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Deep-Water Facies, Processes and Models: A Review and Classification Scheme for Modern and Ancient Sediments

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ABSTRACT

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A review of previous work on modern and ancient deep-water facies, processes and models is presented with a new classification scheme involving 40 distinct facies related to 15 conceptually distinct facies groups. These facies are fixed points in a spectrum of facies generated in a process continuum from resedimentation processes, through semi-permanent bottom-currents, to pelagic settling. In essence, the scheme is descriptive of the sedimentary attributes of sediments, although it is designed to aid interpretation of possible sediment transport/deposition processes. The classification scheme is three-tier with facies classes, groups and constituent facies, and is hierarchical to allow flexibility in its use.

There are seven facies classes, with Classes A–E defined largely on the basis of grain-size differences, Class F on the basis of internal organization, and Class G on composition. The facies classes are: Class A, gravels, muddy gravels, gravelly muds, and pebbly sands, with $\geqslant 5\%$ gravel grade; Class B, sands, with $\geqslant 80\%$ sand grade and $< 5\%$ pebble grade; Class C, sand–mud couplets and muddy sands, with 20–80% sand grade and $< 80\%$ mud grade (mostly silt); Class D, silts, silty muds and silt–mud couplets, with $> 80\%$ mud, $\geqslant 40\%$ silt and 0–20% sand; Class E, muds and clays, with $\geqslant 95\%$ mud grade, $< 40\%$ silt grade and $< 5\%$ sand and coarser grade; Class F, chaotic deposits, with variable grain or clast sizes, and Class G, biogenic oozes, hemipelagites and chemogenic sediments, with $< 5\%$ terrigenous sand and gravel. The second-order classification into facies groups (A1, A2 etc.) is based mainly on organized versus disorganized sediments, the latter lacking marked stratification or grading and the former having clearly-defined primary sedimentary structures. At the level of facies, the criteria used to distinguish different types is more complex and more flexible.

For the purpose of large-scale mapping or reconnaissance fieldwork, either the level of facies classes or groups may be appropriate, whereas for more detailed sedimentology the more detailed facies level will be necessary.

INTRODUCTION

Deep water siliciclastic rocks and sediments are widely reported from modern and ancient environments. Their abundance has led to the need for a

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Kevin T. Pickering, B.Sc., D.Phil., P.G.C.E., F.G.S., graduated from Bristol University, U.K., in 1976; and from Oxford University, U.K., in 1979 where he obtained a D.Phil. based on research into Late Precambrian deep-water sedimentation in Finnmark, N. Norway. In 1985, he joined Leiceister University, U.K., as a lecturer in sedimentology, prior to which he spent four years at London University, U.K. He has worked on: deep marine extensional fault-controlled sedimentation in the Late Jurassic of N.E. Scotland; Late Precambrian active margin sedimentation, Jersey, Channel Islands; Ordovician–Silurian active margin sedimentation and tectonics in north-central Newfoundland, and Ordovician foreland basin development, Quebec Appalachians, Canada. He was a shipboard scientist on the final cruise of R/V Glomar Challenger, DSDP Leg 96 in 1983, to study the Pleistocene–Holocene sedimentology of the Mississippi Fan, and Orca and Pigmy salt-diapir-controlled intraslope basins, Gulf of Mexico. His interests extend beyond academic reserach and teaching, with an active commitment to politics.

Dorrik A.V. Stow, B.A., M.A., Ph.D., F.G.S., graduated from Cambridge University, U.K., in 1974; and from Dalhousie University, Canada, in 1977 where he obtained a Ph.D. in marine geology. He subsequently worked in Britoil, Glasgow (3 years) and at Edinburgh University (NERC/Royal Society Edinburgh Research Fellow, 4 years), before moving to Nottingham Geology Department in 1984 as a lecturer in sedimentology. He has wide-ranging research interests, specialising in fine-grained deep-water sediments, and is an active consultant in petroleum sedimentology. His professional affiliations include the Geological Society (Council Member), Association of Geoscientists for International Development (Vice-President), SEPM (Associate Editor) and IAS (Vice-President elect).

Michael P. Watson, B.Sc., D.Phil., F.G.S., graduated from St. Andrews University, Scotland, in 1974. He then worked for three years as a petroleum geologist with British Petroleum. He completed his doctorate at Oxford University in 1981, researching into facies analysis and depositional models for Lower Palaeozoic submarine fan deposits in New World Island, Newfoundland. He joined British Petroleum in 1981, and worked on the North Sea where his interests in fan sedimentology continued with studies of the Jurassic and Tertiary submarine-fan hydrocarbon reservoirs. He is currently working for British Petroleum, as Chief Geologist, in the People's Republic of China, where his present interests are focused on basin analysis, seismic stratigraphy and tectonic controls on sedimentation in a diverse suite of basin types.

Richard N. Hiscott, B.Sc., Ph.D., graduated from Brock University, Canada, in 1974, and obtained a Ph.D. from McMaster University, Canada, in 1977 with work on Lower Palaeozoic deep-water sedimentation and tectonics in Quebec. He is currently employed as an associate professor at Memorial University, St. John's, Newfoundland. He has had considerable research experience in modern and ancient deep-water sedimentation, including: modern Scotian slope sediments; glacial–interglacial sediments, including turbidites, in Baffin Bay and the Labrador Sea (ODP Leg 105); Late Precambrian basin and slope deposits of the Avalon Zone, eastern Newfoundland; Cambro-Ordovician passive-margin debris flows, western Newfoundland; and Ordovician foreland basin flysch sedimentation, Quebec Appalachians, Canada. Outside of geology, his principal interest is the playing of Irish and Newfoundland fiddle music in a band that has recorded one LP record.

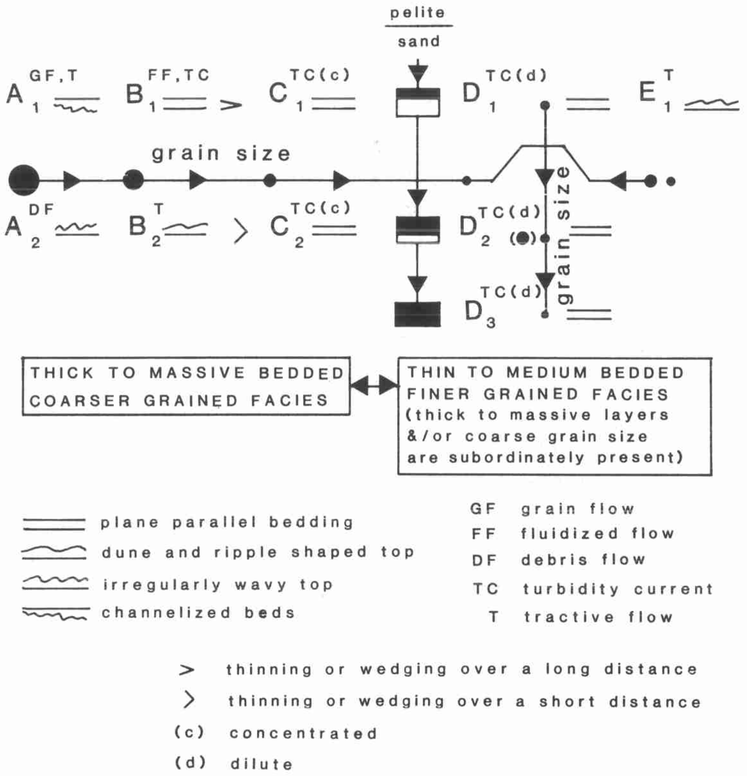


Fig. 1. Classification of deep-water deposits redrawn from Mutti and Ricci Lucchi (1975).

comprehensive classification in terms of facies, facies-associations and sequences, in order to develop and define depositional models for deep water sedimentation.

Currently, the widely used facies classification is that of Emiliano Mutti and Franco Ricci Lucchi (Mutti and Ricci Lucchi, 1972, 1974, 1975, 1978; Mutti, 1977). Their classification (Fig. 1) has proved extremely useful as a tool for interpreting deep water deposits because of its applicability to many successions. Other classifications exist, for example that of Carter (1975), but they have not been widely used because of the introduction of new and confusing terminology, their non-comprehensive nature, and the complex mixing of facies as descriptive terms for field observations with facies as interpretations of transport/deposition processes.

Recent research in modern and ancient deep water environments has led to a better understanding of transport/deposition processes (for a review, see Lowe, 1982), and the definition of facies that do not easily fit into the Mutti and Ricci Lucchi scheme (e.g., contourite deposits, oozes etc.). In view of the shortcomings of the current classification, we believe that there is a need for a comprehensive and flexible scheme of facies. We do not wish to under-value the immense benefits that have accrued from the Mutti–Ricci Lucchi scheme; however, after a decade of applying their classification, the time is ripe for a re-appraisal and re-classification based on more recent research data.

In this paper, we present an updated, thorough classification defining and describing each facies. While we emphasize the deep water siliciclastic facies, we include the associated pelagic–hemipelagic facies that may be largely biogenic in composition. We do not deal with the resedimented carbonates separately since these are considered to be similar to the siliciclastics but with certain notable differences (see Stow, 1984a, b). Finally, we discuss the possible depositional processes for the facies and erect a number of "facies models" that help characterize the features and explain the origins of the various facies. In this paper, we acknowledge that submarine glacial, volcanic (pyroclastic) and carbonate deposits are under-emphasized in relation to their significance. Partly, this is a result of a lack of detailed publications on these topics, but also it reflects the emphasis of this paper on resedimented siliciclastics. It is anticipated that a future modification of the scheme presented here will rectify such omissions.

Our policy with references, where possible, has been to choose the most recent citations that contain a summary of earlier work in a specific area of knowledge, thereby reducing a potentially monumental reference list to manageable proportions. Inevitably, in our search for brevity, we will have omitted some references that others may consider important contributions, but we hope that such omissions are at a minimum.

FACIES TERMINOLOGY

Since the concept of a facies was first introduced by Gressly (1838), there have been many reviews and modified definitions of the term (e.g., Potter, 1958; Teichert, 1958; Selley, 1970; Reading, 1978). For the purpose of our classification, we are using the term "facies" to mean a body of sedimentary rock/sediments with specific physical, chemical and biological characteristics. The chief attributes used to define the different facies are bedding style and thickness, sedimentary structures, composition and texture. The grain-size classes used in this review are defined in Fig. 2. The term 'bed' is generally omitted from our facies definition since it has connotations of deposition from a single sediment transport event and, clearly, it is inappropriate for some facies, for example thick hemipelagic/pelagic mud accumulations.

For the sake of brevity, we have mainly used the terminology for modern, unconsolidated sediments throughout this paper. The terms 'gravel', 'sand',

	U.S. Standard sieve mesh	Millimeters		Phi (φ) units	Wentworth size class
GRAVEL		4096		−12	
		1024		−10	Boulder
		256	256	−8	
		64	64	−6	Cobble
		16		−4	Pebble
	5	4	4	−2	
	6	3.36		−1.75	
	7	2.83		−1.5	Granule
	8	2.38		−1.25	
	10	2.00	2	−1.0	
SAND	12	1.68		−0.75	
	14	1.41		−0.5	Very coarse sand
	16	1.19		−0.25	
	18	1.00	1	0.0	
	20	0.84		0.25	
	25	0.71		0.5	Coarse sand
	30	0.59		0.75	
	35	0.50	1/2	1.0	
	40	0.42		1.25	
	45	0.35		1.5	Medium sand
	50	0.30		1.75	
	60	0.25	1/4	2.0	
	70	0.210		2.25	
	80	0.177		2.5	Fine sand
	100	0.149		2.75	
	120	0.125	1/8	3.0	
	140	0.105		3.25	
	170	0.088		3.5	Very fine sand
	200	0.074		3.75	
	230	0.0625	1/16	4.0	
SILT	270	0.053		4.25	
	325	0.044		4.5	Coarse silt
		0.037		4.75	
		0.031	1/32	5.0	
		0.0156	1/64	6.0	Medium silt
		0.0078	1/128	7.0	Fine silt
		0.0039	1/256	8.0	Very fine silt
MUD		0.0020		9.0	
		0.00098		10.0	Clay
		0.00049		11.0	
		0.00024		12.0	
		0.00012		13.0	
		0.00006		14.0	

Fig. 2. Definition of grain-size intervals used in the classification scheme of this paper (after Wentworth, 1967).

'silt', 'mud' and 'clay' are therefore used to include the ancient, lithified rock types, conglomerate, sandstone, siltstone, mudstone and claystone. Bed thicknesses are defined according to Ingram (1954): laminae, less than 1 cm; very thin beds, 1–3 cm; thin beds, 3–10 cm; medium beds, 10–30 cm; thick beds, 30–100 cm; and very thick beds, greater than 100 cm thick.

CLASSIFICATION SCHEME

The classification scheme that we propose is hierarchical in that facies definitions may be used on relatively simple or complex levels, depending upon the degree of exposure and clarity of sedimentary structures— thus, the scheme is flexible. Should a need for additional facies arise, our system allows for their introduction into the relevant place without drastically altering the scheme. Lumping together and, or, splitting of facies is possible, depending upon the operator's perception of the problem.

We propose a three-tier classification (Tables I, II, Fig. 3) into: (a) facies classes that contain (b) facies groups with (c) constituent facies. The seven facies classes are defined largely on texture of the gravelly, sandy or silty horizons; relative thickness of mud interbeds or caps, and also on internal organization, for Facies Class F, and on composition, for Facies Class G (Table II). For the second-order classification, Facies Classes A to E can be

TABLE I

Summary criteria for recognition of facies classes

Class	Texture of gravelly, sandy or silty divisions			Typical ratio of mud caps to basal gravel, sand or silt part *[1]
	%gravel	%sand	%mud	
A	⩾ 5	< 95	< 95	< 1:10
B	< 5	⩾ 80	< 20	< 1:10
C	< 5	20–80	< 80 *[2]	< 1:1 (up to 4:1)
D	0	0–20	> 80 *[2]	1:1
E	0	< 5	⩾ 95 *[2]	NA
F	chaotic ·			NA
G	< 5 terrigenous sand/gravel, mixtures of hemipelagic mud and biogenics			NA

*[1] Ratios are appropriate for DSDP/ODP-type cores at depths exceeding about 500 m. The ratios would need slight modification for rocks, and more substantial modification for piston cores (see composition data in Hamilton, 1976). NA = not applicable, due to muddy nature of all deposits.

*[2] For Facies Classes C, D and E, much of the mud component in basal 'cohesionless' divisions is silt, not clay.

TABLE II

Facies classes, facies groups and constituent facies for deep water sediments

A	GRAVELS, MUDDY GRAVELS, GRAVELLY MUDS AND PEBBLY SANDS ⩾ 5% gravel grade
A1	Disorganized gravels, muddy gravels, gravelly muds and pebbly sands
A1.1	Disorganized gravels: coarse-grained, poorly sorted clast-supported gravel lacking internal organization. Long-distance transport by high-concentration turbidity currents or debris flows, and final rapid sedimentation of all grains by frictional freezing. Some submarine glacial deposits, formed by dumping of mixed grain sizes during the melting of glacial tongues or icebergs may form this facies. Also, may be the residual deposit after strong bottom current winnowing has removed finer grain sizes.
A1.2	Disorganized muddy gravels: mainly matrix-supported structureless muddy gravel with 10–50% mud/clay grade sediment. Freezing due to inter-granular friction and cohesion from cohesive debris flow. Enormous slabs may slide into place on a cushion of over-pressured or liquefied mud. Some muddy gravels could result from thorough mixing of gravel with mud after sliding down steep slopes.
A1.3	Disorganized gravelly muds: matrix-supported structureless gravelly muds with 50–95% mud/clay grade sediment. Freezing from a cohesive debris flow, as shear stress at the base of the flow becomes less than the cohesive strength. Some gravelly muds could result from thorough mixing of gravel with mud after sliding down steep slopes.
A1.4	Disorganized pebbly sands: very poorly sorted cobbles, pebbles and granules dispersed in a matrix of sand, and lacking features of internal organization. Long-distance transport by high-concentration turbidity current, and finally rapid collective grain deposition of a pebble–sand mixture due to increased inter-granular friction. Also, dumping of mixed grain sizes from glacial tongues or icebergs in deep water.
A2	Organized gravels and pebbly sands
A2.1	Stratified gravels: thick-bedded moderately well sorted pebble–cobble gravel with parallel, low-angle and cross-stratification. Deposition from traction bedload beneath a high-concentration turbidity current. Possible reworking of submarine glacial deposits by strong bottom currents.
A2.2	Inversely graded gravels: thick/very thick-bedded, clast-supported gravel with inverse grading overlain by structureless or normally graded gravel. Rapid deposition by frictional freezing of a high-concentration traction carpet/dispersion beneath a high-concentration turbidity current.
A2.3	Normally graded gravels: thick/very thick-bedded clast-supported gravel with normal grading. Rapid suspension sedimentation from a high-concentration turbidity current.
A2.4	Graded stratified gravels: thick-bedded clast-supported gravel with normal grading, rarely inverse-to-normal grading, passing up into finer grained, commonly matrix-supported and stratified gravel or pebbly sand. Suspension and part traction sedimentation from high-concentration turbidity currents — velocity fluctuations may give rise to traction sedimentation of the finer grain sizes.

