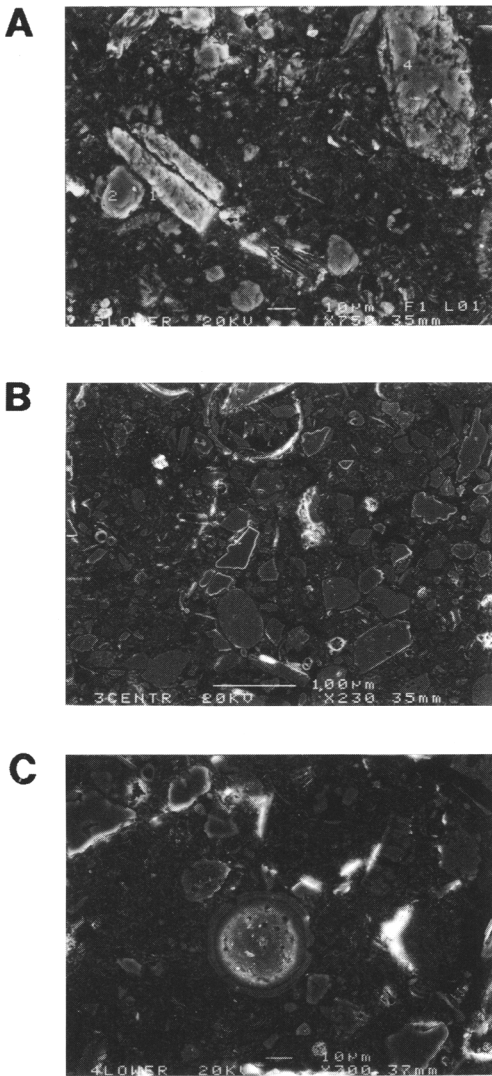


Fig. 8. Microfabric characteristics of Oman margin hemipelagites. Backscatter electron micrographs. Scale bars represent 10 or 100 μm as shown. (a) Minor bioturbation, weak parallel fabric; (b) parallel lamination and weak bioturbation, random fabric; (c) thorough bioturbation, random fabric.

Discussion

Although there are many studies of both modern and ancient deep-sea successions that refer to hemipelagites, often as the 'background' sediment within which the 'more interesting' sediments occur, there are relatively few detailed accounts of hemipelagic facies. Several of these are summarized below to illustrate the range that exists in both marginal and open

ocean settings and everywhere from high latitudes to the equator. Some are dominated by terrigenous input whereas others, especially those associated with upwelling systems, have abundant biogenic material together with preserved organic matter.

Modern examples

Nova Scotia Continental Slope. (Stanley *et al.* 1972; Hill 1984)

Setting: Passive margin, water depth 1000–5000 m, late Quaternary–Recent.

Structure: Bioturbated hemipelagic mud.
Texture: Poorly sorted coarse sandy mud and sandy-silty mud.

Composition: Sand fraction: quartz, glauconite and minor heavy minerals; dominant clays, minor biogenics material.

Sedimentation rate: Holocene (5 cm/ka), late glacial period (20 cm/ka).

Other features: Interbedded with fine-grained turbidites and influenced by bottom currents between 4 and 5 km depth.

Canadian Polar Continental Margin. (Hein *et al.* 1990)

Setting: Passive margin, water depth: 140–283 m, Tertiary–Recent.

Structure: Bioturbated and burrowed hemipelagic mud.

Texture: Pebbly sandy mud–clayey mud, poorly sorted.

Composition: Gravel–sand fraction: quartz, feldspar, augite, clinopyroxene, rock fragments, basalt, granite, etc; dominant clays, minor biogenics material.

Other features: Eight facies are recognized on this margin, of which only one is hemipelagic and the rest are generally of turbiditic origin. The hemipelagic facies contains ice-rafted meltout and fallout deposits.

Western Mediterranean Sea. (Rupke 1975)

Setting: Marginal ocean basin, water depth 2588–2719 m, late Quaternary.

Structure: Bioturbated–burrowed hemipelagic mud.

Texture: Average 8% sand, very poorly sorted mud.

