Geo-Marine Letters, Vol. 5:17–23(1985)

GEO-MARINE
Letters

Fine-Grained Sediments in Deep Water: An Overview of Processes and Facies Models

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Abstract

There appears to be a continuum of processes affecting the transport and deposition of fine-grained sediments in the deep sea. This results in a facies continuum within which we can recognize three broadly different facies groups: turbidites, contourites, and pelagites/hemipelagites. Several distinct facies models can be defined for each group on the basis of their chief structural, textural, and compositional attributes.

Introduction

The recognition and interpretation of deep-water fine-grained sediments are still problematic in many cases, for modern as well as for ancient successions [1]. By taking a process-oriented view, we can identify three broadly different facies groups: turbidites, contourites, and pelagites/hemipelagites. These are related primarily to processes of deposition by, respectively, gravity-driven turbidity currents, thermohaline and wind-driven semipermanent bottom currents, and predominantly vertical settling through the water column. In reality, however, these conceptually distinct processes form parts of a continuum of mechanical behavior, flow concentration, and flow velocity, so that there is also a continuum of the resultant depositional facies [2]. Chemogenic sediments form a fourth facies group, and all of the more "proximal" resedimentation facies (slides, slumps, creep, debris flows) form an important fifth facies group. Neither of these groups, however, are considered in detail here.

In this report, a brief overview is attempted of depositional process, facies models, and the criteria for distinguishing between the different facies groups. For much of the background and details behind the generalizations presented, the reader is referred to other papers in this special issure of *Geo-Marine Letters* and to the publication edited by Stow and Piper [3].

Processes

Within the process continuum operating in the deep sea, some of the major groups of processes controlling deposition of fine-grained sediments can be illustrated (Fig. 1).

Fine-grained terrigenous material is introduced into the marine realm from fluvial and glacial discharges, coastal erosion, and eolian transport. The majority of this material is deposited close to shore, with a progressively diminishing quantity and grain size being transported further out to sea by winds, surface currents, or mid-water suspensions. Part of the nearshore material is moved intermittently across the shelf by current, wave, and storm action. Further movement into deeper water can be initiated by sediment creep and slides (because of load-induced strain or shock failure) or by sediment resuspension (because of storm stirring, internal tides and waves, and bioturbation). Particularly high discharges from rivers or glaciers may continue directly into deep water as low-concentration turbidity currents. Debris flow and high-concentration turbidity currents can also carry a large amount of fine-grained material downslope, some of which may peel off to form lower-concentration overbank flows.

Low-concentration turbidity currents, generated by any one of the mechanisms just described, are estimated to range from less than 10 m to over 500 m in thickness and from relatively small up to several kilometers wide and, perhaps, tens of kilometers long. Flow concentrations are estimated to be of the order of 0.025–2.6 g/liter and flow velocities about 0.1 to 0.5 m/s [4,5]. These currents can transport material up