TABLE II (continued)

- A2.5 Stratified pebbly sands: medium/thick-bedded matrix-supported pebbly sand with stratification and, in some cases, grading. Deposition from traction bed-load or traction carpet at the base of a high-concentration turbidity current.
- A2.6 Inversely graded pebbly sands: thin/medium-bedded, occasionally thick-bedded, pebbly sand with either a single thin inversely graded zone at the base of the bed, or multiple inversely graded strata. Rapid deposition by frictional freezing of a traction carpet driven along by shear at the base of a high-concentration turbidity current.
- A2.7 Normally graded pebbly sands: thick-bedded poorly sorted pebbly sand with well developed normal grading. Rapid grain-by-grain deposition from suspension, with rapid burial and no significant traction transport on the bed, from a high-concentration turbidity current.
- A2.8 Graded stratified pebbly sands: lower unit of normally graded pebbly sand overlain by parallel, oblique of cross-stratification in essentially pebble-free granule sand. Suspension sedimentation of the coarsest fraction of a high-concentration turbidity current. Initially, deposition is so rapid that no subsequent traction transport takes place. At higher levels in the flow, grains are transported as bed-load to form stratification before being buried.

B SANDS

$\geqslant 80\%$ sand grade, $< 5\%$ pebble grade

B1 Disorganized sands

- B1.1 Thick/medium-bedded disorganized sands: thick/medium-bedded sands lacking grading and typically showing sharp flat bounding surfaces. Rapid deposition from a high-concentration turbidity current by freezing of a dense cohesionless suspension and, or, post-depositional liquefaction/fluidization to destroy any sedimentary structures that might have been formed. Sand creep or other grain flow processes on steep slopes could form disorganized sands.
- B1.2 Thin-bedded coarse-grained sands, lacking internal structures or grading. Sedimentation under traction processes; may be a lag deposit resulting from winnowing by strong bottom currents.

B2 Organized sands

- B2.1 Parallel-stratified sands: thick/medium-bedded sands, generally medium- to coarse-grained, with horizontal to near-horizontal stratification throughout. ‘Freezing’ of successively generated, thinner, traction carpets at the base of a high-concentration turbidity current. Grain interaction in this layer produces both the good imbrication and inverse grading. Massive divisions record rapid grain-by-grain suspension fall-out or ‘freezing’ of a thicker unsorted layer (as for Facies B1.1).
- B2.2 Cross-stratified sands: planar, concave to convex beds with high- to low-angle tabular or trough cross-stratification in medium- to granule-grade sands. Reworking of sands by tractional processes, beneath dilute turbidity currents or strong bottom currents, especially in confined channels and, or, in scours.

C SAND–MUD COUPLETS AND MUDDY SANDS

20–80% sand grade, $< 80\%$ mud grade (mostly silt)

C1 Disorganized muddy sands

- C1.1 Poorly sorted muddy sands: poorly sorted mud-rich sand, showing poorly defined normal grading. (?) Rapid deposition from muddy high-concentration turbidity currents or fluid sand-mud debris flows.

TABLE II (continued)

- C1.2 Mottled muddy sands: mostly thin/very thin beds, irregular, bioturbated and rarely laminated. Deposition from strong bottom currents over long periods of time with pervasive bioturbation, and some winnowing and erosion. Thorough bioturbation also is a possible process.
- C2 Organized sand–mud couplets
  - C2.1 Very thick/thick-bedded sand–mud couplets: very thick/thick-bedded sand–mud couplets, with well developed normal grading and commonly Tabc divisions. Deposition from high-concentration turbidity current.
  - C2.2 Medium-bedded sand–mud couplets: medium-bedded sand–mud couplets, with well developed normal grading and commonly Tbcd divisions. Deposition from high-concentration turbidity current.
  - C2.3 Thin-bedded, sand–mud couplets: thin-bedded sand–mud couplets, with well developed normal grading and commonly Tbcde divisions. Deposition from low concentration turbidity current.
  - C2.4 Very thick/thick-bedded, mud-dominated sand–mud couplets: very thick to thick beds with up to 80% in the form of a silty mud cap. Grading is step-wise, and successive divisions may show structures indicating approximately 180 degree reversals of flow. Deposition from large-volume, high-concentration turbidity currents contained within a basin with multiple reflections from basin slopes and internal basin highs. Rapid suspension settling of mud from the ponded mud cloud after cessation of flow.

D SILTS, SILTY MUDS AND SILT–MUD COUPLETS

$>80\%$ mud grade (of which $\geqslant 40\%$ is silt), $<20\%$ sand grade

- D1 Disorganized silts and silty muds
  - D1.1 Structureless silts: medium/thick-bedded structureless silts. Rapid mass deposition from a high-concentration, silt-dominated turbidity current, or very fluid silty debris flow.
  - D1.2 Muddy silts: poorly sorted structureless to poorly graded muddy silts. Rapid deposition of silt grains and mud flocs from a high-concentration, mud-dominated turbidity current. Some sediment creep or sliding may be involved.
  - D1.3 Mottled silts and muds: bioturbated irregular-shaped very thin beds and laminae, lenses and mottles of silt in mud. Deposition from bottom currents over prolonged time periods, with pervasive bioturbation destroying much of the original structure.
- D2 Organized silts, muddy silts and silt–mud couplets
  - D2.1 Graded stratified silts: variably-bedded normally graded stratified silts. Deposition from low-concentration turbidity currents.
  - D2.2 Thick irregular silt and mud laminae: lenticular and irregular silt laminae in mud, microstructures and partial graded laminated units. Relatively rapid deposition from low-concentration turbidity currents.
  - D2.3 Thin regular silt and mud laminae: thin to medium, horizontal, silt laminae in mud, often in graded laminated units. Relatively slow uniform deposition from low-concentration turbidity current. Silt grains and clay flocs are sorted in the viscous sublayer of the flow.

E MUDS AND CLAYS

$\geqslant 95\%$ mud grade (of which $<40\%$ is silt grade), $<5\%$ sand and coarser grade

- E1 Disorganized muds and clays

TABLE II (continued)

E1.1 Structureless muds: essentially structureless muds/clays with poorly defined bedding. Possibly relatively rapid deposition suspected, without significant planktonic biogenics. May result from the ponding of thick turbidity currents and, or, hemipelagic settling with some lateral transfer by deep-ocean currents or sliding processes.

E1.2 Varicoloured muds: varicoloured muds (red, green, brown, grey etc.), often interbedded and generally lacking sedimentary structures. Settling of individual particles or particle aggregates (flocs and faecal pellets).

E1.3 Mottled muds: poorly bedded bioturbated muds with few sedimentary structures. Probably bottom-current-influenced muddy contourites or hemipelagites, often with significant lateral transport.

E2 Organized muds

E2.1 Graded muds: well bedded, graded (often colour-graded) muds, sometimes with very thin silt laminae at the base and bioturbation towards the top. Deposition from low- and high-concentration turbidity currents.

E2.2 Laminated muds and clays: finely laminated or fissile, often dark-coloured organic-rich muds and clays. Grain-by-grain or aggregate settling, low-concentration turbidity currents; varves related to periodic fluctuations in the influx of terrigenous sediments; anoxic bottom waters favour the preservation of organic matter.

F CHAOTIC DEPOSITS

F1 Exotic clasts

F1.1 Rubble: mostly angular to subangular cobbles and boulders of varying composition as lithified and, or, consolidated sediment, associated with later sediment infilling and draping. Submarine rockfall, avalanching and sliding along glide planes and debris flow. Some large blocks travelling in debris flows may have become 'grounded', even though the rest of the flow continued farther into the basin, leaving little or no depositional record in the vicinity of the block.

F1.2 Dropstones and isolated ejecta: clasts in isolation, or in groups, of substantially larger size than their 'matrix' or host sediment; host sediment commonly depressed beneath clasts. Ice-rafting and dumping of clasts due to : (1) melting of ice, or (2) the sudden over-turning of sediment-laden icebergs. Very rarely, dumping from seaweed rafts. Volcanic bombs from explosive eruption processes.

F2 Contorted/disturbed strata

F2.1 Coherent folded/contorted strata: coherent/semi-coherent folded and contorted strata on any scale. Mainly gravity-induced sediment sliding and slumping in which the shear strength is exceeded; some in situ, shock-induced deformation due to earthquakes, tsunamis etc. Also, some current shear applied to unconsolidated sediments beneath flowing sediment gravity flows.

F2.2 Dislocated, brecciated and balled strata: internally dislocated, brecciated and balled strata in layers of variable thickness. Processes similar to F2.1 with more pervasive internal deformation. Some in situ liquefaction and fluidization.

G BIOGENIC OOZES, HEMIPELAGITES AND CHEMOGENIC SEDIMENTS

$< 5\%$ terrigenous sand and gravel

G1 Biogenic oozes and arls

G1.1 Biogenic oozes: $> 75\%$ calcareous/siliceous biogenic material in layers of variable thickness, no primary sedimentary structures, bioturbation often pervasive. Very slow accumulation of calcareous/siliceous biogenic material by settling of single grains or aggregates through the water column.

TABLE II (continued)

G1.2 Muddy pelagic ooze (arl): 25–75% biogenics and mainly clay-size terrigenous material in layers of variable thickness, devoid of primary sedimentary structures with common bioturbation. Mainly very slow accumulation by settling, with dissolution or dilution of biogenic material. Clays may have been transported to the sea surface by wind and then settled through the water column.

G2 Hemipelagites

G2.1 Hemipelagite: 5–75% biogenics with > 40% of the terrigenous component as silt-grade material, as layers of variable thickness, devoid of primary sedimentary structures, commonly pervasively bioturbated. Relatively slow accumulation of biogenic and terrigenous material by settling, with substantial addition from land run-off, and some lateral transfer by weak mid- and bottom-water currents.

G3 Chemogenic sediments

(includes ferro-manganese nodules and crusts, phosphorites and other authigenic sediments)

divided into disorganized and organized facies groups (A1, A2, etc.); that is, those that lack clear stratification or grading and those that show clearly defined sedimentary structures. Facies Class F is mainly disorganized and can be divided into two groups: (1) exotic clasts, and (2) contorted strata. Facies Class G is divided into pelagic biogenic oozes, hemipelagites and chemogenic sediments.

Our classification is based entirely on the descriptive elements of the facies although it is designed to aid interpretation of the possible transport/deposition processes. We do not claim that we have covered every conceivable facies since there are many rare, unusual deposits. However, the flexibility of our classification should enable a researcher to modify the scheme at our facies level in order to fully describe the deposits without radically altering the essence of our categories.

We have retained the general outlines of the Mutti–Ricci Lucchi scheme. However, the main differences are: (a) the abolition of their Facies E that is now subsumed in parts of the other facies; (b) the restriction of Facies Class D (their Facies D) to silt and silt–mud units, rather than including sands; (c) the addition of a much-needed new Facies Class E for muds; and (d) the definition of three tiers of classification rather than two, allowing for a greater number of facies within a scheme that is still manageable.

Facies classes, groups and constituent facies are preferred to facies with sub-facies because of the definition of a facies as the fundamental building block in understanding sedimentary environments. It should be stressed, however, that facies are mostly defined at fixed points on what is really a spectrum of facies resulting from process-continuums in the marine environment. Confusion and ambiguity is therefore likely to arise, particularly with

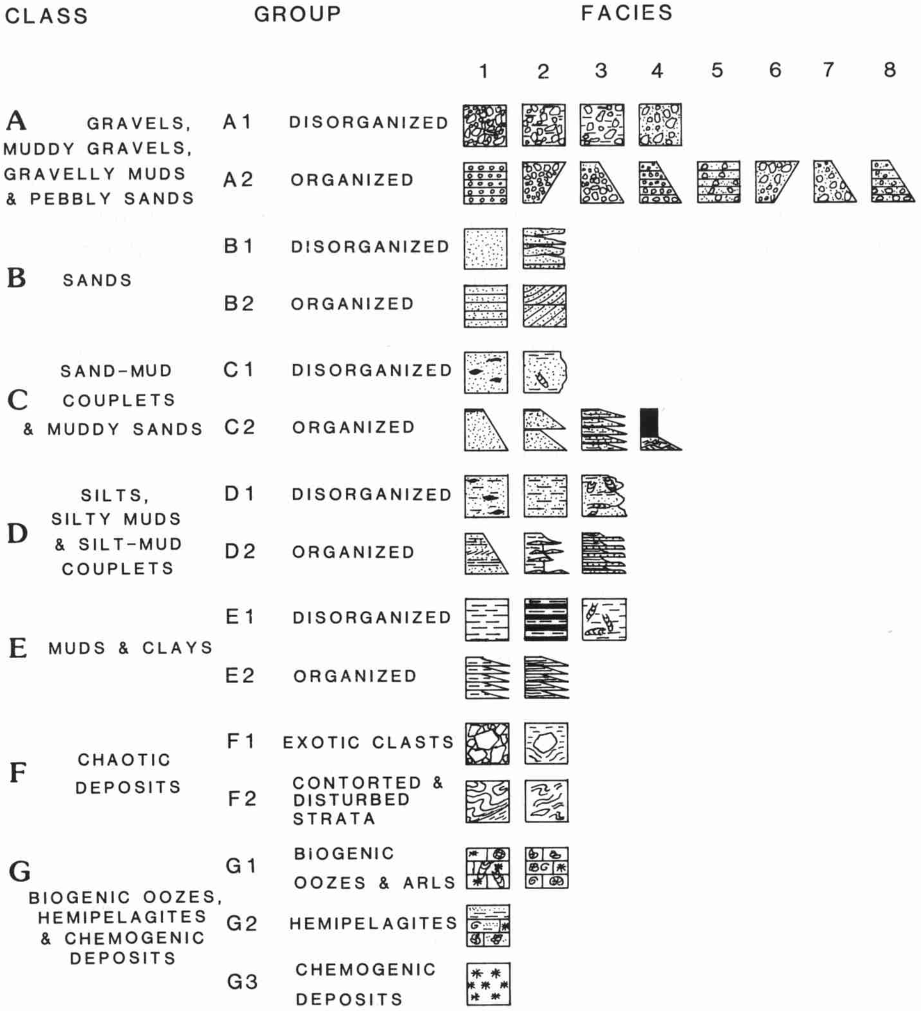


Fig. 3. Classification scheme for deep-water sediments used in this paper. Diagram illustrates hierarchical nature of scheme. Facies classes are defined on the basis of grain size (Facies Classes A–E), internal organization (Facies Class F) and composition (Facies Class G). Facies groups mainly are distinguished on the basis of internal organization of structures and textures. Individual facies are based on internal structures, bed thicknesses and composition.