Composition: Sand fraction: foraminifera and

- pteropods; CaCO₃: 35–40%; clays abundant.
- Sedimentation rate:** 23 cm/ka.
- Other features:** This abyssal plain basin is bordered by narrow shelves and slopes. Hemipelagic mud occurs at the surface of a thin sediment fill, which is estimated to be 300–400 m thick and to comprise mainly turbidites.
- California Borderland Basins.* (Hein 1985)
- Setting:** Slope-aprons of active margin strike-slip basins, water depth 180–1800 m, Pleistocene–Recent.
- Structure:** Bioturbated–burrowed; laminated where organic carbon rich.
- Texture:** Poorly sorted.
- Composition:** Clay minerals include smectite (>50%), vermiculite, illite, chlorite and kaolinite; organic C 0.5–5.3%; CaCO₃ 0.5–13%.
- Sedimentation rate:** Range from >20 cm/ka for inner basins to <8 cm/ka for outer basins.
- Other features:** Some of region under the influence of upwelling system; hemipelagites interbedded with various resedimented facies.
- Levantine Sea–Nile Cone.* (Stanley & Maldonado 1979)
- Setting:** Marginal ocean basin, water depth >500 m, late Quaternary.
- Structure:** Bioturbated hemipelagic mud.
- Texture:** Sand fraction 5–10%, poorly sorted mud.
- Composition:** Sand fraction: pteropods, planktonic foraminifera; CaCO₃ 5–45%; clays abundant, organic carbon rich in parts.
- Sedimentation rate:** 2.9–62.7 cm/ka.
- Other features:** Cyclic nature of sediment sections (turbidite–hemipelagite cycles).
- Okushiri Ridge, Northeast Japan Arc.* (Tokuyama *et al.* 1992)
- Setting:** Back-arc basin, water depth 3500–3700 m, Miocene–Recent.
- Structure:** Structureless.
- Texture:** Poorly sorted.
- Composition:** Sand fraction: quartz, feldspar, volcanic grains, clays dominant, biogenic material common.
- Sedimentation rate:** ‘High’ rate of sedimentation.
- Other features:** Alternation of siliceous hemipelagites and turbidites; thick basin fill.
- Mozambique Basin, Southwest Indian Ocean.* (Kolla *et al.* 1980)
- Setting:** Abyssal plain, water depth 2000–5000 m, Quaternary–Holocene.
- Structure:** Structureless.
- Texture:** Fine sand–silty clay.
- Composition:** Mn nodules; sand fraction: foraminifera and diatoms; CaCO₃ 10–85%, clays 10–80%.
- Sedimentation rate:** <1 cm/ka during Quaternary, 1–2 cm/ka during Holocene.
- Other features:** Hemipelagites influenced by bottom currents in part.
- Japan Sea.* (Tamaki *et al.* 1992)
- Setting:** Back-arc basin, water depth 3500–4000 m, Miocene–Pliocene–Recent.
- Structure:** Bioturbated.
- Texture:** Poorly sorted.
- Composition:** Sand fraction: quartz, feldspar, glass, pyrite, inorganic calcite, biotite; organic carbon 0.02–7.45; CaCO₃ 1–74% (generally low); clays dominant.
- Sedimentation rate:** 4.9–5.6 cm/ka during Miocene; 7.7 cm/ka during Pliocene; 7.4 cm/ka during Quaternary.
- Other features:** Light–dark (organic-poor–organic-rich) cyclicity; interbedded turbidites in parts; thick basin fill.
- Sierra Leone Rise.* (Dean *et al.* 1981)
- Setting:** Passive margin, water depth 3200–3700 m, Tertiary.
- Structure:** Structureless.
- Textures:** Poorly sorted.
- Composition:** Chalk; marl; CaCO₃ c. 80%; clays minor.
- Sedimentation rate:** 5 cm/ka.
- Other features:** Chalk, marl and limestone show 20–60 cm thick cyclic alternations of clay-rich and clay-poor beds.

- Walvis Ridge, SE Atlantic.* (Hay *et al.* 1984; Stow 1987)
 Setting: Crest of aseismic ridge, ocean margin; water depth 365 m, Miocene–Recent.
 Structure: Thoroughly bioturbated and burrowed.
 Texture: Silty clay grade, with biogenic sand fraction (<15%).
 Composition: Sand fraction; diatoms and foraminifera, minor terrigenous debris; principal components, calcareous and siliceous biogenic material; proportions of clays vary through time and cyclically; organic carbon 0.5–8%.
 Sedimentation rate: 4–8 cm/ka.
 Other features: This region lies within the influence of the Benguela upwelling system off Namibia, which results in high primary productivity and high rates of sedimentation rich in biogenic silica and organic carbon. There is a clear cyclic bedding (0.4–1.0 m thick beds) of organic-rich–organic-poor hemipelagite, but bioturbation is thorough and no lamination is preserved.
- Peru Margin.* (Kemp 1990; Brodie & Kemp 1994)
 Setting: Forearc basin, water depth 500–1000 m, late Quaternary.
 Structure: Slightly bioturbated, well laminated.
 Texture: Poorly sorted.
 Composition: Sand fraction: quartz, feldspar, foraminifera, diatoms; organic carbon 3–12% (site 680) or 1–5% (Site 686); clays abundant.
 Sedimentation rate: 6.7 cm/ka (Site 680), and 18.25 cm/ka (Site 686).
 Other features: The waters of the Peruvian shelf are the site of one of the world's most persistent wind-driven coastal upwelling systems. The sustained high flux of organic matter beneath this highly productive region rapidly depletes oxygen and creates anoxic conditions both within the sediment and in the water column, resulting in extensive preservation of laminated sediments in the forearc basins of the shelf and upper slopes (Suess *et al.* 1988).
- Weddell Sea, Abyssal Plain.* (Pudsey *et al.* 1988; Pudsey 1992)
 Setting: Abyssal plain–distal rise, water depth >450 m, Pleistocene–Recent.
 Structure: Bioturbated, mottled and burrowed hemipelagic mud.
 Texture: Mostly very fine-grained, poorly sorted, silty mud. Ice-rafted sand and pebbles locally.
 Composition: Dominant terrigenous fraction: quartz, feldspar and clays; minor siliceous biogenic material; locally ice-rafted rock fragments.
 Sedimentation rate: Generally low: <0.5 to >1.6 cm/ka.
 Other features: Interbedded with fine-grained turbidites and ash-fall layers and influenced by bottom currents along northern margin of basin.
- NW Hebridean Continental Margin.* (Stoker 1990; Howe 1994; Howe *et al.* 1994)
 Setting: Passive margin, slope and rise, water depth 500–1500 m, Pleistocene–Recent.
 Structure: Bioturbated, mottled and burrowed hemipelagic mud.
 Texture: Poorly sorted silty mud, locally with ice-rafted sand and pebbles.
 Composition: Mixed terrigenous (60–90%) and biogenic (10–40%) fractions; quartz, clays and carbonate biogenic material dominant; ice-rafted rock fragments.
 Sedimentation rate: Difficult to separate from other facies, probably <10 cm/ka.
 Other features: Interbedded with turbidite and contourite facies.
- West Iberian Margin.* (Young 1995)
 Setting: Passive margin, Lisbon and Setubal canyon fill, water depth 200–2500 m, Holocene.
 Structure: Bioturbated and burrowed hemipelagic mud.
 Texture: Poorly sorted mud, clay–silty-clay grade.