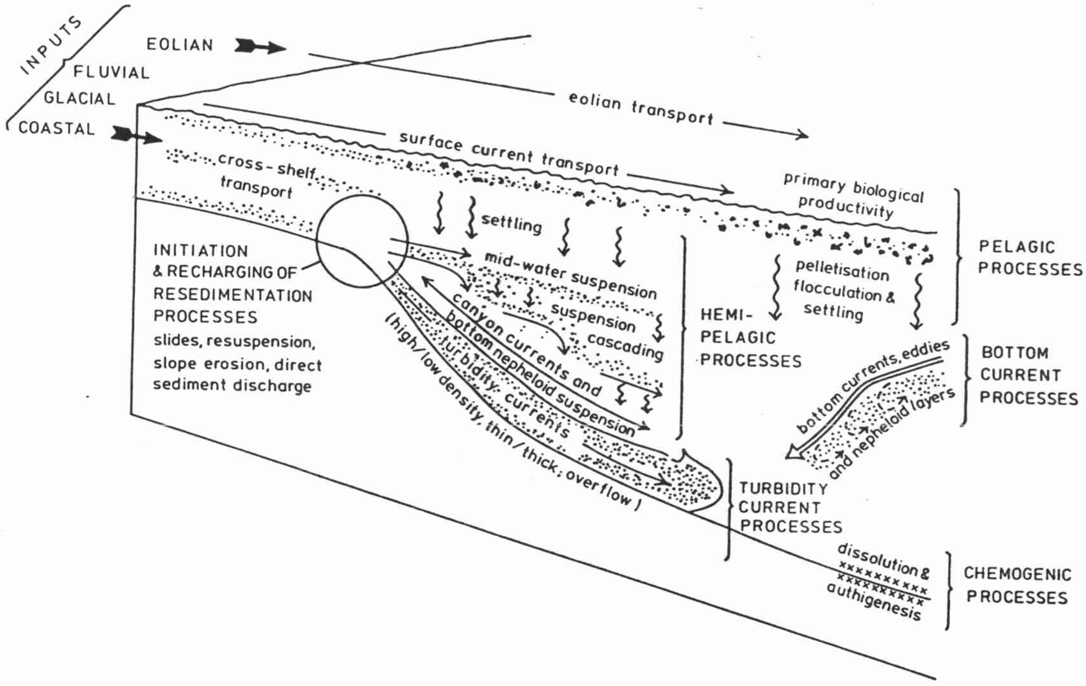

Figure 1. Diagram schematically showing the major group of processes controlling the transport and deposition of fine-grained sediments in deep water.

to several thousands of kilometers over very gentle sea-floor gradients (<<1°) in channelized or nonchannelized flows. The flow is sustained and the sediment supported by a process of turbulent autosuspension. Considerable flow instability and fluctuation are likely, particularly in the larger-sized currents.

At the other end of the process spectrum, far-travelled terrigenous material mixes with the fall-out from primary biological productivity in surface waters and settles slowly through the water column. The extremely slow rate of pelagic settling for very fine-grained particles (on the order of 10^{-4} to 10^{-6} m/s) is augmented by processes of flocculation and pelletization so that actual settling rates may be several orders of magnitude higher (10^{-2} to 10^{-3} m/s) [6].

Between these turbiditic and pelagic processes are a range of overlapping depositional mechanisms that can most conveniently be termed hemipelagic processes. The materials involved are an admixture of terrigenous and primary biogenic particles, the latter forming at least 5 to 10% of the sediment and the former comprising a significant percentage of silt-sized particles (>40%). Deposition is primarily by slow settling through the water column in the absence of any *substantial* bottom current or turbidity current activity. However, there is usually a component of current-induced lateral advection of suspended sediment [7] in mid- or bottom-water nepheloid layers, sometimes involving suspension cascading, up and down canyon currents, or very thin turbid-layer flows.

Any fine-grained material on its way to the deep sea floor, as well as sediment already deposited, may come under the action of semipermanent bottom (contour) currents [8,9]. Where such currents have significantly eroded or transported and deposited sediment, the resulting deposit is known as a contourite. In most cases, the concentration (0.025 to 2.5 mg/liter) and velocity (average 0.05 to 0.2 m/s) of such flows are significantly lower than those of low-concentration turbidity currents. Bottom nepheloid layers associated with some of the more powerful semipermanent bottom currents range up to 2000 m in thickness and may transport material for several thousands of kilometers. The flows appear to vary significantly in terms of velocity, direction, and space wherever longer-term (3 to 12 months) measurements have been made [8,9].

Facies

Although there is a clear overlap between the different process groups just outlined and many deep-water sediments will have been influenced by a combination of processes, we can, nevertheless, recognize certain sedimentary characteristics that reflect each of the main processes where they have been the sole or strongest influence during deposition. These structural, textural, and compositional features can be summarized in terms of several distinct facies models within each of the three facies groups considered in this report: turbidites, contourites, and pelagites/hemipelagites.

For fine-grained turbidites, four facies models have been constructed [1]: 1) silt turbidites, 2) mud turbidites, 3) biogenic turbidites, and 4) disorganized turbidites (Fig. 2). Although different in detail, these all show idealized sequences