'intermediate' sediment types. Although there are shortcomings in our scheme, we believe that it represents a useful and valuable up-dating of the last decade of research into deep-water deposits. It is based on a large amount of data from modern sediments and processes, as well as ancient rock successions.

For the purposes of large-scale mapping or reconnaissance fieldwork, either the level of facies class or facies group may be appropriate (Table II).

For much more detailed sedimentology, the more complete facies level will be necessary.

Finally, it should be noted that facies classes and groups are composed of facies taken out of context from adjacent facies, whereas facies-associations represent the temporal and spatial association of facies. In erecting models to describe and define the various deep-water sedimentary environments, it is often useful to lump facies together, and it is at this level of description that our facies classes and groups become particularly useful.

FACIES CLASS A — GRAVELS, MUDDY GRAVELS, GRAVELLY MUDS, PEBBLY SANDS; ⩾ 5% GRAVEL GRADE

Facies Class A consists of the coarsest grained members of deep water clastic sediments, with greater than 5% pebble-grade or coarser material. This facies class includes clast-supported gravels, gravels with a supportive sand matrix, muddy gravels and gravelly muds. The latter two lithologies may contain more mud than gravel, but their transport process may be identical to that of deposits of this class with a small amount (< 10%) of mud matrix; these mud-rich deposits were included in Facies Class F by Stow (1985).

Deep water gravels and pebbly sands are commonly termed 'resedimented' to set them apart from the fluvial and shallow marine deposits: they are believed to have accumulated first in shallow water and subsequently to have been resedimented into deeper water (Walker, 1975a). In many cases, features of resedimented gravels taken in isolation from the associated facies and features of a succession are not sufficient evidence for indicating deep-water sedimentation. The resedimented gravels, muddy gravels, gravelly muds and pebbly sands possibly include some of the glacio-marine sediments that accumulate in deep water; others are in Facies Class F.

Following extensive research on deep-water gravels and conglomerates, there now appears to be a consensus about the main features to observe and record (Walker, 1975a,b, 1977, 1978; Davies and Walker, 1974; Surlyk, 1978, 1984; Hein, 1982; Hein and Walker, 1982). However, the relative significance that should be attached to such features remains equivocal. Walker (1975a) attempted to establish a descriptive model for resedimented conglomerates that incorporated the sedimentary structures into a sequence analogous to the Bouma sequence (Bouma, 1962) for turbidites. In this and subsequent papers (Walker, 1976, 1977, 1978), Walker developed the model to suggest four end-members (Fig. 4). He believed that the depositional process and the rate of deposition determined the degree of organization in the final conglomeratic deposit. This fundamental dichotomy between 'organized' and 'disorganized' conglomerates forms the basis of most classifi-

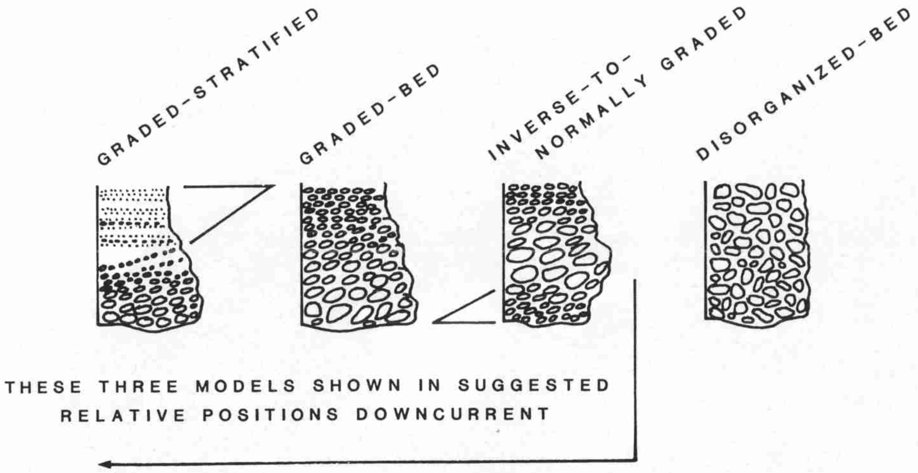


Fig. 4. Four models for resedimented conglomerates redrawn from Walker (1978). Characteristics are: (1) "graded-stratified model", imbrication, stratification, no grading; (2) "graded-bed model", imbrication, no inverse grading, no stratification; (3) "inverse-to-normally graded model", imbrication, no stratification; and (4) "disorganized-bed model", imbrication rare, no grading, no inverse grading, no stratification.

cations (e.g., Walker and Mutti, 1973; Kelling and Holroyd, 1978; Walker, 1978; Piper et al., 1978), and for similar reasons we likewise adopt this approach. Walker (1975a) speculated that conglomerate facies are arranged spatially such that disorganized beds are most proximal, inverse-to-normally-graded beds are intermediate in position, and graded and graded–stratified beds are most distal. Surlyk (1978, 1984) carefully documented the spatial distribution of conglomeratic facies for 15 km away from a steep, faulted basin margin in East-Greenland, and found no such spatial pattern. Instead, Surlyk found that conglomerate facies appear to have no simple relationship with proximality.

Facies Group A1, 'disorganized gravels, muddy gravels, gravelly muds and pebbly sands'

Gravels in this group may be supported by clast contacts, by a sand matrix, or by a mud matrix. Bed thicknesses are variable, although these deposits tend to occur in medium to thick and very thick beds. The shape of beds reflects the topography over which the sediment gravity flow travelled to a greater extent than the internal hydrodynamic parameters within a flow. Four facies are recognized: A1.1 = disorganized gravels; A1.2 = disorganized muddy gravels; A1.3 = disorganized gravelly muds; and A1.4 = disorganized pebbly sands.

Fig. 5. Disorganized gravel (Facies A1.1), Upper Ordovician–Lower Silurian Milliners Arm Formation, New World Island, Newfoundland. Hammer for scale 35 cm. Beds young towards top of plate.

Facies A1.1 — disorganized gravels

Recognition: coarse-grained, poorly sorted clast-supported gravel lacking internal organization (Fig. 5).

In general, this facies is thicker bedded relative to other gravel facies, and, exceptionally, single beds appear to reach several tens of metres although, more commonly, thicknesses are from 0.5 to 5 m. However, in some cases, beds or layers may be thin to very thin as stringers of gravel as little as one pebble thick. Beds may be flat-based to deeply scoured. Upper surface geometry may be irregular, wavy or with individual clasts projecting above the bed. Laterally, there may be gradual dilution of the clasts such that ill-defined stringers of clasts give a crude stratification. Lateral dilution of clasts can also occur as a 'tailing' giving pod-shaped gravel bodies.

Clast size ranges from fine pebble to boulder grade, and beds are characteristically poorly sorted. Clast shape is dependent upon composition and inherited shape, consequently disorganized gravels have been described with well-rounded clasts, as well as those that are better defined as breccias.

This facies generally contains clasts that lack an ordered fabric, although if concentrated, elongate clasts may exhibit a poorly defined parallel align-

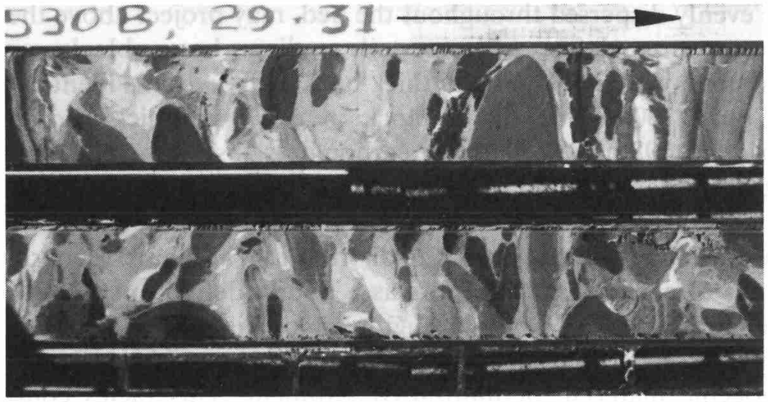


Fig. 6. Disorganized muddy gravel (Facies A1.2). Plio–Pleistocene sediments, DSDP Leg 75, Site 530B, Angola Basin. Core widths 7 cm.

ment with bedding, or a slight imbrication (Hiscott and James, 1985). Mudstone intraclasts commonly occur and may be plastically deformed at high angles to bedding, or aligned parallel with bounding surfaces. Facies A1.1 may pass laterally and, or, vertically into Facies A1.4 (see below); i.e., with increasing dilution of clasts, in a finer grained matrix, disorganized gravels grade into disorganized pebbly sands.

Depositional process: long-distance transport by high-concentration turbidity currents or debris flows, and final rapid sedimentation of all grains by frictional freezing. Some submarine glacial deposits, formed by dumping mixed grain sizes during the melting of glacial tongues or ice-bergs may form this facies. Some Facies A1.1 may be the residual deposit after strong bottom-current winnowing to remove finer grain sizes.

Selected references: Marschalko, 1964, 1975; Hendry, 1973; Carter and Norris, 1977; Long, 1977; Stanley et al., 1978; Surlyk, 1978, 1984; Winn and Dott, 1978; Johnson and Walker, 1979; Nemec et al., 1980; Hein, 1982; Hein and Walker, 1982; Hiscott and James, 1985.

Facies A1.2 — disorganized muddy gravels

Recognition: mainly matrix-supported structureless muddy gravel with 10–50% mud/clay grade sediment (Fig. 6).

Facies A1.2 is matrix-supported structureless muddy gravel with 10–50% mud/clay grade matrix. Units are medium to very thick-bedded. Bed shape may appear tabular in small outcrops, but many beds taper to a blunt snout. The base of beds generally show little erosion into underlying units, but the tops of beds commonly are irregular and hummocky. Large cobbles and boulders may be evenly dispersed throughout the bed, may project above the top of the unit, or may define a coarse-tail grading. Large blocks or olistoliths may be contained in 100–200 m thick beds with divisions identical to this facies, e.g., a 300 × 150 × 30 m block in a 170 m thick bed in Yugoslavia (Marjanac, 1985), and platform carbonate slabs 50 m thick and about 1 km long in 'megaturbidites' up to 200 m thick in Spain (Labaume et al., 1983).

Clasts tend to show a polymodal grain size distribution, and have a poorly organized fabric. If a fabric exists, it occurs as a poorly defined parallel to sub-parallel lamination and, or, a crude alignment of disc- or rod-shaped clasts in bedding. Clast composition may be igneous, metamorphic, sedimentary, lithified biogenic material, or unlithified sediment. This facies commonly is associated with other Class A deposits or with deposits of Class F.

Depositional process: freezing due to inter-granular friction and cohesion from cohesive debris flow. Enormous slabs may slide into place on a cushion of over-pressured or liquefied mud. Some muddy gravels could have formed from thorough mixing of gravel and mud after sliding down steep slopes (see Crowell, 1957).

Selected references: Jeffery, 1922; Crowell, 1957; Johnson, 1965, 1970; Hampton, 1972, 1975; Mutti and Ricci Lucchi, 1972; Rodine and Johnson, 1976; Embley, 1976; Enos, 1977; Middleton and Southard, 1978; Kurtz and Anderson, 1979; Winn and Dott, 1979; Damuth and Embley, 1981; Naylor, 1982; Page and Suppe, 1981; Lowe, 1982; Labaume et al., 1983; Pickering, 1984a; Hiscott and James, 1985; Marjanac, 1985.

Facies A1.3 — disorganized gravely muds

Recognition: matrix-supported structureless gravelly muds with 50–95% mud/clay grade sediment (Fig. 7).

Facies A1.3 includes the pebbly mudstones and olistostromes described from many rock successions, particularly at ancient active continental margins. The characteristics are similar to those of Facies A1.2, except that the deposits contain 50–95% mud or clay grade sediment. Beds range from decimetres to metres in thickness, although individual beds may be tens of metres thick. Many beds are laterally discontinuous and very irregular in geometry at outcrop scale, and show marked variations in the degree of internal organization, matrix content and bed shape over very short lateral distances. Grading is absent.

Clast compositions are like those of Facies A1.2, commonly with the addition of abundant silt–mud chips and slabs. In ancient examples, the ductility contrast between the matrix and clasts may result in a tectonically sheared matrix surrounding relatively undeformed clasts, as in some melanges.

Fig. 7. Disorganized gravelly mud (Facies A1.3). Late Precambrian Kongsfjord Formation, Finnmark, N. Norway. Hammer for scale 35 cm. Prominent parting surfaces are cleavage-bedding intersections.

Depositional process: freezing from a cohesive debris flow, as shear stress at the base of the flow becomes less than the cohesive strength. Some gravelly muds could form from thorough mixing of gravel and mud after gravel sliding down steep slopes into mud (see Crowell, 1957).

Selected references: as for Facies A1.2.

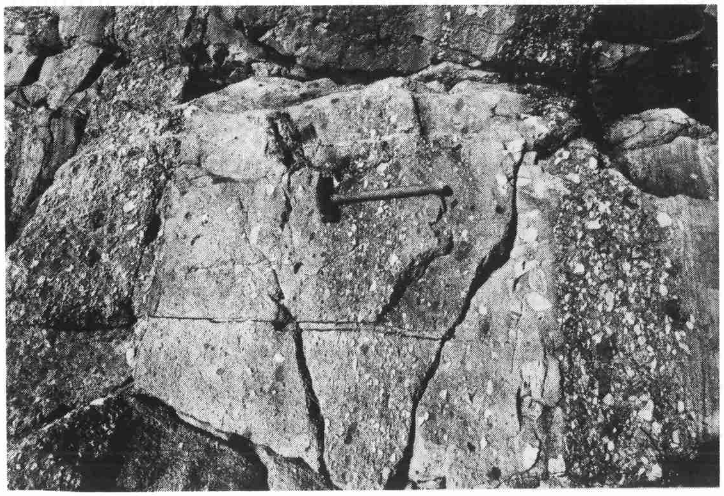


Fig. 8. Disorganized pebbly sand (Facies A1.4). Upper Ordovician–Lower Silurian Milliners Arm Formation, New World Island, Newfoundland. Hammer for scale 35 cm. Beds young to right.

Facies A1.4 — disorganized pebbly sands

Recognition: very poorly sorted cobbles, pebbles and granules dispersed in a matrix of sand, and lacking features of internal organization (Fig. 8).

Facies A1.4 is distinguished from A1.1 (above) by the dispersion of larger clasts in a finer grained matrix. By definition, the matrix is sandy although mud-grade sediment can account for up to a few percent. Increasing mud content means a gradation into gravelly mud (A1.3) and related deposits such as 'slurry deposits' (Carter, 1975), diamictites (Winn and Dott, 1979) or tilloids, and slides and slumps (see Facies Class F).

Bed shape and thickness are similar to Facies A1.1. Where clasts are widely dispersed, the definition of bedding surfaces is poor. Scouring, loading and larger-scale sole marks are well documented from pebbly sands. Clasts of fine to coarse pebble-grade appear to be most common, with cobbles and boulders dispersed in a sandy matrix being less common. Clast concentration is variable, with irregular patches and stringers of more concentrated clasts occurring down to one pebble in thickness; mudstone clasts are also common to Facies A1.4, and where such concentrations are very high, and the clasts are angular, the beds are best termed mud-flake breccias.

Grading, stratification, and preferred fabric of the larger clasts are generally absent in Facies A1.4. Larger clasts may be concentrated towards the base of a bed and then pass abruptly up into dilute pebbly sand. Alternatively, there may be a gradual upward decrease in the size of the 'floating' clasts to give the appearance of a coarse-tail grading.

Depositional process: long-distance transport by high-concentration turbidity current, and finally rapid collective grain deposition of a pebble–sand mixture due to increased inter-granular friction. Also, dumping of mixed grain sizes from glacial tongues or ice-bergs in deep water.