Composition: Mixed terrigenous (65–90%) and biogenic (10–35%) fractions; quartz, clays and calcareous biogenic material dominant.

Sedimentation rate: Extremely high: 58–838 cm/ka.

Other features: High sedimentation rates may be explained by sediment focusing in slope canyons. Area of moderate upwelling and organic carbon contents up to 2%.

Stow & Piper (1984) defined hemipelagites as those sediments with >10% biogenic and >10% terrigenous material, with over 40% of the terrigenous component being silt sized (4–63 μm). The American Geophysical Institute (AGI) definition states that hemipelagic deposits in the deep sea are sediments in which more than 25% of the fraction coarser than 5 μm is of terrigenous, volcanogenic, and/or neritic origin. Such deposits usually accumulate near the continental margin and its adjacent abyssal plain, so that continentally derived sediment is more abundant than in eupelagic deposits, and the sediment has undergone lateral transport. Berger (1974) proposed a very similar definition but also noted that the median grain size of the terrigenous component is >5 μm . The more recent review of deep-sea sediments and environments by Stow *et al.* (1996) does not give rigorous compositional or textural boundaries for hemipelagites, referring to them simply as ‘fine-grained sediments with both biogenic and terrigenous components’ and emphasizing the combination of vertical settling and lateral (hemipelagic) advection for their accumulation.

Ancient examples

Still fewer detailed studies of ancient hemipelagites are reported in the literature. Hesse (1975) provided a careful account from the Upper Cretaceous flysch sequence in the eastern Alps, and showed how to distinguish between interbedded calcareous turbidites and carbonate-free hemipelagic mud deposited below the CCD. These hemipelagites are very different from those described from the Cretaceous Tertiary Scaglia Rossa formation of the central Apennines, in which the calciturbidites and pelagites are equally carbonate rich and difficult to distinguish, whereas the hemipelagites are more typical marls (Stow *et al.* 1984).

Limestone–marl cyclic sedimentation is commonly reported from ancient successions (see papers in Einsele *et al.* 1991; De Boer & Smith 1994). In some cases, the marls are best interpreted as hemipelagites, whereas in others they are more properly pelagites. In both instances, however, the original characteristics and composition have been extensively modified by subsequent diagenesis, although the primary control on cyclicity was climatic.

Those successions without significant cyclic bedding that have been interpreted as hemipelagic slope deposits include part of the Cretaceous Humps Island formation in the Antarctic (Pirrie 1989), and part of the Pissouri Marlstone member of the Nicosia Formation in Cyprus (Stow *et al.* 1994). In the latter case, the hemipelagic marlstones become interbedded upwards with volcanoclastic turbidites, the succession showing many features in common with the Mio-Pliocene Misaki Formation of south central Japan (Stow *et al.* 1997).

Hemipelagite definition and distinction from related facies

Various workers have proposed specific definitions in terms of composition and grain size.

Clearly there is a general consensus on what the term means. However, as hemipelagites have been recovered from many different parts of the world’s oceans, from the poles to the tropics and from the upper slope to abyssal plain, they display a wide range of characteristics. It is equally clear, therefore, that over-restrictive limits placed on their structural, textural and compositional attributes are meaningless. We therefore propose the following definition: ‘Hemipelagites are fine-grained sediments typically occurring in marginal deep-water settings. They comprise an admixture of biogenic pelagic material (generally >10%) and terrigenous or volcanogenic material (>10%), in which a significant proportion (over *c.* 40%) of the terrigenous (volcanogenic) fraction is of silt size or greater (*i.e.* >4 μm), and the overall grain-size distribution is poorly sorted. They are deposited by a combination of vertical settling and slow lateral advection.’

They have certain similarities with other deep-water sediments with which they are commonly found in close association, including: (1) pelagites, both biogenic oozes and red clays; (2) fine-grained turbidites and other mud-rich mass-flow deposits; (3) muddy contourites; (4) hemiturbidites. There is a complete gradation between pelagites and hemipelagites (Stow *et al.* 1996). True pelagic oozes have a high percentage of biogenic material, typically >70%, and a terrigenous component that is dominantly clay

sized, without a significant silt or sand fraction. Abyssal red clays have low biogenic content (<30%) and a high clay content (>70%), also without a significant silt or sand fraction. Accumulation rates for pelagites are mostly <1 cm/ka or ≤ 1 cm/ka, whereas hemipelagic rates are >1 cm/ka and typically between 5 and 15 cm/ka.