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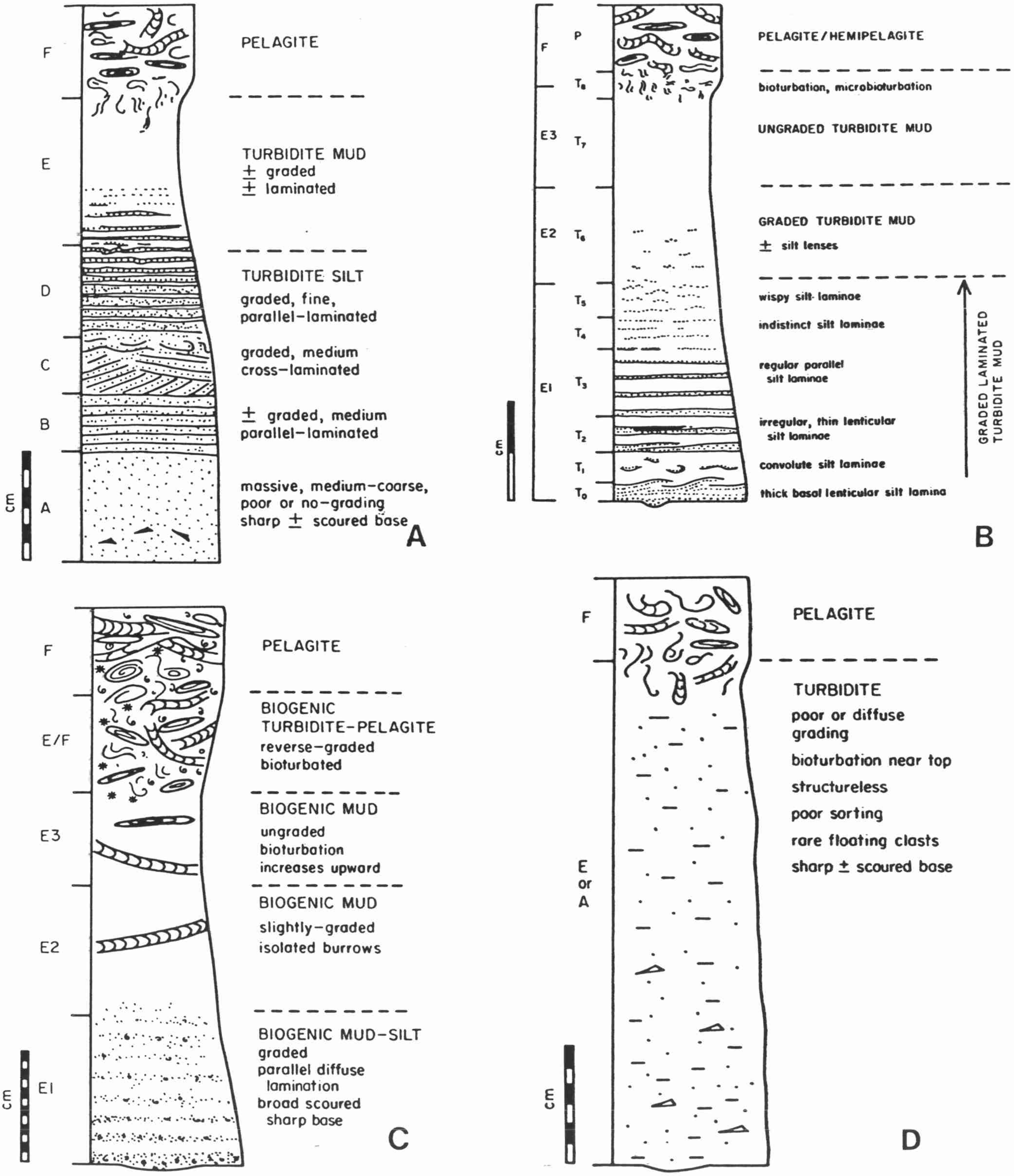

Figure 2. Four facies models for fine-grained turbidites (after [1]). (A) silt turbidites, (B) mud turbidites, (C) biogenic turbidites, (D) disorganized turbidites.