Selected references: Dzulynski et al., 1959; Bartow, 1966; Ricci Lucchi, 1969; Walker and Mutti, 1973; Carter and Lindqvist, 1975; Lowe, 1976a; Surlyk, 1978; Walker, 1978; Winn and Dott, 1978; Hein, 1982; Hein and Walker, 1982.

Facies Group A2, 'organized gravels and pebbly sands'

Organized gravels and pebbly sands are described with close reference to the evolutionary scheme of Lowe (1982). The following facies are erected:

A2.1	Stratified gravels;	A2.5	Stratified pebbly sands;
A2.2	Inversely graded gravels;	A2.6	Inversely graded pebbly sand;
A2.3	Normally graded gravels;	A2.7	Normally graded pebbly sands;
A2.4	Graded stratified gravels;	A2.8	Graded stratified pebbly sands.

While this scheme may appear cumbersome, the eight facies are easy to recognize, and in predominantly conglomeratic successions these divisions should prove considerably more useful than any simpler classification scheme.

Facies A2.1 — stratified gravels

Recognition: thick-bedded, moderately well sorted pebble-cobble gravel with parallel, low-angle and cross-stratification (Fig. 9).

Facies A2.1, stratified clast-supported gravels, appear to be rare relative to the other facies in this group. Stratification in resedimented gravels is most commonly reported in fine pebble gravels and pebbly sands; the only good examples of stratified coarse-grained clast-supported gravels known to us have been described by Winn and Dott (1977, 1978) from southern Chile and Hein (1982) from Quebec. These beds are lenticular and wedge-shaped with inclined strata up to 12 m in thickness and dune-shaped bodies up to 4 m thick. Individual strata range from a single pebble thickness to over 1 m thick. Scours and erosional sole marks have been described from these gravels (conglomerates).

Imbrication is well developed — Winn and Dott (1977, 1979) report *ab*-planes of clasts dipping upstream with *a*-axes parallel to the flow direction. Large scale stratification, especially where stratal boundaries are not sharp, may be difficult to distinguish from individual stacked graded and massive gravel beds.

Depositional process: deposition from traction bed-load beneath a high concentration turbidity current. Possible reworking of submarine glacial deposits by strong bottom currents.

Selected references: Winn and Dott, 1977, 1979; Hein, 1982.

Facies A2.2 — inversely graded gravels

Recognition: thick/very thick-bedded, clast-supported gravel with inverse grading overlain by structureless or normally graded gravel (Fig. 10).

Inversely graded gravels make up a significant proportion of many resedimented coarse-grained successions. Beds are commonly lenticular with basal erosion, lateral thinning and variations in clast concentration causing complex bed shapes. Inversely graded beds reach a maximum thickness of several metres, but most commonly seem to vary between 0.5 and 4 m. Poor sorting and large clast sizes are typical of this facies.

The diagnostic feature of this facies is inverse grading. Most commonly, it occurs in the thicker beds where the lowest 5–20% of the bed contains finer clasts (usually fine to coarse pebbles) compared to the immediately overlying parts. There is an abrupt transition from the basal finer grained zone to the coarser sediment, therefore, rather than inverse grading sensu stricto, the coarser clasts are concentrated at a certain distance above the base of a bed.

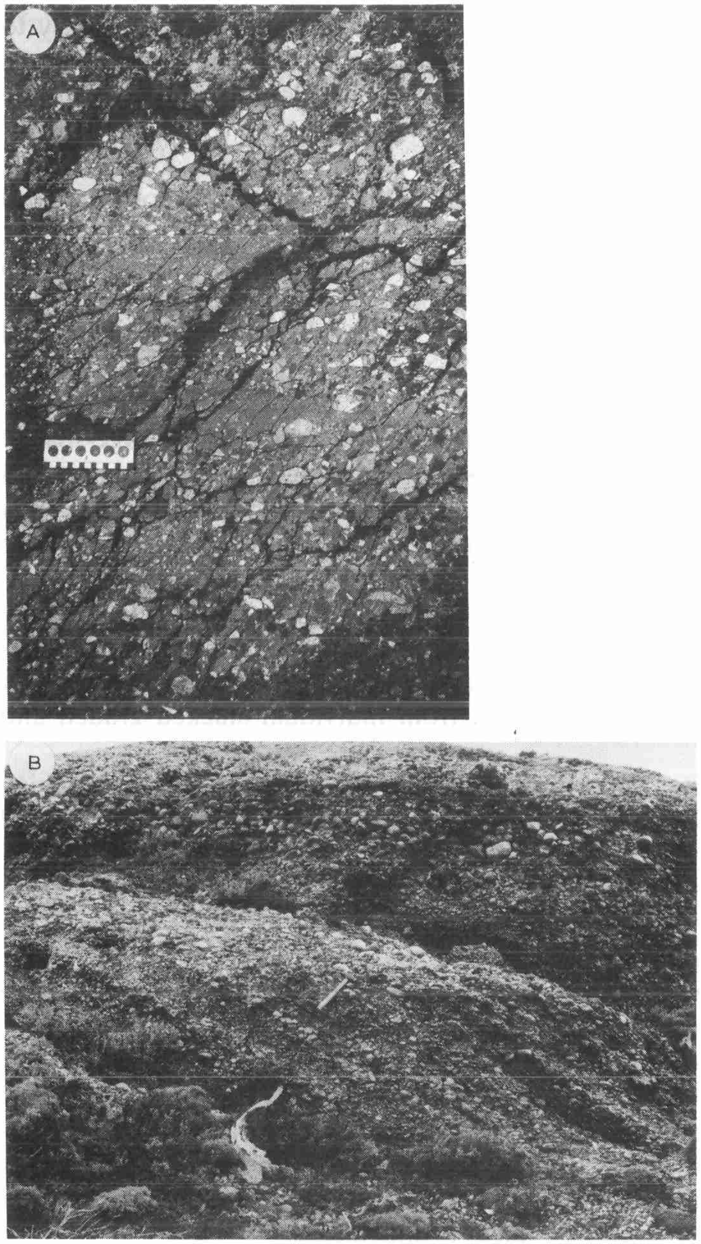


Fig. 9. A. Stratified gravel (Facies A2.1). Late Precambrian Rock Harbour Group, Flat Island, Placentia Bay, Newfoundland. Scale 15 cm. Beds young towards top of plate. B. Cross-stratified gravel/stratified gravel (Facies A2.1). Upper Cretaceous Lago Sofia Conglomerate, southern Chile. Photograph kindly supplied by R.H. Dott, University of Wisconsin, U.S.A. Hammer for scale.

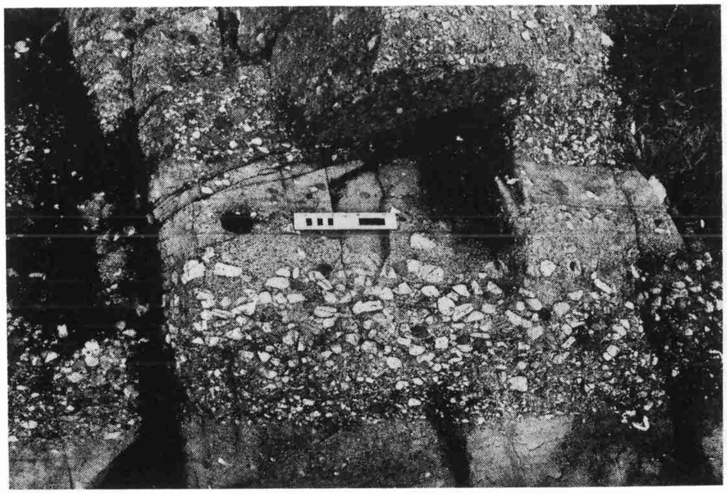


Fig. 10. Inversely graded gravel (Facies A2.2). Upper Ordovician–Lower Silurian Milliners Arm Formation, New World Island, Newfoundland. Scale 15 cm. Beds young towards top of plate.

Inverse grading may be developed such that distribution grading occurs from the finest through to the coarsest clasts. The entire bed may be inversely graded, or the gravel overlying the inversely graded zone may be structureless or normally graded. The tops of inversely graded gravels may be abrupt, showing a sharp break between gravel and sand, or there may be an upward increase in sand content such that the uppermost part of a bed has a bi-modal size distribution. Clast imbrication, as described above, appears to be better developed in the inversely graded gravels of Facies A2.2 than for any other facies.

Depositional process: rapid deposition by frictional freezing of a high concentration traction carpet/dispersion beneath a high concentration turbidity current.

Selected references: Davies and Walker, 1974; Surlyk, 1978, 1984; Howell and Link, 1979; Johnson and Walker, 1979; Winn and Dott, 1979; Nemec et al., 1980; Watson, 1981; Hein, 1982; Lash, 1984.

Facies A2.3 — normally graded gravels

Recognition: thick/very thick-bedded clast-supported gravel with normal grading (Fig. 11).

Normally graded gravels are mostly finer grained than inversely graded or disorganized beds within any single clastic succession. However, bed thicknesses are similar to those of the other gravel facies, ranging from about 0.5 to several metres. Beds show marked thickness changes as a result of

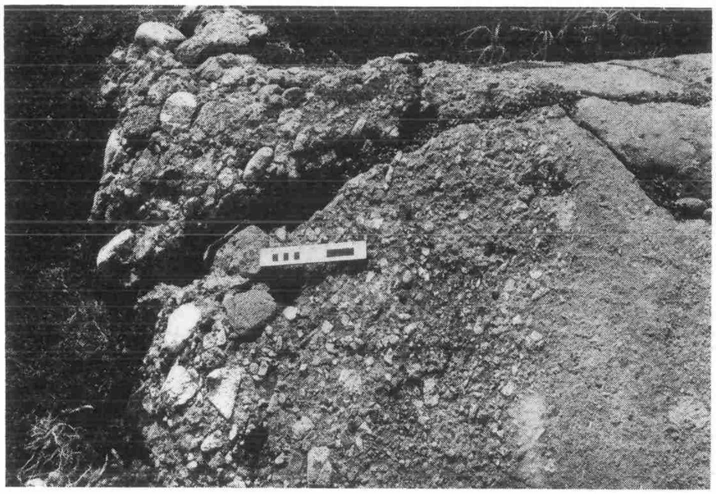


Fig. 11. Normally graded gravel (Facies A2.3). Upper Ordovician–Lower Silurian Milliners Arm Formation, New World Island, Newfoundland. Scale 15 cm. Beds young to right.

localized deep scour infills and more gradual large-scale down-cutting into less concentrated pebbly sands. Normally graded gravel appears to be one of the most abundant of the clast-supported facies.

Normal grading occurs in several modes. Abruptly graded beds mainly show a coarse-tail grading where the coarsest clasts are only present in the lowest part of a bed and rapidly give way upwards to fine pebbles. Distribution grading, showing grading throughout the bed from cobbles to granule sand, is less common but can occur in very thick beds. Imbrication appears to be less well developed in this facies compared with the inversely graded gravel facies (A2.2).

Depositional process: rapid suspension sedimentation from a high-concentration turbidity current.

Selected references: Marschalko, 1964; Hendry, 1972, 1978; Mutti and Ricci Lucchi, 1972; Davies and Walker, 1974; Walker, 1977; Winn and Dott, 1978; Nemec et al., 1980; Hein, 1982; Hein and Walker, 1982; Surlyk, 1984.

Facies A2.4 — graded stratified gravels

Recognition: thick-bedded clast-supported gravel with normal grading, rarely inverse-to-normal grading, passing up into finer grained, commonly matrix-supported and stratified gravel or pebbly sand (Fig. 12).

Graded stratified gravels have been described from several ancient deep-water clastic successions. Walker (1975a, 1976) established a 'graded-stratified bed model' in which parallel, inclined and cross-stratification overlie

Fig. 12. Graded stratified gravel (Facies A2.4). Late Precambrian Rock Harbour Group, Flat Island, Placentia Bay, Newfoundland. Beds young towards top of plate. Height of book is 20 cm.

graded gravel. Stratification appears to be developed in finer pebbly sand overlying the clast-supported gravel. Beds of graded stratified gravel are generally thinner bedded and finer grained than other clast-supported gravels. Bed shape is less variable, with sharp planar bases, although some scouring with trough-shaped scour-and-fill stratification is common.

Overall, the clast size may decrease towards the top of a bed as successive strata become finer grained. Alternatively, the lower clast-supported part of the bed may show 'delayed grading'. Graded stratified gravels are considered as transitional between the clast-supported cobble/pebble gravels and the matrix-supported pebbly sands.

Depositional process: suspension and part traction sedimentation from high-concentration turbidity currents — velocity fluctuations may give rise to traction sedimentation of the finer grain sizes.

Selected references: Hubert et al., 1970; Hendry, 1972; Mutti and Ricci Lucchi, 1972; Davies and Walker, 1974; Rocheleau and Lajoie, 1974; Walker, 1975a, 1976, 1977, 1978; Aalto, 1976; Surlyk, 1978, 1984; Johnson and Walker, 1979; Hein, 1982; Hein and Walker, 1982.

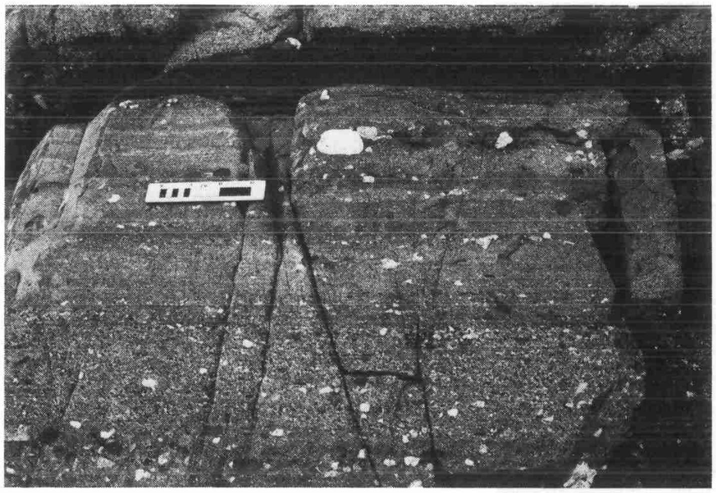


Fig. 13. Stratified pebbly sand (Facies A2.5). Upper Ordovician–Lower Silurian Milliners Arm Formation, New World Island, Newfoundland. Scale 15 cm. Beds young towards top of plate.

Facies A2.5 — stratified pebbly sands

Recognition: medium/thick-bedded matrix-supported pebbly sand with stratification and, in some cases, grading (Fig. 13).

Bed shape is highly variable, with typical bed thicknesses from 0.5 to 3 m. Defining individual beds may be difficult since a "unit" may represent composite events. Generally, entire beds are poorly sorted and coarse pebbles, and rarely cobbles, may be present as irregular stringers and scour fills.

Beds of stratified pebbly sands comprise an alternation of pebble and sand-rich layers that may show an overall grading. If such grading is well developed, then the beds are assigned to Facies A2.8. Commonly, individual strata have gradational contacts with both normal and inverse grading occurring. Strata may pinch and swell and split into irregular stringers and lenses. Stratification also occurs on a finer scale as granule-grade layers with a few pebbles alternating with coarse to medium-grained sand layers.

Depositional process: deposition from traction bed-load or traction carpet at the base of a high-concentration turbidity current.

Selected references: Hendry, 1973, 1978; Hein, 1982; Hein and Walker, 1982; Lowe, 1982; Surlyk, 1984.

Facies A2.6 — inversely graded pebbly sands

Recognition: thin/medium-bedded, occasionally thick-bedded, pebbly sand with either a single thin inversely graded zone at the base of the bed, or multiple inversely graded strata (Fig. 14).