Fine-grained turbidites are more readily distinguished from hemipelagites. They are mostly well bedded, clearly structured and/or graded, and moderately to well sorted. Where interbedded, the two facies generally have different compositions, and show a more or less gradational and bioturbated contact passing upwards from turbidite into hemipelagite. Certain other rapidly deposited mass-flow facies such as muddy debrites, disorganized fine-grained turbidites, fine-grained bioclastic turbidites and muddy megabeds (homogenites or unifites) (Stanley 1981; Stow 1985b), can show superficial similarities to hemipelagites. However, they are structureless rather than bioturbated and mostly show well-defined beds, even if these may be tens of metres thick.

At the other end of the spectrum, hemiturbidites are fine-grained sediments with partly turbiditic and partly hemipelagic characteristics (Stow & Wetzel 1990). They have indistinct bedding, poor to moderate sorting, very subtle grading, distinctive continuous bioturbation and a composition equivalent to that of the interbedded distal turbidites. They have only recently been recognized as the deposits that result from an essentially stationary suspension cloud formed by reversing buoyancy during the terminal stage of turbidity current flow (Sparks *et al.* 1993). Hemiturbidites are truly transitional to hemipelagites and, in many cases, cannot be readily distinguished.

Muddy contourites can also display very similar features to those of hemipelagites and we must recognize that the boundary between these facies is partly gradational. Both types of deposits are typically bioturbated, fine grained, poorly sorted and of mixed biogenic-terrigenous composition. Very subtle differences in sorting, grading and primary sedimentary structures may be observable on close inspection at the scale of the core or outcrop, whereas in many cases differentiation must rely on larger-scale factors such as depositional setting and geometry, known bottom-current patterns, hiatuses and sedimentation rates.

A summary of the principal differences between these various deep-water facies is given in Table 3.

Facies model

Based on our detailed studies of the Makran and Oman margin hemipelagites, coupled with an extensive review of previous work by various workers, we have established below the main features of a facies model for hemipelagites (Fig. 9). These include sedimentary characteristics (structure, fabric, texture and composition), the nature of bedding and cyclicity, the distribution and rates of sedimentation, and the processes of deposition.

Structures. Hemipelagites deposited in open-water oxygenated conditions are completely devoid of primary sedimentary structures, but are generally highly bioturbated. Ichnofacies are those for quiet, oxygenated, deep water, and typically include *Zoophycos*, *Planolites*, *Chondrites*, *Phycosiphon* and others. Trace fossil zonation (or tiering) is most evident in more rapidly deposited hemipelagites (Wetzel 1984), especially where they are interbedded with turbidites or other resedimented facies. Complete bioturbational mottling is more common in slowly accumulated deposits.

Where bottom waters are low in oxygen or completely anoxic, then weak to well-developed parallel lamination is preserved, with low to absent bioturbation (Kemp 1990; Brodie & Kemp 1994). The lamination is most commonly a 'fissile-lamination' (Stow 1987; Stow & Atkin 1987) in which the laminae have a subparallel wavy anastomosing pattern. Lamination tends to be better developed at relatively high rates of sedimentation, but shows no evidence of current influence. In passing from oxic to anoxic conditions the ichnofossils decrease in size, abundance and variety from a highly mixed assemblage through to no bioturbation (Stow 1987; Wignall 1994).

Fabric. The submicroscopic fabric of hemipelagites requires more detailed study. However, some results from this study together with those reported by O'Brien (1980) and Shepard & Rutledge (1991) suggest that open-water hemipelagites have a relatively close-packed fabric with subparallel alignment of clays, nannofossils and other platey components. Larger grains and bioturbation cause disturbance of this fabric. Under anoxic conditions, well-laminated hemipelagites show a still tighter, uniform, subparallel fabric (Kemp 1990).

Textures (Fig. 9). Grain size of hemipelagites is strongly influenced by the sediment composition

Table 3. Diagnostic criteria for the recognition and distinction of fine-grained turbidites, muddy contourites, hemipelagites and pelagites; modified and expanded from Stow (1985b)