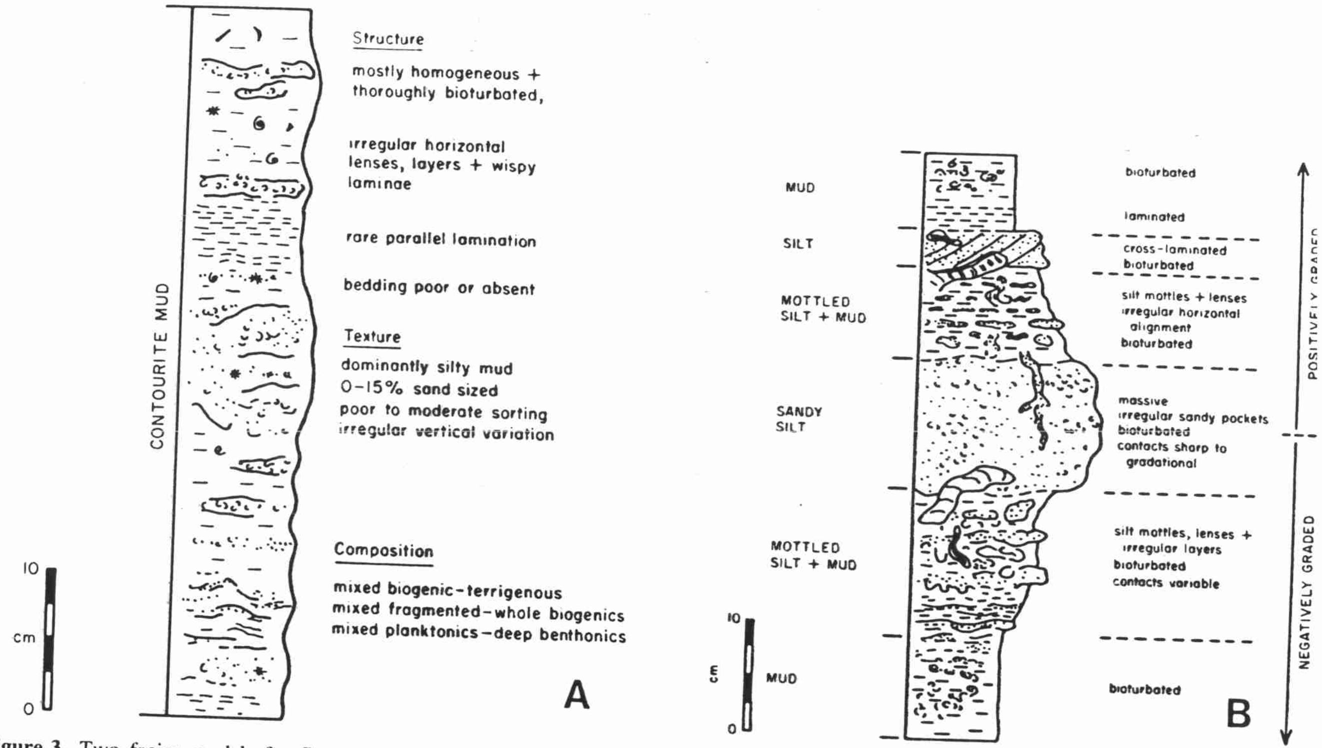

Figure 3. Two facies models for fine-grained contourites (after [1]) (A) muddy contourites, (B) vertical sequence of muddy, silty, and fine s contourites.

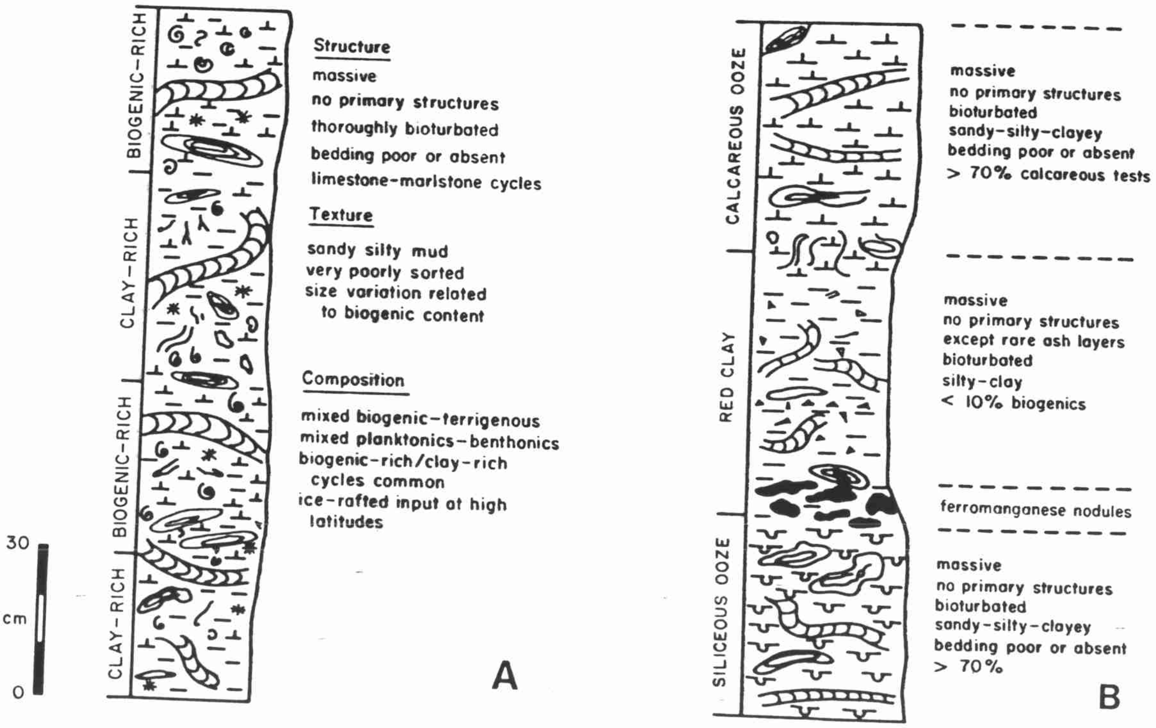

Figure 4. Facies models for (A) pelagites and (B) hemipelagites (after [1]).