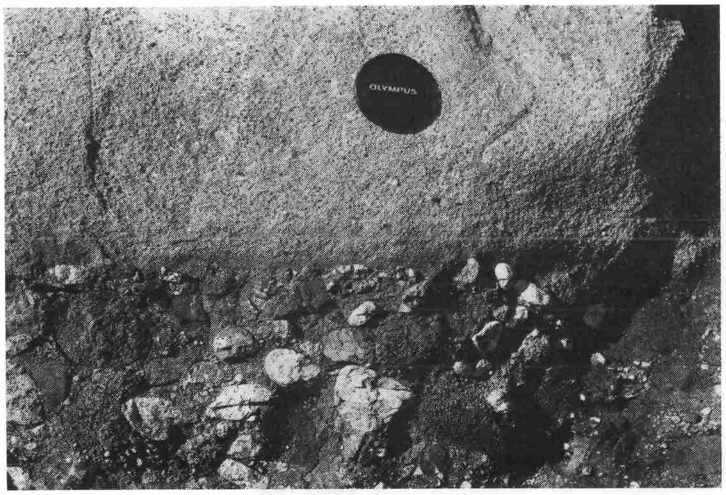


Fig. 14. Inversely graded pebbly sand (Facies A2.6). Upper Ordovician–Lower Silurian Milliners Arm Formation, New World Island, Newfoundland. Camera lens cap for scale. Beds young towards top of plate. N.B., only lower part of plate is Facies A2.6.

Pebbly sands with well developed inverse grading throughout are analogous to the inversely graded gravels of Facies A2.2, and appear to be relatively rare. However, it is more usual to find a pebble-free zone several centimetres thick that passes rapidly upwards into structureless or normally graded pebble sand. Alternatively, there may be several repeated finer grained, pebble-poor zones giving 5–10 cm thick indistinct stratification; in such cases, it is very difficult to define individual sedimentation units.

Facies A2.6 tends to occur in planar-based beds that generally are thinner than the other pebbly sand facies. Well developed multiple inversely graded layers suggest a transition into thicker bedded granule sands with 'near-horizontal stratification' (Facies B2.1).

Depositional process: rapid deposition by frictional freezing of a traction carpet driven along by shear at the base of a high-concentration turbidity current.

Selected references: Watson, 1981; Lowe, 1982.

Facies A2.7 — normally graded pebbly sands

Recognition: thick-bedded poorly sorted pebbly sand with well developed normal grading (Fig. 15).

Normally graded pebbly sands are very common in deep-water clastic successions. Generally, this facies is thicker bedded than the stratified and inversely graded pebbly sands. Common scour structures tend to give most beds an irregular appearance. Bed contacts may be diffuse where amalgamation occurs and clast concentrations are low.

Fig. 15. Normally graded pebbly sand (Facies A2.7). Upper Ordovician–Lower Silurian Milliners Arm Formation, New World Island, Newfoundland. 35 cm long hammer for scale in centre of plate. Beds young to right.

Facies A2.7 typically displays well defined normal grading that is most commonly coarse-tail grading, although distribution grading also occurs. There are many reported examples of Facies A2.7 showing normal grading from base to top in beds 2–3 m thick.

Depositional process: rapid grain-by-grain deposition from suspension, with rapid burial and no significant traction transport on the bed, from a high-concentration turbidity current.

Selected references: Hubert et al., 1970; Aalto, 1976; Long, 1977; Walker, 1977, 1978; Stanley et al., 1978; Watson, 1981; Hein, 1982.

Facies A2.8 — graded stratified pebbly sands

Recognition: lower unit of normally graded pebbly sand overlain by parallel, oblique or cross-stratification in essentially pebble-free granule sand (Fig. 16).

Facies A2.8 is similar to Facies A2.7 in terms of bed thickness, bed shape and clast size. Lateral transitions between these two facies are common. Basal scouring is common, and upper-bed contacts are sometimes poorly defined where stringers of pebbles occur high in a bed.

Beds show an overall normal grading although strata of coarser clasts are repeated upwards throughout beds. However, clasts coarser than very fine pebbles and granules appear to be confined to the lower graded portion of beds, such that stratification is developed mainly in sand and granules. Stratification ranges from parallel, through oblique, to multiple cross-cutting

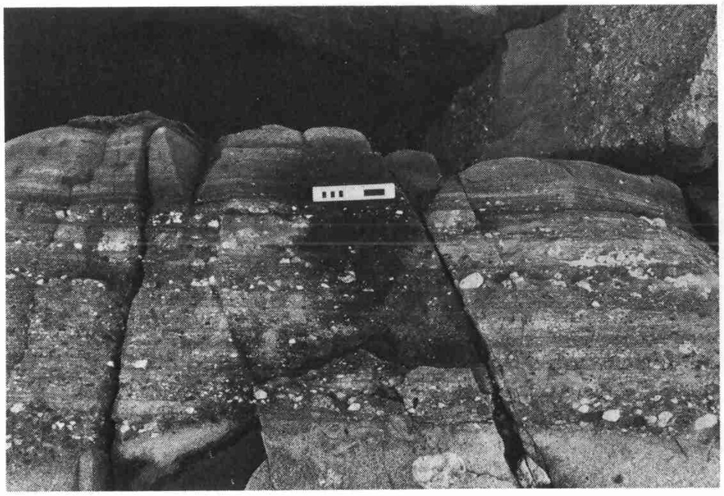


Fig. 16. Graded stratified pebbly sand (Facies A2.8). Upper Ordovician–Lower Silurian Milliners Arm Formation, New World Island, Newfoundland. Scale 15 cm. Beds young towards top of plate.

events with trough-filling and dune cross-bedding. Facies A2.8 is considered to be transitional between graded-stratified gravels of Facies A2.4 and the sands of Facies Class B (see below).

Depositional process: suspension sedimentation of the coarsest fraction of a high-concentration turbidity current. Initially, deposition is so rapid that no subsequent traction transport takes place. At higher levels in the flow, grains are transported as bed-load to form stratification before being buried.

Selected references: Hubert et al., 1970; Rocheleau and Lajoie, 1974; Aalto, 1976; Walker, 1978; Hein, 1982; Hein and Walker, 1982; Surlyk, 1984.

FACIES CLASS B — SANDS, ⩾ 80% SAND GRADE, < 5% PEBBLE GRADE

This class contains the sands with less than 20% mud and silt matrix and less than 5% pebble-grade material. Facies Class B is divided into organized and disorganized facies groups, based on sedimentary structures. Bed thickness and shape are highly variable. Class B embraces the large number of sands containing sedimentary structures that are not demonstrably part of the Bouma (1962) sequence.

Deposits with characteristics common to our Facies Class B are well documented, for example, some of the ‘arenaceous facies’ of Mutti and Ricci Lucchi (1972), the structureless beds of Sanders (1965), some ‘fluxoturbi-

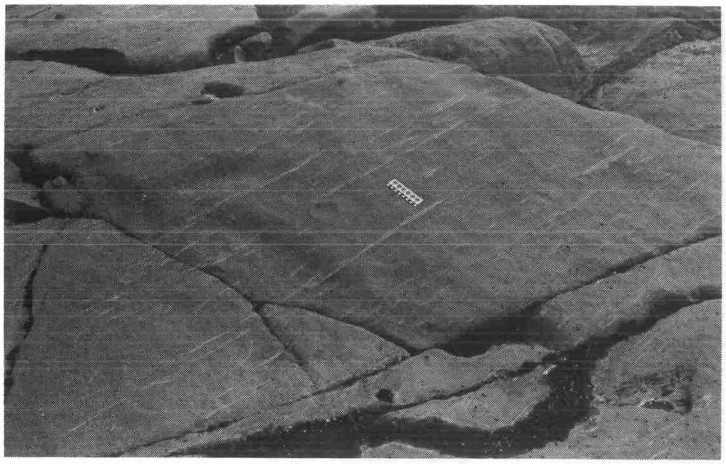


Fig. 17. Thick/medium-bedded disorganized sand (Facies B1.1). Lower Ordovician Tourelle Formation, Quebec, Canada. Scale 15 cm. Beds young towards top right of plate and view is approximately perpendicular to bedding. N.B., "vertical" fluidization structures.

dites' as described by Stanley and Unrug (1972), Dzulynski et al., (1959) and Kuenen (1964).

Facies Group B1, 'disorganized sands'

Disorganized or "massive" sands, comparable to Walker and Mutti's (1973) Facies B1 and B2 massive sands with or without dish structure, and Mutti and Ricci Lucchi's (1972) Facies B sands, are recorded from many flysch successions (Stauffer, 1967; Carter and Lindqvist, 1975; Keith and Friedman, 1977; Piper et al., 1978; Hiscott and Middleton, 1979; Cas, 1979; Hiscott, 1980; Lowe, 1982). Facies Group B1 consists of two facies.

Facies B1.1 — thick / medium-bedded disorganized sands

Recognition: thick/medium-bedded sands lacking grading and typically showing sharp flat bounding surfaces (Fig. 17).

Typically, Facies B1.1 consists of laterally continuous, parallel-sided to highly irregular, medium-to-thick beds. Grading is absent or poorly developed such that coarse-tail grading may occur with small pebbles and granules concentrated in a thin basal layer. The most obvious internal sedimentary feature may be fluid escape structures that tend to occur about half way up through a bed such as subvertical sheet structures (Laird, 1970), and dish structures associated with fluidization pipes and pillars (Wentworth, 1967; Lowe and Lopicollo, 1974; Lowe, 1975). Sole marks tend to be rare.

Aalto (1976) defined similar deposits as massive fine/medium-grained sands with sharp flat undulose or loaded bases. Cas (1979) referred to non-graded massive bedded divisions as 'a2' in which coarse-tail grading sometimes occurs. Jordan (1981) recognized similar deposits as massive and thickly bedded sands in which the beds lacked grading, Bouma sequences, sole marks and fine-grained interbeds. Also, Lowe (1982) defined an S3 division, typical of thick-bedded sands, showing many of the features in common with Facies B1.1.

Depositional process: rapid deposition from a high-concentration turbidity current by freezing of a dense cohesionless suspension and, or, post-depositional liquefaction/fluidization to destroy any sedimentary structures that might have been formed. Sand creep or other grain flow processes on steep slopes could form disorganized sands.

Selected references: Stauffer, 1967; Middleton, 1969, 1970; Carter and Lindqvist, 1975; Aalto, 1976; Lowe, 1976a; Keith and Friedman, 1977; Piper et al., 1978; Cas, 1979; Hiscott and Middleton, 1979; Jordan, 1981; Lowe, 1982.

Facies B1.2 — thin-bedded coarse-grained sands

Recognition: thin beds with granule/very coarse-grained sands, lacking internal structures or grading (Fig. 18).

Facies B1.2 is distinguished from the other facies in the class by its thin-bedded nature yet very coarse grain size. Beds mainly consists of very coarse/granule-grade material (rarely pebbles). Angular silt and mud clasts may occur in the beds that are otherwise structureless.

Beds are typically irregular with common wedging-out or pinch-and-swell geometry. Tops are sharp. This facies is associated with Facies B2.2 in many cases, and in some respects resembles Facies E of Mutti and Ricci Lucchi (1972, 1975), but is generally coarser grained and lacks internal structures. There is no grading, and rarely small pebbles may occur within beds as stringers: sometimes, pebbles protrude above the bed into overlying facies.

Depositional process: sedimentation under traction processes; may be a lag deposit resulting from winnowing by strong bottom currents.

Selected references: Mutti and Ricci Lucchi, 1972, 1975; Mutti, 1977.

Facies Group B2, 'organized sands'

Facies Group B2 includes any sand showing clearly defined sedimentary structures that are not clearly part of the Bouma sequence for sand-mud turbidites (Facies Group C2). Various fluid escape structures may be present (as in Facies Group B1) but without destroying substantial amounts of the original structures. Our Facies Group B2 contains deposits that show many

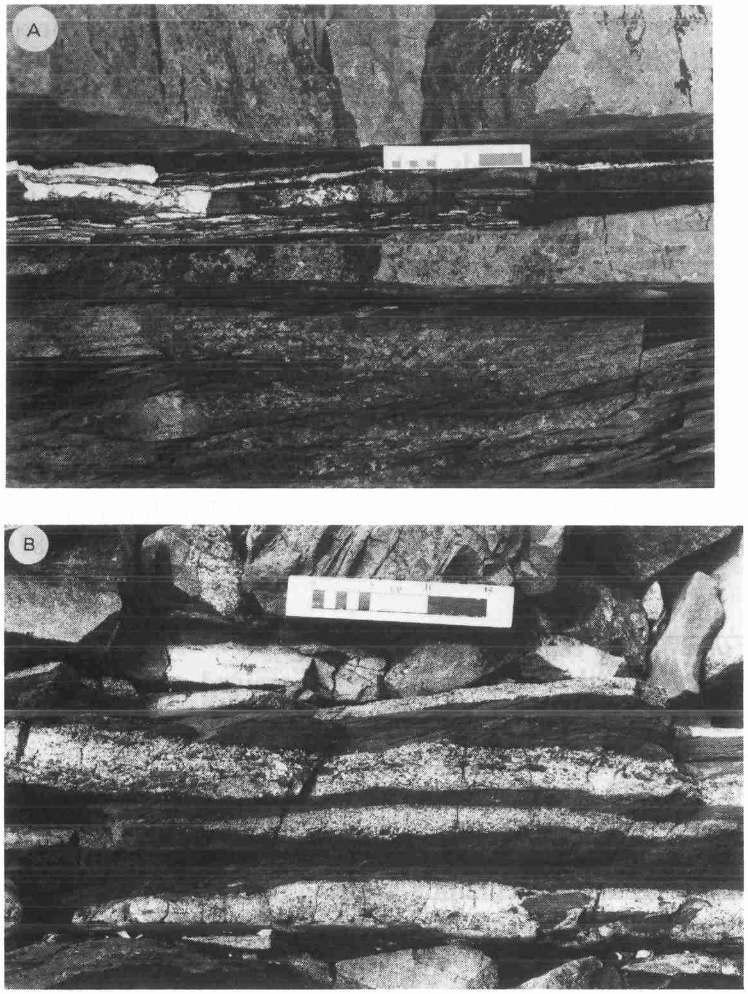


Fig. 18. A. Thin-bedded coarse-grained sand (Facies B1.2). Late Precambrian Kongsfjord Formation, Finnmark, N. Norway. Scale 15 cm. Prominent parting surfaces oblique to bedding are cleavage. Beds young towards top of plate. N.B., lenticularity of bedding. B. Thin-bedded coarse-grained sand (Facies B1.2). Upper Ordovician–Lower Silurian Milliners Arm Formation, New World Island, Newfoundland. 15 cm scale. Beds young towards top. Rare granule-grade example.

features of Mutti and Ricci Lucchi's sub-facies B1 and B2. We recognize two facies in this group.

Facies B2.1 — parallel-stratified sands

Recognition: thick/medium-bedded sands, generally medium to coarse-grained, with horizontal to near-horizontal stratification throughout (Fig. 19).

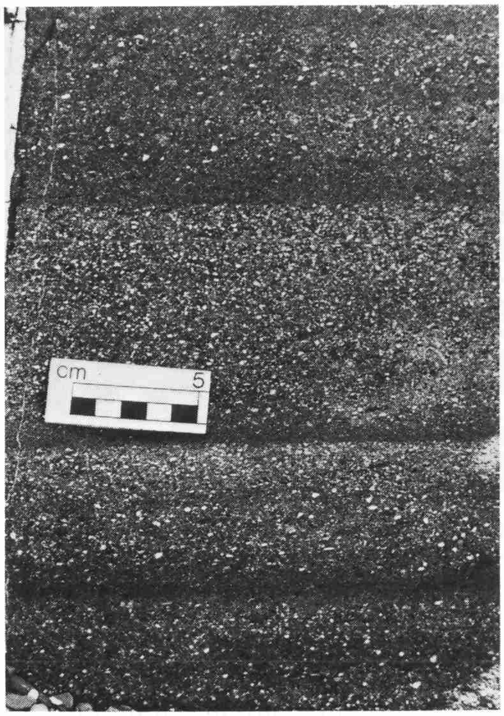


Fig. 19. Parallel-stratified sand (Facies B2.1). Middle Ordovician Cloridorme Formation, Quebec, Canada. Beds young towards top of plate.