	Turbidites (fine grained, thin bedded)	Turbidites—Unifites (fined grained, very thick bedded)	Hemiturbidites (Stow & Wetzel 1990)	Contourites (fine grained, depositional)	Hemipelagites	Pelagites (biogenic ooze)	Pelagites (abyssal red clay)
<i>Bedding</i>	Usually well defined, continuous, thin bedded, regular	Usually well defined, regular, extensive; beds >1 m, and may exceed 25 m thick	Poorly defined bedding	Poorly defined and irregular, may be absent; irregular, variation of very thin to very thick beds	Poorly defined or moderate, regular, but may be absent; beds when present may be even bedded and medium thick	Poorly defined to absent	Poorly defined to absent
<i>Structures</i>							
<i>Lamination</i>	lenticular and parallel, regular or indistinct; micro-cross-lamination, low-amplitude climbing ripples, fading ripples and convolute lamination common	Structureless or with very indistinct parallel lamination near base of bed	Primary structures absent, but may cap fine-grained laminated turbidite	Lamination in parts only, mainly irregular, wavy, indistinct or lenticular, cross-lamination only rarely present in silt or fine-sand layers; irregular mottling very common	No primary structures, but may develop fine fissile lamination where deposited under anoxic conditions	No primary structures	No primary structure
<i>Contacts</i>	usually sharp at bases and sharp or gradational at top; laminae; micro-scours, loading and injection structures	sharp at bases and sharp or gradational at top; little or no scouring evident	Contacts gradational and bioturbated	Contacts can be sharp or gradational at tops and bases of layers and laminae; often gradations between the two along same contact; often irregular, sometimes erosive	Contacts between beds always gradational and bioturbated	Contacts gradational and bioturbated	Contacts gradational and bioturbated
<i>Bioturbation</i>	episodic, concentrated near tops of beds, often small scale, sometimes absent, rarely destroys all primary structures	in upper part of beds	continuous throughout bed; may be distinctive monospecific ichnofacies	continuous and intensive, throughout sequence; several tiers of burrows, types vary according to contourite facies; can markedly alter or destroy primary structures	continuous and intensive throughout sequence; several tiers of burrows, uniform ichnofacies; may become homogenized	continuous and intensive as for hemipelagites	continuous; may be less evident than in oozes and hemipelagites; mottling and homogenization common
<i>Textures</i>	from fine to sand to clay grade	typically from silt to clay	very fine silt- and clay	from sand to clay grade	from sand to clay grade, with >40% of terrigenous fraction being silt-sized; locally coarser	from sand to clay grade	from sand to fine silt

HEMIPELAGITES

<i>Distribution</i> and moderate to good <i>sorting</i> indicate current deposition; silt and mud laminae usually well separated; silts often positively skewed (fine tail)	<i>Sorting</i> moderate to poor	<i>Sorting</i> moderate to poor	<i>Sorting</i> usually poor to moderate, but <i>distribution</i> does indicate current deposition; silt and mud often have low positive or negative skew (i.e. both coarse and fine tails)	<i>Sorting</i> poor to moderate, no current indications	<i>Sorting</i> , poor to moderate
<i>Grading</i> positive, often in regular graded-laminated units	<i>Grading</i> absent or very slight positive grading	<i>Grading</i> generally absent	<i>Grading</i> irregular, both positive and negative sequences	<i>No true grading</i> , but irregular grain-size fluctuation may be present	<i>No grading</i>
<i>Fabric</i> <i>Grain alignment</i> (silts) parallel to downslope currents	<i>Fabric</i> not studied; presumed similar to thin-bedded turbidites	<i>Fabric</i> not studied	<i>Grain alignment</i> (silts) may be parallel to alongslope currents; more often disturbed by bioturbation	<i>No grain alignment</i>	<i>No grain alignment</i>
<i>Mud fabric</i> may show large particle clusters (flocs) with random orientation			<i>Mud fabric</i> may show small particle clusters and isolated horizontal orientation where not bioturbated	<i>Mud fabric</i> with small clusters and isolated particles; bed parallel	<i>Fabric</i> with small clusters and isolated particles, bed parallel
<i>Magnetic fabric</i> (?) parallel to downslope currents			<i>Magnetic fabric</i> (?) parallel to alongslope currents	<i>No magnetic fabric</i>	<i>Random magnetic fabric</i>
<i>Composition</i> <i>Allochthonous</i> elements introduced into an area, so that turbidite composition often differs markedly from that of interbedded sediments	<i>Allochthonous</i> composition	Mainly <i>allochthonous</i> composition as for associated turbidites, plus admixture of hemipelagic input	<i>Uniform</i> composition at scale of drift or margin deposit; part may be far-travelled, but most derived locally from pelagic and turbiditic input and bottom-current resuspension	<i>Uniform</i> composition derived from primary productivity in surface waters	<i>Uniform</i> composition
<i>Nature</i> can be terrigenous, biogenic, volcanogenic, or mixed, often containing shallow-water elements; may show compositional grading	Terrigenous, biogenic, volcanogenic or mixed; may show compositional grading		<i>Nature</i> usually a mixture of terrigenous and biogenic; can be >80% one or other, can also include volcanogenic debris; reworked biogenic material common, often as broken and iron-stained debris; Fe-Mn rich in parts	<i>Nature</i> , calcareous, siliceous or mixed; with rare volcanogenic, terrigenous and cosmogenic input; Fe-Mn nodules and crusts locally	<i>Terrigenous</i> and <i>volcaniclastic</i> clays and fine silts; wind-blown dust, cosmogenic input, microtektites, Fe-Mn nodules and crusts