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Table 1. Diagnostic Criteria for Recognition of Fine-Grained Turbidite, Contourite, and Hemipelagite Facies Groups

	Turbidites (fine-grained, thin-bedded)	Contourites (fine-grained, depositional)	Hemipelagites
Bedding	Usually well-defined, continuous, thin-bedded, regular; thick and very thick bedding less common.	Poor and irregular, may be absent; irregular variation of very thin to very thick beds.	Poor or moderate, regular, but may be absent; beds when present may be even-bedded and medium thick.
Structures	*Lamination* lenticular and parallel, regular or indistinct; microcross-lamination, low-amplitude climbing ripples, fading ripples, and convolute lamination common.	*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 sedimentary structures.
	Contacts usually sharp at bases and sharp or gradational at top of laminae; micro-scours, loading and injection structures.	*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.
	Bioturbation episodic, concentrated near tops of beds, often small-scale, sometimes absent, rarely destroys all primary structures.	*Bioturbation* continuous and intensive, throughout sequence; several tiers of burrows, types vary according to contourite facies; can markedly alter or destroy primary structures.	*Bioturbation* continuous and intensive throughout sequence; several tiers of burrows, uniform ichnofacies.
Textures	*Grain size* from fine sand to clay grade.	*Grain-size* from fine sand to clay grade.	*Grain-size* from fine sand to clay grade, with >40% of terrigenous fraction being silt-sized.
	Distribution and moderate to good *sorting* indicate current deposition; silt and mud laminae usually well separated; silts often positively skewed (fine tail).	*Sorting* usually poor to moderate, but *distribution* does indicate current deposition; silt and mud often irregularly mottled; silts often have low positive or negative skew (i.e., both coarse and fine tails).	*Sorting* very poor, *distribution* uniform with no current indications.
	Grading positive, often in regular graded-laminated units.	*Grading* irregular, both positive and negative sequences.	*No true grading*, but irregular grain-size fluctuation may be present.
Fabric	*Grain alignment* (silts) parallel to downslope currents.	*Grain-alignment* (silts) may be parallel alongslope currents more often disturbed by bioturbation.	*No grain alignment*.
	Mud fabric may show large particle clusters (flocs) with random orientation.	*Mud fabric* may show small particle clusters, with horizontal orientation where not bioturbated.	*Mud fabric* may show small particle clusters.
	Magnetic fabric (?) parallel to downslope currents.	*Magnetic fabric* (?) parallel to alongslope currents.	*No magnetic fabric*.
Composition	*Allochthonous* elements introduced into an area, so that turbidite composition often differs markedly from that of interbedded sediments.	*Uniform* 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.	*Uniform* composition, local and far-travelled in surface currents, varied inputs.
	Nature can be terrigenous, biogenic, volcanogenic, or mixed, often containing shallow-water elements (e.g., shelf-biogenics, glauconite); reworked biogenics common and can form dominant biogenic component; marked sorting of components with respect to grading is common.	*Nature* usually a mixture of terrigenous and biogenic (part pelagic, part benthonic) elements; can be >80% one or other; can also include volcanogenic debris; reworked biogenics common, often as broken and iron-stained debris; slight sorting of components with respect to different facies common.	*Nature*, a mixture of terrigenous and >5% biogenic (dominantly pelagic) elements, can include volcanogenic debris; not reworked.
Distribution	*Vertical sequence* 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.	*Vertical sequence* often an irregular succession of positively- and/or negatively-graded intervals (10–100-cm thick); larger-scale sequences not yet clearly defined.	*Vertical sequence* absent, or with regular cycles in carbonate/noncarbonate ratio.