Facies B2.1 typically consists of medium to thick beds with flat, planar upper and lower surfaces. Grain sizes are mainly in the range coarse to medium-grained sand, and there is a horizontal to near-horizontal stratification throughout part of the bed.

Hiscott and Middleton (1979, 1980) were the first to document this facies in detail. Much stratification in this facies is defined in bands up to 10 cm thick, each showing inverse distribution grading although, overall, there is normal grading in a bed. Stratification band bases may be erosive over lateral distances of several metres. Upwards through each stratification band, Hiscott and Middleton (1979) recognized the following sequence of structures and textures: (1) a basal horizontal or near-horizontal erosional surface; (2) a subdivision of inversely graded sand, typically grading from 2–3φ to approximately 1φ; and (3) a subdivision of massive -1 to 1φ sand, commonly showing good grain imbrication. Sand between divisions of near-horizontal stratification is massive and may contain fluid-escape structures like Facies B1.1. Bed tops grade into silt and may have an upper division of ripple lamination.

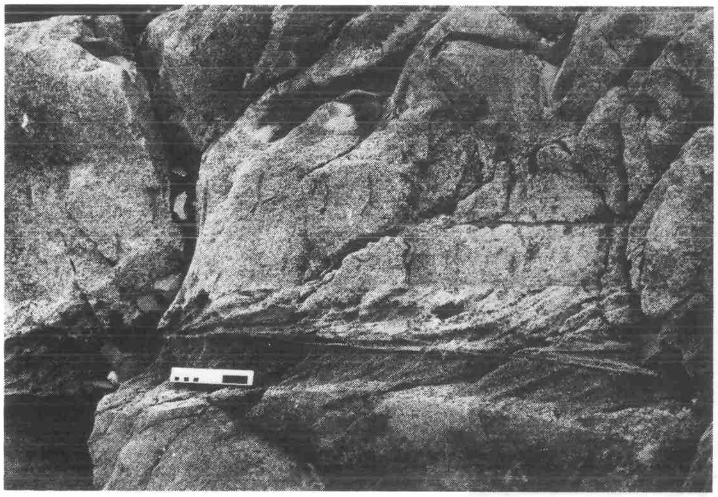


Fig. 20. Cross-stratified sand (Facies B2.2). Late Precambrian Kongsfjord Formation, Finnmark, N. Norway. Scale 15 cm. Beds young towards top of plate. N.B., two sets of relatively "clean" sand compared to the underlying sand. Facies B2.1 overlying cross-stratified sand.

Depositional process: 'freezing' of successively generated, thinner, traction carpets at the base of a high-concentration turbidity current. Grain interaction in this layer produces both the good imbrication and inverse grading. Massive divisions record rapid grain-by-grain suspension fall-out or 'freezing' of a thicker unsorted layer (as for Facies B1.1).

Selected references: Chipping, 1972; Mutti and Ricci Lucchi, 1975 (subfacies B1); Hendry, 1972; Hiscott and Middleton, 1979, 1980.

Facies B2.2 — cross-stratified sand

Recognition: planar, concave to convex beds with high- to low-angle tabular or trough cross-stratification in medium to granule-grade sands (Fig. 20).

Typically, Facies B2.2 consists of granule-grade to very coarse-grained sands that are much better sorted than any other sand facies. The thin-bedded varieties of this facies are distinctive in having a very coarse grain size for their thickness.

The beds consists of cross-stratification in sets that are typically from 10 to 25 cm thick. They may occur as single or multi-storey sets that are tabular to trough-like. Internally, the lamination ranges from low- to high-angle, planar to concavo-convex sets. Beds are commonly irregular with lensing, splitting and amalgamation: basal contacts may be erosive and the tops are sharply defined by single grain size changes as alternations of coarser and finer grained layers with concentrations of coarser grained material towards the toes of foresets. Individual sets may show high-angle laminae up to about 25° with only slightly tangential lower contacts, or else are asymptotic to bedding at their bases. Oversteepened and recumbently folded cross-bedding (similar to Type 1 of Allen and Banks, 1972) may occur in Facies B2.2. Also, although in relatively few cases, this facies contains abundant mud chips.

Recently, Valentine et al. (1984) document active dune forms of well sorted to poorly sorted, granular to slightly granular, coarse- to medium-grained sands at depths of at least 550 m, and up to 3 m high and with wavelengths up to 15 m.

Depositional process: reworking of sands by tractional processes, beneath dilute turbidity currents or strong bottom currents, especially in confined channels and, or, in scours.

Selected references: Scott, 1966; Hubert, 1966; Piper, 1970; Mutti and Ricci Lucchi, 1972; Hiscott and Middleton, 1979; Pickering, 1982a; Mutti, 1977; Lowe, 1982; Valentine et al., 1984. N.B., lenticular complexes with relatively thin-bedded "dune" forms have been defined as Facies E by Mutti and Ricci Lucchi (1972) and Mutti (1977): we assign such beds to our Facies B2.2.

FACIES CLASS C — SAND-MUD COUPLETS, AND MUDDY SANDS, 20–80% SAND-GRADE, < 80% MUD GRADE (MOSTLY SILT)

Facies Class C consists of sand–mud couplets in which the ratio of the sand to mud-grade sediment is usually greater than one. Most Facies Class C beds are described using the Bouma (1962) sequence Tabcde and the structures described by Sheldon (1928). Bed shape is variable and cannot be used to differentiate the constituent facies. In general, however, beds are sheet-like. In many cases, the deposits of single sediment gravity flows are graded, with most of the mud present in the upper part of the bed as a cap on top of the bed. In these cases, the lower sandy divisions may not be particularly muddy, even though the entire deposit is best called a muddy sand.

Deposits assigned to this class are amongst the most widely reported sediment gravity flow deposits found within flysch successions (e.g., Kuenen and Migliorni, 1950; Dzulynski et al., 1959; Bouma, 1962, 1964; Bouma and Brouwer, 1964; Dzulynski and Walton, 1965). Most of the research undertaken on the flow mechanics and resulting deposits has focused on turbidity currents (e.g., Kuenen, 1951; Middleton, 1966a, b, 1967a, b; Pantin, 1979; Luthi, 1981; Southard and Mackintosh, 1981; Parker, 1982; Middleton and Southard, 1984), therefore the depositional process for the facies of class C is well understood relative to most of the other deep marine processes.

This facies class is similar to, although not strictly speaking analogous to, Facies C1 and C2 of Mutti and Ricci Lucchi (1972, 1975) and Walker and Mutti (1973), which they defined on the basis of recognizing the Ta division. Facies Class C beds are the 'classic' turbidites of Walker (1976, 1978). The terms 'proximal' and 'distal' as qualifying terms for describing the beds in this class (as advocated by Walker, 1967, 1970) are not employed here in describing the thicker versus the thinner beds, respectively, because it is now widely recognized that such a distinction is often fallacious (see Nelson et al., 1975).

Facies Class C is divided into an organized and a disorganized group of facies, with facies distinctions being made on the basis of the internal sedimentary structures/features for the disorganized group, and bed thickness for the organized group. The rationale behind using bed thickness is that it appears to be a useful environmental indicator and permits easy recognition in the field. Bed thickness is broadly related to grain size and to the sequence of internal sedimentary structures, such that the facies represent a gradational spectrum from the coarsest and thickest to the thinnest and finest grained beds.

Facies Group C1, 'disorganized muddy sands'

Facies C1.1 — poorly sorted muddy sands

Recognition: poorly sorted mud-rich sand, showing poorly defined normal grading (Fig. 21).

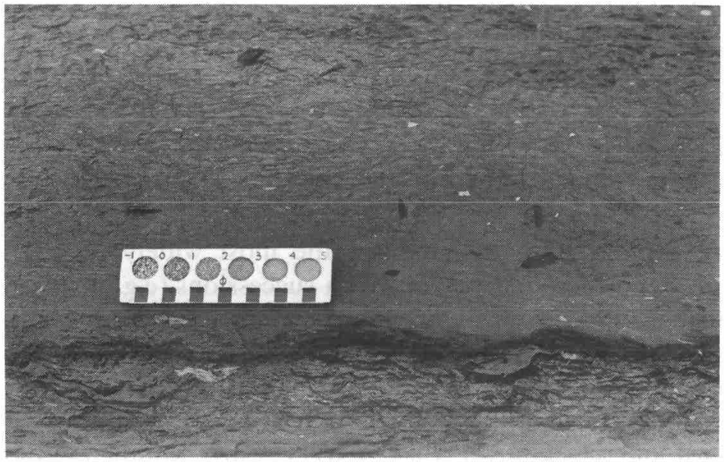


Fig. 21. Poorly sorted muddy sand (Facies C1.1). Lower Ordovician Tourelle Formation, Quebec, Canada. Scale 15 cm. Beds young towards top of plate. N.B., dispersed clasts, mainly of mudrocks.

Facies C1.1 is characterized by the high content of mud-grade sediment (up to 80%) in poorly sorted beds. Normal distribution grading may occur and, in some cases, a coarse-tail grading may be present in the very coarse/coarse-grained sand-grade. Typically, the uppermost part of a bed is silty mud and the lower part is muddy sand. Bounding surfaces are generally clearly defined, with the bases showing a range of sole marks whereas the tops are planar or gradational. Grain sizes are typically from coarse to fine-grained for the sand fraction.

Internal sedimentary structures are mainly absent, but indistinct parallel-lamination may occur in the lowest few centimetres, as well as convolute lamination associated with pseudonodules of silty mud. These liquefaction structures can give the beds a swirled appearance, and are partly responsible for the fact that they have been termed 'slurry beds' by some workers (Morris, 1971; Hiscott and Middleton, 1979; Strong and Walker, 1981). Silty mud clasts or 'chips' occur in varying proportions. In some beds, large rafts up to several metres long occur 'suspended' within the deposit (Hiscott, 1980). The beds are essentially structureless, but show a gradation into Facies Group C2 deposits.

Depositional process: (?) rapid deposition from muddy high-concentration turbidity currents or fluid sand-mud debris flows.

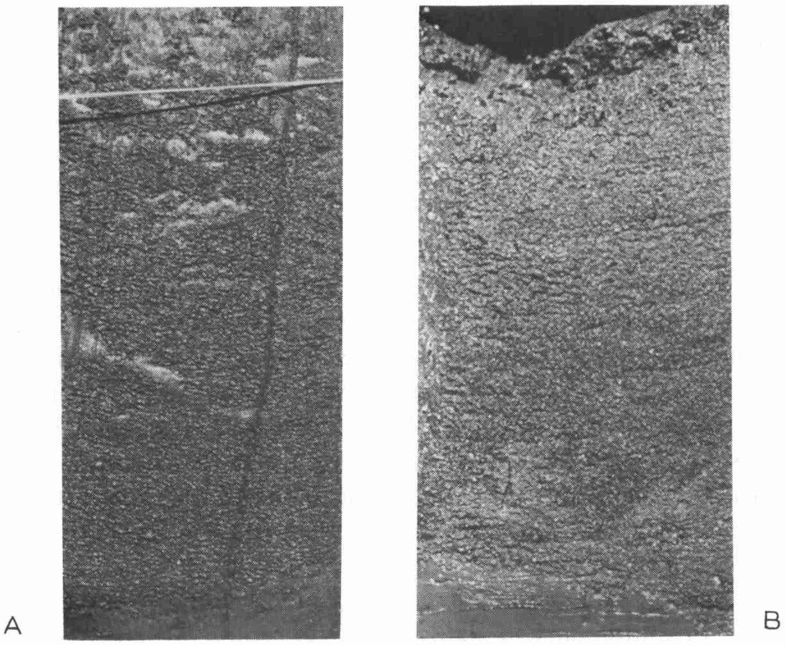


Fig. 22. Mottled muddy sand (Facies C1.2). Pleistocene Faro Drift, Gulf of Cadiz. Core widths 7 cm. N.B., bioturbational mottling throughout and absence of grading.

Selected references: Enos, 1969a, b; Burne, 1970; Morris, 1971; Skipper and Middleton, 1975; Mutti et al., 1978; Hiscott and Middleton, 1979; Hiscott, 1980; Strong and Walker, 1981; Pickering, 1981; Pickering and Hiscott, 1985.

Facies C1.2 — mottled muddy sands

Recognition: mostly thin/very thin beds, irregular, bioturbated and rarely laminated (Fig. 22).

Mottled muddy sands occur mostly as thin or very thin beds (range, less than 1 cm to greater than 20 cm), with an irregular to sub-parallel shape. Both tops and bases of beds may be sharp or gradational and are variable from one part to another of the same bed. Internal cross-lamination and parallel-lamination is rare, but irregular concentrations (layers or lenses) of coarser material are common. An indistinct normal or inverse grading can be present.

Bioturbation is often pervasive and may have destroyed much of the primary dynamic structure. The grain size is mostly fine-sand size (gradational to the mottled silts of Facies D1.3), and beds are poorly to moderately well sorted. The composition is often of a mixed terrigenous/biogenic nature, but this is clearly dependent on the original sediment source.

Depositional process: deposition from strong bottom currents over long periods of time with pervasive bioturbation, and some winnowing and erosion. Thorough bioturbation of turbidity current deposits also is a possible mechanism.

Selected references: McCave, 1979; Stow, 1982; Stow and Holbrook, 1984; Gonthier et al., 1984.

Facies Group C2, 'organized sand-mud couplets'

Facies Group C2 consists of the moderately well sorted to poorly sorted sand-mud units, often occurring as couplets, and generally showing partial or complete Bouma sequences Tabcde. Beds tend to show good normal grading (Kuenen, 1953; Ksiazkiewicz, 1954). Sole structures are common to many beds, and the base of the bed may show deep scour structures, load structures or be smooth and planar. The tops of the beds generally are smooth to planar if the upper part of a bed contains substantial amounts of silt and mud-grade sediment. Bioturbation may occur within or throughout a bed, but is more common towards the tops of beds.

The typical sequence of sedimentary structures, Tabcde, may be complete or show base-, top- or middle-absent sequences. Wet-sediment deformation occurs in many of the beds as various fluidization and liquefaction structures.

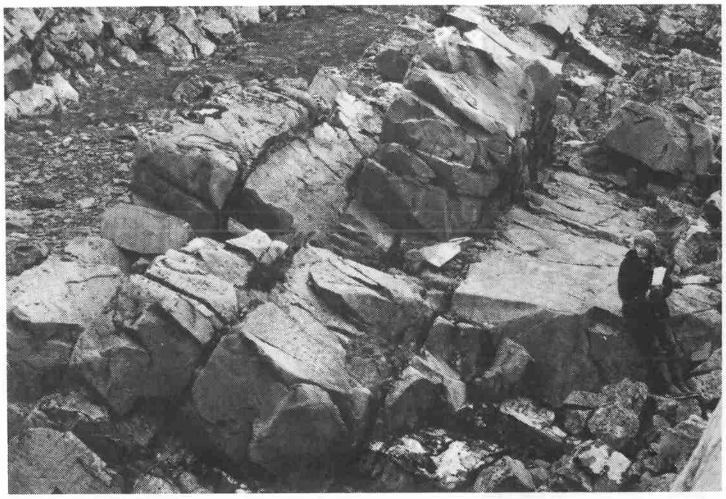


Fig. 23. Very thick/thick-bedded sand–mud couplets (Facies C2.1). Late Precambrian Kongsfjord Formation, Finnmark, N. Norway. Beds young to left.

Facies C2.1 — very thick / thick-bedded sand-mud couplets

Recognition: very thick/thick-bedded sand-mud couplets, with well developed normal grading and commonly Tabc divisions (Fig. 23).