continued

Table 3. *Continued*

Turbidites (fine grained, thin bedded)	Turbidites—Umfites (fined grained, very thick bedded)	Hemiturbidites (Stow & Wtzel 1990)	Contourites (fine grained, depositional)	Hemipelagites	Pelagites (biogenic ooze)	Pelagites (abyssal red clay)
<i>Distribution</i> <i>Vertical sequence</i> often a regular succession of positively graded beds, or graded-laminated units (2–20 cm thick); these can form part of thicker coarsening- or fining-upward sequences	Typically occur as isolated <i>megabeds</i>	Typically occur within distal turbidite basin-plain succession	<i>Vertical sequence</i> often an irregular succession of positively and/or negatively graded intervals (10–100 cm thick); larger-scale sequences not yet clearly defined	<i>Vertical sequence</i> absent or as regular cycles of more and less biogenic-rich composition	<i>Vertical sequence</i> absent or as regular cycles of more and less biogenic-rich composition	No <i>vertical sequence</i>
<i>Sedimentation rates</i> <i>Horizontal trends</i> of sedimentary features (e.g. bed thickness, grain size, composition) along turbidity current pathways, i.e. downslope trends	<i>Horizontal trends</i> generally absent or very subtle	<i>Horizontal trends</i> absent	<i>Horizontal trends</i> of sedimentary features (e.g. grain size, composition) along bottom-current pathways (i.e. the margin or drift)	<i>Horizontal trends</i> not present or weakly developed over large area	<i>Horizontal trends</i> not present or weakly developed over large area	No <i>Horizontal trends</i>
<i>Current evidence</i> (ripples, flute-casts, fabric) also shows downslope trends			<i>Current evidence</i> (ripples, fabric) where preserved, also shows alongslope trends	No <i>bottom-current evidence</i>	No <i>bottom-current evidence</i>	No <i>bottom-current evidence</i>
<i>Episodic</i> turbidite sedimentation, background sedimentation continuous, hiatuses uncommon except when associated with coarser-grained turbidites	<i>Episodic</i> , typically less frequent than thin-bedded turbidites	<i>Episodic</i> events but with very long settling periods (e.g. 0.5–1 a)	<i>Semi-continuous</i> sedimentation, with irregularly spaced, often prolonged hiatuses when bottom currents particularly strong	<i>Continuous</i> sedimentation, no hiatus	<i>Continuous</i> sedimentation, but may be very reduced in places	<i>Continuous</i>
<i>Rate</i> very variable, <10 to 1000 cm/ka			<i>Rates</i> variable, low to moderate, <2 to 15 cm/ka	<i>Rates</i> relatively constant, commonly low, <10 cm/ka; may vary with carbonate cycles; locally may be moderate to very high (>100 cm/ka)	<i>Rates</i> very low, typically <1 cm/ka; very rarely up to 5 or 10 cm/ka	<i>Rates</i> extremely low, <<1 cm/ka; may be <0.1 cm/ka