Table 1. *Continued*

	Turbidites (fine-grained, thin-bedded)	Contourites (fine-grained, depositional)	Hemipelagites
	Horizontal trends of sedimentary features (e.g., bed thickness, grain-size, composition) along turbidity current pathways, ie. downslope trends, often perpendicular to the margin.	*Horizontal trends* of sedimentary features (e.g., grain size, composition) along bottom current pathways (i.e., alongslope trends parallel to the margin or drift).	*Horizontal trends* not present.
	Current evidence (ripples, flute-casts, fabric) also shows downslope trends.	*Current evidence* (ripples, fabric) where preserved, also shows alongslope trends.	*No current evidence.*
Sedimentation rates	*Episodic* turbidite sedimentation, background sedimentation continuous, hiatuses uncommon except when associated with coarser-grained turbidites.	*Semi-continuous* sedimentation, with irregularly-spaced, often prolonged hiatuses when bottom currents particularly strong.	*Continuous* sedimentation, no hiatuses.
	Rates very variable, <10 to 1000 cm/1000 years.	*Rates* variable, low to moderate, <2 to 15cm/1000 years.	*Rates* relatively constant, commonly low. <10cm 1000 years, may vary with carbonate cycles.

of structures and grain size through single-event deposits from a few centimeters to a few tens of centimeters in thickness. These are closely analogous to the classical Bouma sequence for sandy turbidites [10]. In nature, such deposits show great variability in terms of bed thickness and unit completeness (e.g., top-absent, base-absent units). They may also show some variability in structural sequence, perhaps related to flow instability.

Both the silt and mud turbidite models represent deposition in more distal or overbank settings from mature and relatively large siliciclastic turbidity currents. The biogenic turbidite model represents the deposits of turbidity currents derived from exclusively biogenic (calcareous or siliceous) material. The differences from the siliciclastic equivalents are probably due in part to the different hydrodynamic behavior of the particles involved and in part to the different depositional environments. Disorganized turbidites are less readily interpreted; they may result from the ponding of large flows in small basins, or have been deposited from immature turbidity currents.

The two contourite models shown in Figure 3 are for muddy (Fig. 3a) and silty/fine sandy (Fig. 3b) contourites. These show the range of characteristics found in fine-grained contourites common in sediment drifts, as well as the typical vertical arrangement of mud, silt, and fine-sand facies in negatively-graded and then positively-graded units over a few tens of centimeters [11]. As with turbidites, there is much variability in the thickness and completeness of these "sequences," as well as in the degree of lamination preserved and intensity of bioturbation. The composition of contourites is largely dependent on the sediment source, and ranges from almost completely biogenic to mainly terrigenous or volcanogenic. It is not yet fully clear how these compositional differences affect the structural and textural attributes.

Both contourite models represent primarily depositional contourites, with accumulation taking place over a few thousands of years for the sections shown (rather than the instantaneous depositional units of the turbidite models). Nondepositional hiatuses or erosional breaks within the sequence will depend on the frequency and intensity of bottom current maxima or "storm events" [12].

Four different pelagite/hemipelagite facies are recognized: 1) pelagic ooze with greater then 75% calcareous and/or siliceous biogenic debris; 2) muddy pelagic ooze with 25 to 75% biogenic debris and a terrigenous component dominantly of clay; 3) pelagic clay with less then 25% biogenic debris and greater than 60% clay in the terrigenous fraction; and 4) hemipelagite with greater than 5% biogenic debris and a terrigenous component with greater than 40% silt. These are illustrated in Figure 4, which emphasizes the common interbedding of biogenic-rich and biogenic-poor intervals, each on the order of a few tens of centimeters thick, in both pelagites and hemipelagites.

There is a notable absence of features indicative of current influence during deposition. The more important controls on facies characteristics are primary productivity, carbonate compensation depth, sea-level, climatic fluctuation, supply of terrigenous material, and growth of authigenic minerals.

Summary

1) The chief diagnostic criteria for recognition of deep-water fine-grained sediments in each of the facies groups discussed are summarized in Table 1.

2) Within each of these facies groups, several distinct facies models can be recognized. These are useful for interpreting subtle differences between facies in terms of their environments and processes of deposition.

3) Fine-grained sediments have always been difficult to study, largely because of their grain size. There is a need

for continued development of sophisticated methods in our approach to this class of rocks.

4) In future studies, effort must also be made to compare the processes and facies of these deep-water sediments with those of shallow-water and continental environments.

Acknowledgments

Financial assistance was provided by the Natural Environment Research Council, the Royal Society of Edinburgh, and the Nuffield Foundation. Technical and secretarial support at the Grant Institute of Geology, Edinburgh and at the Geology Department, Nottingham is gratefully acknowledged.

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Manuscript received 18 September 1984; revision received 27 December 1984.