Facies C2.1 occurs as beds with thicknesses greater than 30 cm. Typically, the beds show a structureless lower division overlain by parallel-lamination, and possibly passing up into ripple-lamination. The most common sole marks are flutes and load structures. Bed shape is highly variable although tops tend to be planar. Typical grain sizes are in the range very coarse to medium-grained sand, with both normal distribution and coarse-tail grading. Amalgamation and packeting of beds is common, each bed being separated by a thin mud interval or, more commonly, amalgamated with the adjacent bed. The average sand : mud ratio is about 4 : 1.

Facies C2.2 — medium-bedded sand-mud couplets

Recognition: medium-bedded sand-mud couplets, with well developed normal grading and commonly Tbcd divisions (Fig. 24).

Facies C2.2 occurs as 10–30 cm thick beds that may show complete Tabcde divisions but more usually show the Tbcd divisions. Bed thicknesses tend to be more regular than for Facies C2.1. Sole marks tend to be similar to Facies C2.1. Generally, the grain sizes range from coarse to very fine-grained sand-size, with normal distribution grading occurring throughout beds. Amalgamation of beds may occur and beds vary from parallel, smooth planar bounding surfaces, to highly irregular shapes. Facies C2.2 is transi-

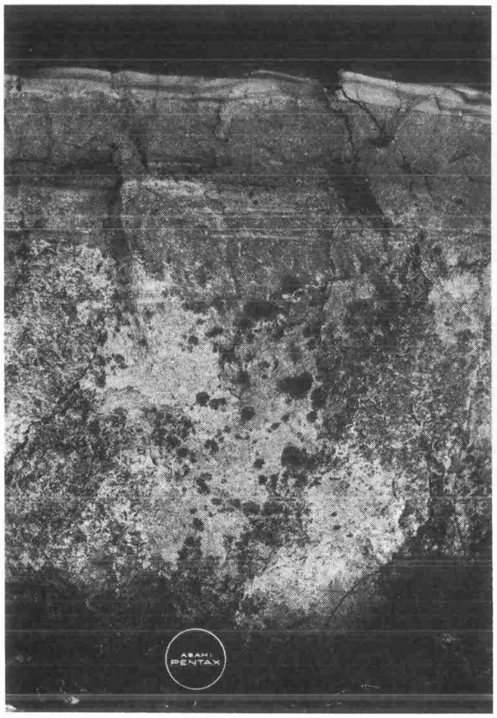


Fig. 24. Medium-bedded sand–mud couplet (Facies C2.2). Late Precambrian Kongsfjord Formation, Finnmark, N. Norway. Camera lens cap for scale. N.B., from base of bed upwards, Bouma divisions: Ta (graded sand); Tb (laminated sand); Tc (current-rippled sand); Td (parallel-laminated silt); and Te (structureless mud as very thin cap to this bed).

tional between Facies C2.1 and C2.3 in terms of its sedimentary attributes. The average sand : mud ratio is of the order of 1 : 1.

Facies C2.3 — thin-bedded sand-mud couplets

Recognition: thin-bedded sand-mud couplets, with well developed normal grading and commonly Tbcde divisions (Fig. 25).

Facies C2.3 occurs in beds less than 10 cm thick. Typically, beds are fine- to very fine-grained sand in the lower part that grades up into silty mud. Amalgamation is rare, although Facies C2.3 may occur as stacked beds or packets. Thicker beds may show a lower parallel-laminated Tb division, whereas the thinner beds tend to start with the Tc division. Ripple-drift lamination (Walker, 1963; Jopling and Walker, 1968) is common. Sole marks are less common than in Facies C2.1 and C2.2, but small flutes, grooves, prod and frondescent marks may occur at the base of some beds — load structures are relatively abundant. Bed shape, generally, is the most consistent and parallel-sided of the facies in Group C2.

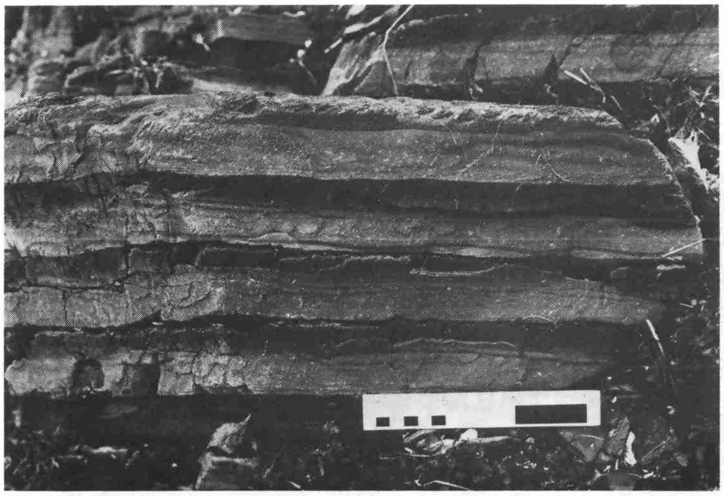


Fig. 25. Thin-bedded sand–mud couplets (Facies C2.3). Late Precambrian Kongsfjord Formation, Finnmark, N. Norway. Scale 15 cm. Beds young towards top of plate.

A distinctive form of Facies C2.3 is as very thin beds, usually less than 3 cm thick, with high sand : mud ratios (> 1), in which there are low amplitude ripples (typically < 2 cm) with relatively large wavelengths up to decimetres. These ripples may occur with stoss-side erosion and only lee-side preservation, followed abruptly by a silt/mud drape giving the beds a 'form surface': some of Mutti's (1977) Facies E are included in this category.

Depositional process: (for Facies C2.1, C2.2 and C2.3) deposition from turbidity currents, ranging from high concentration (C2.1) to low concentration (C2.3).

Selected references: literature on Facies C2.1, C2.2 and C2.3 is abundant. Instead of providing an excessively long list, we refer the reader to references in books edited by: Stanley and Kelling, 1978; Doyle and Pilkey, 1979; Siemers et al., 1981; Tillman and Ali, 1982; Stow and Piper, 1984.

Facies C2.4 — very thick / thick-bedded, mud-dominated sand–mud couplets

Recognition: very thick to thick beds with up to 80% in the form of a silty mud cap. Grading is step-wise, and successive divisions may show structures indicating approximately 180° reversals of flow (Fig. 26).

Facies C2.4 comprises very thick/thick-bedded (1–15 m), mud-dominated, sand–mud couplets that may show internal evidence of flow reversals during deposition, and that commonly have a mud cap accounting for about 80% of the total bed thickness. The sandy basal divisions are graded, although the grading may be step-wise, with mud breaks between divisions with opposed

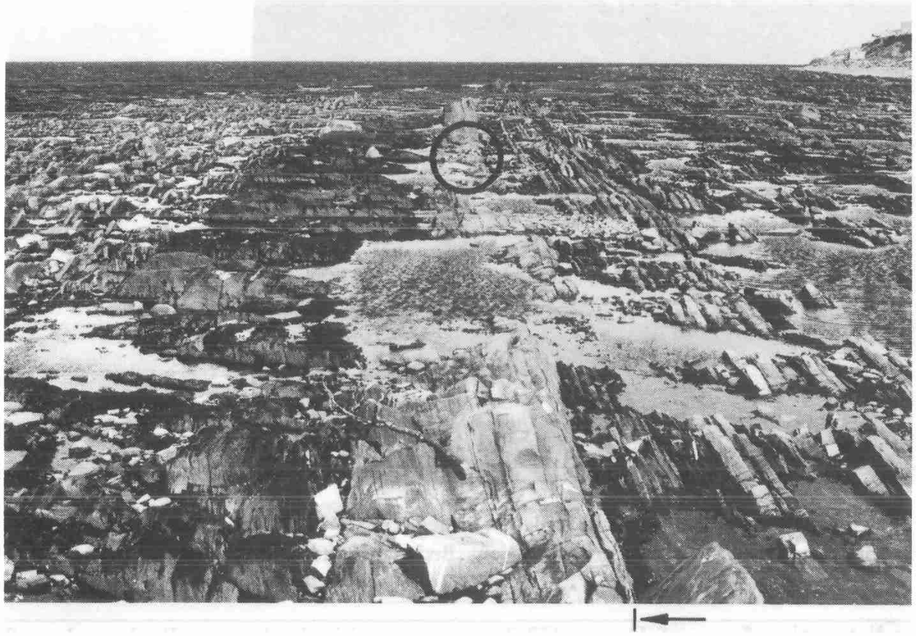


Fig. 26. Very thick/thick-bedded, mud-dominated sand–mud couplet (Facies C2.4). Middle Ordovician Cloridorme Formation, Quebec, Canada. 1-m bar scale circled. Beds young to left. Base of bed arrowed, and note very thick structureless mudstone cap above sandstone lower part — bed about 540 cm thick. Surrounding Facies C2.3 and Facies Class D deposits.

senses of flow (Hiscott and Pickering, 1984; Pickering and Hiscott, 1985). Internal structures include megaripple form sets, ripple and climbing-ripple lamination, wavy and parallel lamination, and pseudonodules.

Bed shape tends to be parallel-sided, tabular, and laterally continuous, typically over tens of kilometres. Basal flute casts and load casts are abundant. Wet-sediment deformation structures may include convolute lamination and clastic dykes intruding the upper silty mud cap from the lower sandy division.

Depositional process: Pickering and Hiscott (1985) interpret this unusual facies as the deposits of large-volume, high concentration turbidity currents confined within relatively small basins, such that multiple deflections and reflections of the initial current occur during deposition of the sand-silt load. The thick silty mud caps are deposited by rapid settling of flocs formed in the highly concentrated mud cloud that becomes ponded above the basin floor after cessation of flow. In order to emphasize the importance of reflections and ponding during deposition of Facies C2.4, Pickering and Hiscott (1985) called the emplacing flows “contained turbidity currents”.

Selected references: Van Andel and Komar, 1969; Ricci Lucchi and Valmori, 1980; Cita et al., 1984; Hiecke, 1984; Hiscott and Pickering, 1984; Pickering and Hiscott, 1985.

FACIES CLASS D — SILTS, SILTY MUDS AND SILT–MUD COUPLETS, > 80% MUD GRADE (OF WHICH ⩾ 40% IS SILT), < 20% SAND GRADE

Facies Class D contains those sediments that are dominantly silt and clay grade. The deposits range from sediments with over 90% medium-coarse silt, to those with about 40%, much of which may be very fine-grained. The coarser silts are commonly in distinct beds or laminae inter-stratified with mud and clay. The class encompasses a wide range of sedimentary characteristics: (a) beds over 1 m in thickness to laminae less than 1 mm thick; (b) parallel-sided, lenticular or highly irregular layers; (c) structureless or thinly-laminated sediment with a variety of other small scale current-generated structures; (d) poorly developed to absent normal or inverse grading and graded laminated units; and (e) layers of coarse silt with a relatively high proportion of fine sand and sections with only 10% fine silt laminae in a mud.

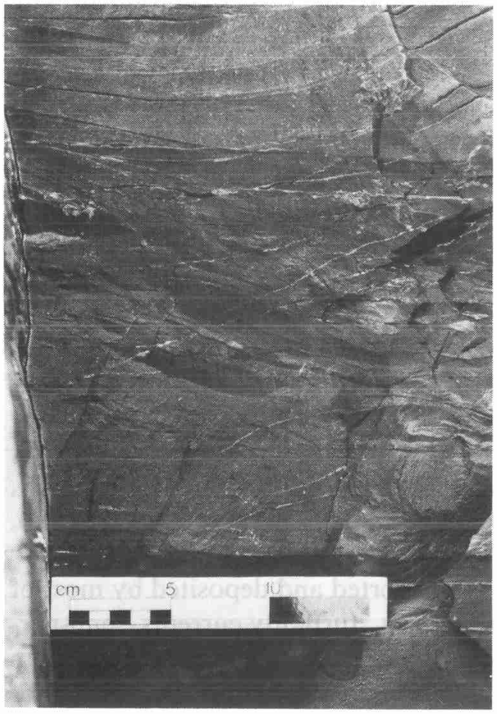
This facies class, in which silt has replaced sand as the dominant "coarse" grain size is similar to Facies D1 and D2 of Mutti and Ricci Lucchi (1972). It is now much better documented; some of the key synthesis papers include those by Mutti (1977), Nelson et al. (1978), Piper (1978), Stow (1979, 1981), Stow and Lovell (1979), Lundegard et al. (1980), Kelts and Arthur (1981), Stanley and Maldonado (1981), Gorsline (1984), Stow and Piper (1984a), and the volume edited by Stow and Piper (1984b).

Sediments in this class include those transported and deposited by most of the main processes operating in deep water, e.g., turbidity currents, semi-permanent and permanent bottom currents, and grain-by-grain settling from hemipelagic suspensions. In particular, they may form from the tail-end of high-density turbidity currents, the bulk volume of low-density turbidity currents, or the terrigenous component of deep-water bottom currents. Silts and clays can also be transported by surface currents and winds, and settle through the water column, mostly resulting in the hemipelagic deposits of Facies Class G. Facies Class D deposits are commonly involved in large-scale downslope resedimentation processes (sliding, slumping, creep, debris flow etc.) giving rise to some of the facies of Class F.

Within Class D, we recognize two main facies groups, disorganized (D1) and organized (D2), both of which contain several distinct facies. As with the bedding thicknesses of sand–mud turbidites in Facies Group C2, the subdivision of Facies Group D2 is on the basis of layer thickness which is, to some extent, arbitrary.

Facies Group D1, 'disorganized silts and silty muds'

Facies Group D1 contains all those silts, muddy silts and irregularly interlayered silts and muds that show little regular or consistent organiza-



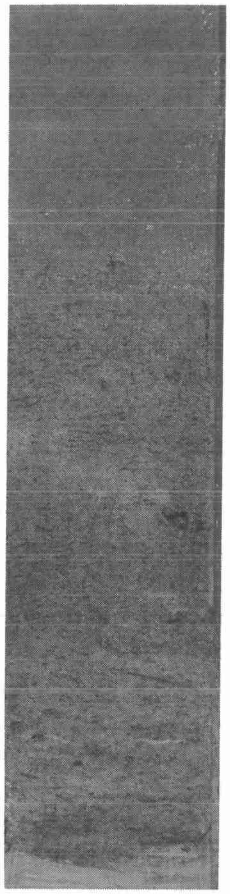


Fig. 27. Structureless silt (Facies D1.1). Late Precambrian Kongsfjord Formation, Finnmark, N. Norway. Beds young towards top of plate. N.B., abundant mudstone clasts.

Fig. 28. Muddy silt (Facies D1.2). Pleistocene Mississippi Fan, Gulf of Mexico, DSDP Leg 96, Site 616. Core width 7 cm.

tion. They may, however, show poor indistinct grading and irregular layering and lensing.

Facies D1.1 — structureless silts

Recognition: medium/thick-bedded structureless silts (Fig. 27).

Facies D1.1 commonly occurs as medium- to thick-bedded, parallel-sided, essentially structureless silts. There may be a poorly defined normal and, rarely, an inverse grading at the base of a bed. Commonly, the sediments are fine to coarse silt size, often sandy and with floating mud clasts, and they range from poor to well sorted.

Depositional process: rapid mass deposition from a high-concentration, silt-dominated turbidity current, or very fluid, silty debris flow.

Selected references: Piper, 1973, 1978; Jipa dn Kidd, 1974; Maldonado and Stanley, 1976, 1979; Stanley and Maldonado, 1981; Stow, 1984a, b.

Facies D1.2 — muddy silts

Recognition: poorly sorted structureless to poorly graded muddy silts (Fig. 28).

Facies D1.2 occurs as thin to thick-bedded, poorly sorted, essentially structureless muddy silts. Grading is absent unless as an ill-defined normal grading. Typically, the base of a bed is sharp, possibly with scouring, while the upper surface is gradational into finer grained facies. Bioturbation commonly occurs towards the tops of many Facies D1.2 beds.

Depositional process: rapid deposition of silt grains and mud flocs from a high concentration, mud-dominated turbidity current. Some sediment creep or sliding may be involved.

Selected references: Wetzel, 1978; Piper, 1978; Chough and Hesse, 1980; Stow, 1984b; Stow et al., 1986.