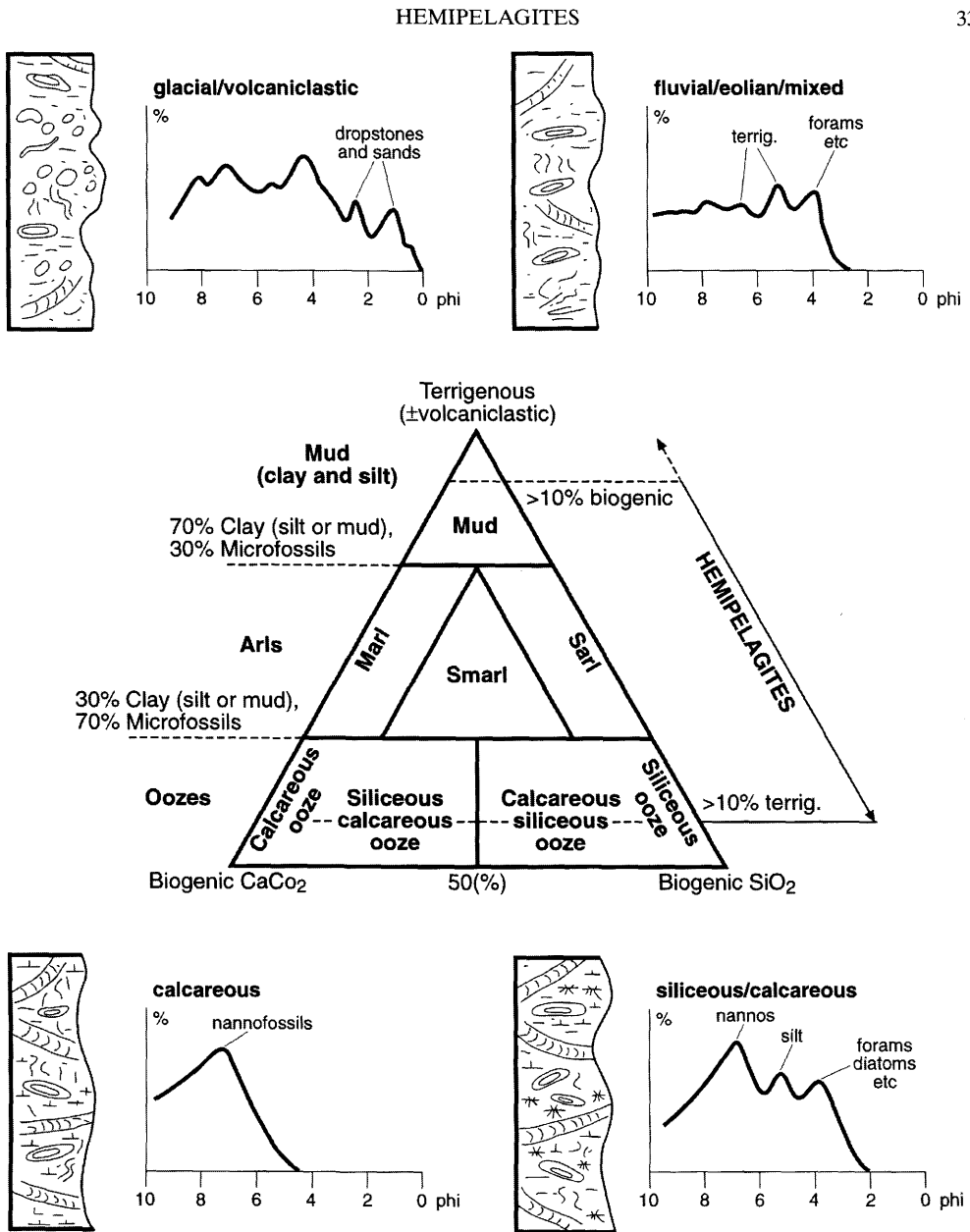


Fig. 9. Composite model for hemipelagite facies. Compositional characteristics indicated on terrigenous mud–calcareous ooze–siliceous ooze triangular plot. Most of the ooze, marl and mud fields can be hemipelagites. Typical grain-size characteristics shown for hemipelagites of different compositions and principal sediment sources. Schematic sediment logs illustrate minor grain-size variation related to components, intense bioturbation, and terrigenous or biogenic components.

and hence source. In general, however, they are fine grained with a mean size of 5–35 μm, poorly sorted with a broad spread of grain sizes, in some cases bimodal, trimodal or polymodal in distribution. Skewness values are slightly to markedly negative; kurtosis shows no standard pattern,

although platykurtic distributions are more typical. The fine silt-sized mode (5–7 μm) is probably most common, and is the result of a dominant nannofossil contribution. Smaller peaks or modes at coarse silt sizes are dependent on specific terrigenous inputs of fluvial, aeolian,

volcanic or glacial origin and therefore vary with the tectonic or oceanographic setting. Coarser grain sizes (sand and even gravel) may be introduced by floating ice or volcanoclastic activity. Other biogenic pelagic components (e.g. foraminifers, radiolarians, diatoms) can give minor grain-size peaks at coarse silt and fine sand grades.

Composition (Fig. 9). The composition of hemipelagites is very variable within the broad range allowed by definition, i.e. normally >10% biogenic and >10% terrigenous. The biogenic component is dominated by open-ocean planktonic microfossils, either calcareous (nannofossils and foraminifers) or siliceous (radiolarians and diatoms). Minor amounts of other biogenic material (e.g. sponge spicules, silicoflagellates, dinoflagellates, benthic foraminifers, etc.) may also be present. We take >90% biogenic fraction as the absolute upper limit for hemipelagites, above which the sediment is a pelagite. Biogenic contourites and turbidites can also show >90% biogenic material. Many pelagic oozes in fact have >70% biogenic material, but the terrigenous fraction is dominantly clay rather than silt size.

The terrigenous fraction is dependent on the nature of the supply pathway and hence on the tectonic and geographic setting. Surface plumes of major rivers will carry clays and silts far into the ocean basins, the mineralogy being dependent on source area. Aeolian transport of silt and dust from deserts and arid lands can include chemogenic particles (e.g. palygorskite) as well as terrigenous grains (e.g. quartz, feldspar and clays). Ice-rafting at high latitudes is a major supplier of both fine and coarse terrigenous fraction, much of which may be compositionally immature (e.g. lithic grains). Along some active margins (island-arc settings) and around volcanic seamounts, chains or plateaux, a volcanoclastic component can dominate the terrigenous fraction. Hemipelagites that accumulate close to a dominant terrigenous source may have >90% terrigenous material as, for example, in high-latitude glacio-marine hemipelagites, where there is negligible biogenic productivity because of sea ice.

Chemogenic components form authigenically in some slowly deposited hemipelagites, including phosphorites, glauconite and ferromanganese nodules or crusts. Iron monosulphides as precursors to pyrite are very common, especially in organic-rich hemipelagites. High total organic carbon content is characteristic of laminated hemipelagites deposited under anoxic conditions.

Cyclicality and bedding. Cyclic alteration of composition, colour, grain size or structures within hemipelagic sequences and cyclic interbedding with associated facies are both common. The periodicity of such cycles is typically on a Milankovitch time-scale (i.e. approximately 19–23, 41 or 100 ka cycles being most common). Where hemipelagites are interbedded with turbidites, then the turbidity current frequency will dominate the periodicity. Hemiturbidites, contourites and pelagites are other associated facies that occur in cyclic interbeds with hemipelagites.

Where cyclic changes are very marked then bedding may be distinct. More typically, however, the changes are subtle and gradual so that bedding is indistinct with bioturbated and gradational bed boundaries. Bed thickness varies from a few centimetres to a few metres, with 10–100 cm being most common.

Occurrence and rates of sedimentation. Hemipelagites occur in all tectonic and oceanographic settings, at all latitudes, and are most common within about 300 km of the coastline surrounding both continental landmasses and oceanic islands. Provided that there is adequate supply of silt-size terrigenous material, then hemipelagites may also occur far from land in open-ocean settings, but this is not normally the case. Water depths range from that of the shelf-break (typically 100–200 m) to oceanic depths in excess of 4–5 km. Outer shelf hemipelagites are here considered as a different facies that have a shallow-water signature and are affected by shelf processes. Clearly there will be a transition, however, between outer shelf and upper slope hemipelagites.

Rates of hemipelagic sedimentation typically range from <5 cm/ka (i.e. relatively slow) to >20 cm/ka (i.e. relatively rapid). In many cases, the sedimentation rate varies consistently with changes in the sedimentary characteristics outlined above. Hemipelagites formed in areas of high sedimentation rate, for example, tend to have a coarser mean grain size, a higher terrigenous/biogenic ratio and a better developed tiering structure of burrows than hemipelagites that have accumulated more slowly. Regions of upwelling and high biogenic productivity commonly show moderately high rates of sedimentation but with increased siliceous biogenic and organic carbon contents. Exceptionally high rates of sedimentation (e.g. >100 cm/ka) are associated with zones of hemipelagic sediment focusing, such as shelf-to-slope canyon systems.

Depositional processes (Fig. 10). There is a range of depositional processes responsible for

deep-water fine-grained sedimentation, including turbidity currents and associated mass-flow events, bottom currents, hemipelagic advection and pelagic settling (e.g. Stow *et al.* 1996). Conceptually, these different processes are relatively well defined although the nature of hemipelagic sedimentation is particularly complex.

Turbidity currents and associated mass-flow processes are distinctly episodic, short duration, and infrequent events. They are bottom-hugging flows that mainly travel down-gradient on steeper slopes. Even the reverse buoyancy and upward mixing that produce hemiturbidites are episodic events, though their duration may be from 3 to 12 months (Stow & Wetzel 1990). Bottom currents also flow over the sea floor, but generally parallel to contours, and are semi-permanent (i.e. continuous through a measurable episode of geological time). They show significant variation in nature, intensity and location that contributes to their distinctive vertical sequences and other primary features. Pelagic sedimentation is the result of slow vertical settling under the influence of gravity in the absence of either turbidity currents or bottom currents.

Between vertical slow settling and low-density turbidity currents is a range of overlapping mechanisms that can be called hemipelagic processes (Fig. 10). The sedimentary materials involved are an admixture of terrigenous and primary biogenic components. The origin and deposition of primary biogenic material is

governed by the same controls (productivity, dissolution and masking) as for pelagic sedimentation. The terrigenous input is from a combination of aeolian, fluvial, glacial, or coastal-shelf mechanisms, all of which serve to introduce suspended plumes and dispersed particles to the sea surface. In addition, the finest portions of low-concentration turbidity currents are in some cases stripped off at density discontinuities within the water column. Large eddies can become detached from bottom currents and further contribute their very dilute suspensions to the hemipelagic fallout. Internal tides and waves, interacting with the sea floor at the shelfbreak, within canyons (clear-water canyon currents) or on the upper slope, stir up fine-grained surficial sediments and mix them upwards into the overlying waters.

Some suspensions are dispersed across the sea surface by tides and other currents, whereas those with sufficient excess density will sink and move downslope as very dilute slow-moving density flows (or turbid layer flows). Where these encounter a density discontinuity they detach from the bed and flow out into the water column as an interflow. Such flows decelerate and material settles vertically to regroup at a deeper density interface and flow further basinwards before settling and regrouping once more. This process is known as suspension cascading. Less distinct and very dilute suspensions form thick mid- and bottom-water nepheloid layers

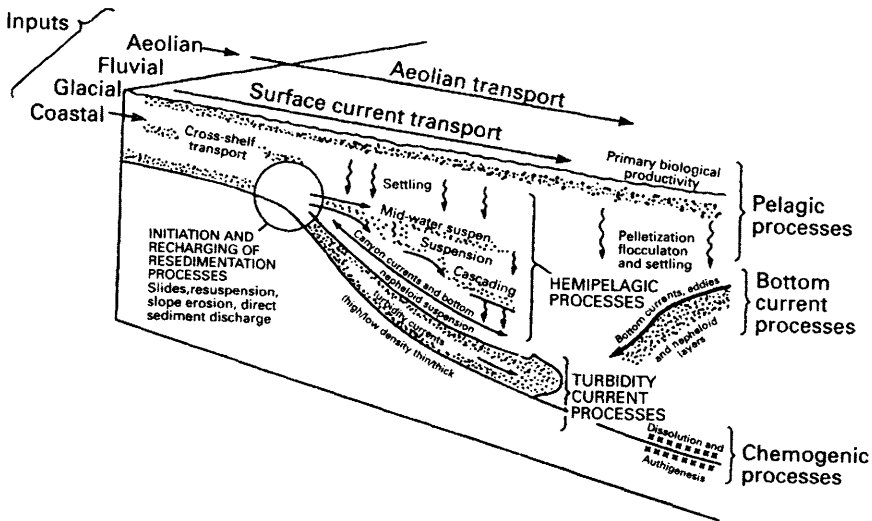


Fig. 10. Composite model for the deposition of fine-grained sediments in deep-water environments (modified from Stow 1985; Stow *et al.* 1996). The group of hemipelagic processes shown in the central part of the water column involve part vertical settling and part slow lateral advection. This distinguishes hemipelagic sedimentation from the other processes illustrated.

that may move along- and downslope by slow lateral advection. This combination of vertical settling and lateral advection has been documented by various workers (McCave 1972; Drake *et al.* 1978; Stow 1985b, 1994; Stow *et al.* 1996) and constitutes hemipelagic deposition.

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