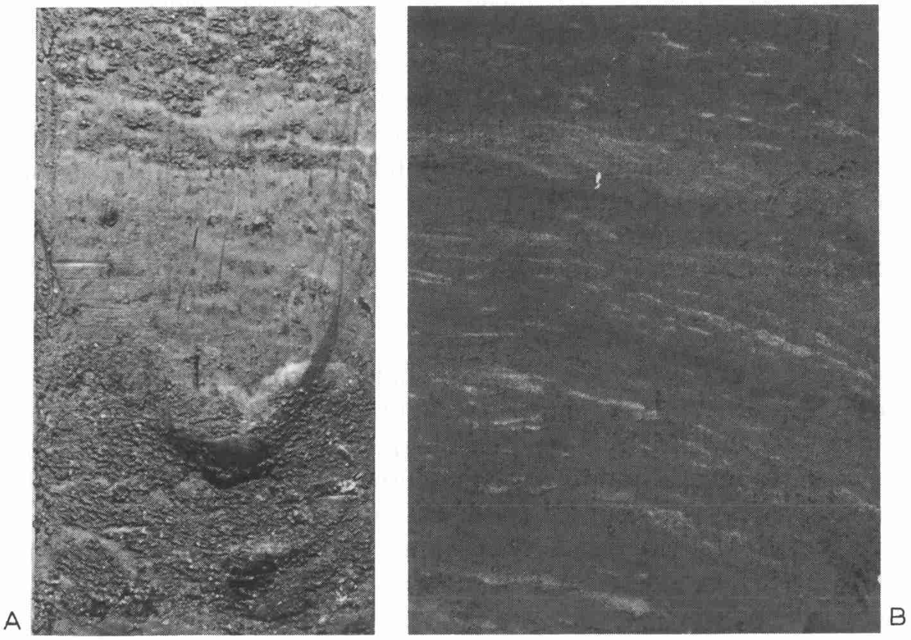


Fig. 29. Mottled silt and mud (Facies D1.3). A. Pleistocene Faro Drift, Gulf of Cadiz, DSDP Leg 75. Mottling due to bioturbation and note poorly developed lamination. B. Pleistocene Mississippi Fan, Gulf of Mexico, DSDP Leg 96, Site 622. Core widths 6 cm.

Facies D1.3 — mottled silts and muds

Recognition: bioturbated irregular-shaped very thin beds and laminae, lenses and mottles of silt in mud (Fig. 29).

Typically, Facies D1.3 consists of very thin beds, laminae, lenses and mottles of silt in mud. Bed shape is characteristically irregular and both bases and tops of the beds vary from sharp to gradational with adjacent facies. Normal and inverse grading may occur at the scale of individual laminae and over intervals up to several tens of centimetres in thickness, although the grading is mostly rather irregular in nature. Silt and clay grain sizes characterize this facies, and sorting is poor to moderate. Bioturbation is extensive throughout the beds/layers. At coarse grain sizes, this facies grades into Facies C1.2 (mottled muddy sands) and at finer grain sizes into Facies E1.3 (mottled muds).

Depositional process: deposition from bottom currents over prolonged time periods or from low-concentration turbidity currents, with pervasive bioturbation destroying much of the original structure.

Selected references: Piper and Brisco, 1975; Stow, 1982; Faugères et al., 1984; Gonthier et al., 1984; Stow and Holbrook, 1984; Stow and Piper, 1984a.

Facies Group D2, 'organized silts, muddy silts and silt-mud couplets'

The facies of group D2 consist of graded, internally-structured silts, silty muds and silt-mud couplets either as discrete beds or as inter-laminated units of mud and silt with variable ratios of silt to mud. This group also includes the fissile, organic-rich, muds with silt lenses or laminae (organic-rich variant of Facies D2.3). Stratification, grading and a predictable sequence of sedimentary structures (Piper, 1978; Stow and Shanmugam, 1980) are common attributes of Facies Group D2.

Facies D2.1 — graded stratified silts

Recognition: variably bedded, normally graded stratified silts (Fig. 30).

Facies D2.1 is commonly thin to medium-bedded (less than 30 cm), but rarely thick-bedded. The bases are often sharp and scoured whereas the tops tend to be gradational. Grading is of the normal distribution type, and the internal sedimentary structures are well described using the Bouma (1962) sequence. In many cases, Facies D2.1 occurs as beds that are thoroughly laminated. Beds are silt- (rather than sand-) size, grading upwards to clay-sized sediments. This facies, to a certain extent, overlaps in terms of its description, with Facies C2.2 and C2.3. The recently described "CCC" turbidites of Walker (1985) are included in this facies although, undoubtedly, they are gradational into Facies C2.3.

Fig. 30. Graded stratified silt (Facies D2.1). Late Precambrian Kongsfjord Formation, Finnmark, N. Norway. Camera lens cap for scale. Beds young towards top of plate.

Depositional process: deposition from low concentration turbidity currents.

Selected references: Piper, 1973, 1978; Jipa and Kidd, 1974; Stow and Piper, 1984a; Walker, 1985.

Facies D2.2 — thick irregular silt and mud laminae

Recognition: lenticular and irregular silt laminae in mud, microstructures and partial graded-laminated units (Fig. 31).

The sediments of Facies D2.2 are typified by medium to thick lenticular silt laminae in mud and, or, thin irregular, convolute and sub-horizontal silt laminae and lenses. In some cases, extreme loading of the silt laminae into the underlying muds produces deep irregular load structures, pseudonodules and balls with intervening mud flame structures protruding upwards into the silt layers (e.g., Cremer and Stow, 1986). Typically, silt : mud ratios are greater than 7 : 3. Facies D2.2 often contains thick silt laminae with sharp, commonly rippled, tops and scoured sharp bases. An internal micro-lamination and slight normal grading may be present through individual laminae. Groups of laminae may be arranged in normally graded-laminated units showing partial structural sequences. The grain sizes are mostly medium to coarse silt inter-laminated with fine silt and mud. Facies D2.2 is gradational with Facies D2.1 and D2.3. Facies D2.2 is equivalent to the Piper E1 (base), and Stow and Shanmugam (1980) T0-2 divisions.

Depositional process: relatively rapid deposition from low-concentration turbidity currents.

cover of continental slopes and rises. They are deposited by the same range of catastrophic, semi-permanent or permanent marine processes as for the facies of Class D, and are similarly involved in submarine sliding, sediment creep and debris flows.

To date, there have been many descriptions of deep-sea muds, mostly cursory but others quite detailed, although there has been little effort to synthesize this data in an attempt to understand more fully the environments and processes of deposition. Key papers that attempt at least a partial synthesis of muds include: Piper (1978); Stow and Lovell (1979); Hoffert (1980); Stanley and Maldonado (1981); Stanley (1981); Gorsline (1981); Gorsline et al. (1984); Stow and Piper (1984a), and the volume edited by Stow and Piper (1984b).

In common with the other facies classes discussed so far, there appears to be a natural distinction between a disorganized (E1) and an organized (E2) facies group. Given the grain sizes involved, the optimum visual appreciation of many of the attributes of the facies in this class can be achieved using X-radiographed thin slabs or peels of sediments.

Facies Group E1, 'disorganized muds and clays'

Facies Group E1 is one of the most enigmatic of the entire spectrum of facies. It consists of muds, silty muds and clays, often in thick uniform, essentially structureless sections, with only very subtle sedimentary features that allow their distinction and, in some cases, an interpretation in terms of origin and depositional process. Nevertheless, three facies can be recognized.

Facies E1.1 — structureless muds

Recognition: essentially structureless muds/clays with poorly defined bedding (Fig. 33).

The structureless muds and clays of Facies E1.1 commonly occur in thick sections where bedding is poorly defined or absent. The sediments are mostly devoid of clear sedimentary structures. This facies appears to be common in both modern and ancient successions, often occurring in layers greater than 1 m to many metres thick. While there is a notable absence of structures, both primary and secondary, an indistinct banding or lamination and zones of bioturbational mottling may be locally developed. Where banding occurs, it is picked out by subtle textural, compositional or colour changes. The muds are either clay-grade or mixed silt and clay grades; sand-sized material is less common. The composition may be remarkably uniform, being dominantly terrigenous. Facies E1.1 tends to occur in association with hemipelagites (G2), mud turbidites (E2.1), slides (F2) and debris flow deposits (A1.3, A1.4).

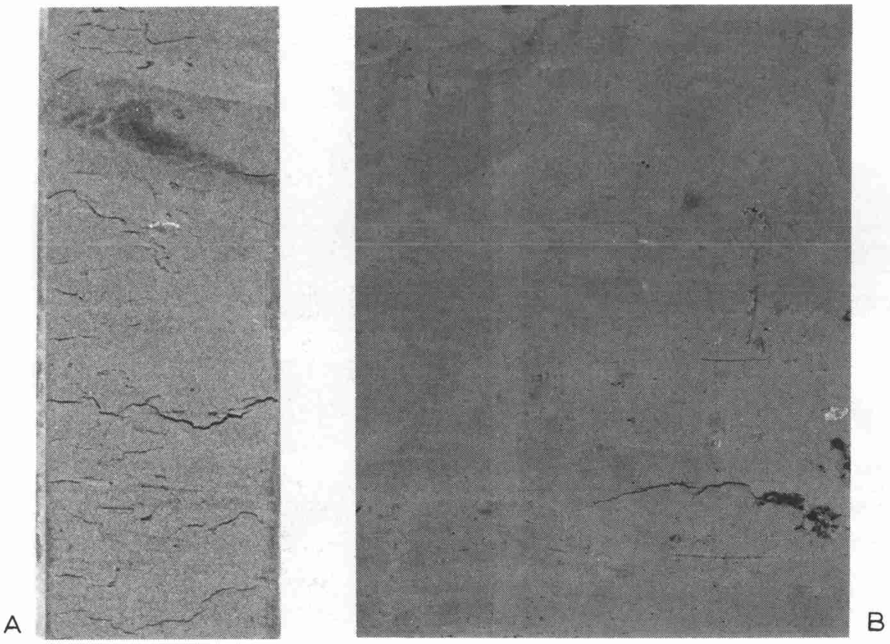


Fig. 33. Structureless mud (Facies E1.1). A. Pleistocene Mississippi Fan, Gulf of Mexico, DSDP Leg 96, Site 621; N.B., gas cracks. B. Pleistocene Orca Basin, Gulf of Mexico, DSDP Leg 96, Site 618; N.B., minor mottling and gas cracks. Core widths 6 cm.

Depositional process: possibly, relatively rapid deposition suspected, without significant planktonic biogenics, may result from the ponding of thick, dilute turbidity currents and, or, hemipelagic settling with some lateral transfer by deep-ocean currents or sliding processes.

Selected references: Piper, 1978; Stanley and Maldonado, 1981; Stanley, 1981; Hill, 1981; Kelts and Arthur, 1981; Wetzel, 1983; Stow, 1984a, b; Pickering and Hiscott, 1985; Cremer and Stow, 1986; Stow et al., 1986.

Facies E1.2 — varicoloured muds

Recognition: varicoloured muds (red, green, brown, grey etc.), often interbedded and generally lacking sedimentary structures (Fig. 34).

Many mud-dominated successions contain not only the classic "pelagic red clay" but interbedded muds of various colours, mostly lacking sedimentary structures; these are assigned to Facies E1.2. Such successions may be up to tens of metres thick. Individual beds or layers are defined on the basis of the colour changes that vary from laminae to bed thicknesses. Layers or beds may be parallel-sided or more irregularly shaped with either abrupt or gradational bases and tops. Primary (dynamic) structures are mostly absent, whereas secondary structures such as bioturbation, mottling and burrowing,

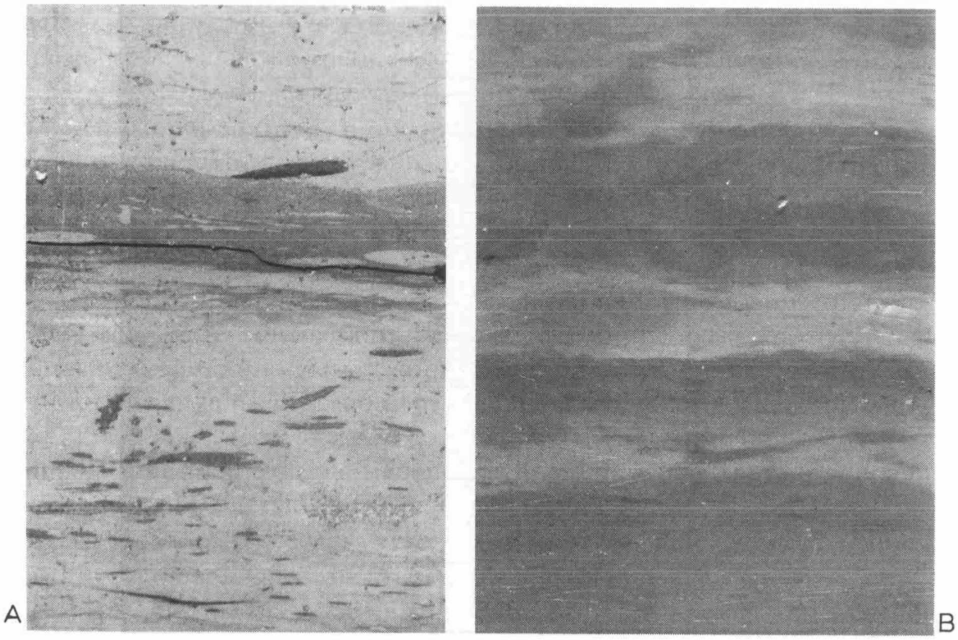


Fig. 34. Varicoloured muds (Facies E1.2). A. Albian sediments, Angola Basin, DSDP Leg 75, Site 530A; core width 6 cm; inter-bedded light grey and greenish muds, bioturbated. B. Pleistocene Pigmy Basin, Gulf of Mexico, DSDP Leg 96, Site 619; core width 5 cm; inter-bedded dark grey, light grey, brownish and olive-grey muds with bioturbational mottling.

tend to be common. Grain sizes are mainly fine silt-grade to clay-grade. Facies E2.1 is predominantly terrigenous in composition (up to about 30% biogenic material), often with a significant volcanogenic fraction and authigenic minerals. Ferro-manganese nodules and crusts are common and enrichment in trace metals may occur. Subtle differences in chemical composition, oxidation states and the amount of organic carbon control the colour differences. High organic carbon content can give a black mud (Facies E2.2). Facies E1.2 is commonly associated with pelagic biogenic sediments (Facies Group G1) and fine-grained turbidites (Facies Groups D2 and E2).

Depositional process: settling of individual particles or particle aggregates (flocs and faecal pellets).

Selected references: Arthur and Natland, 1979; Hoffert, 1980; Jenkyns, 1986.

Facies E1.3 — mottled muds

Recognition: poorly bedded bioturbated muds with few sedimentary structures (Fig. 35).

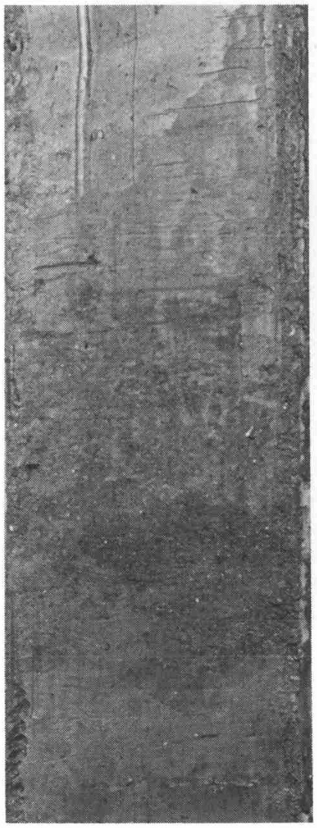


Fig. 35. Mottled mud (Facies E1.3). Pleistocene–Holocene Faro Drift, Gulf of Cadiz. Core width 8 cm. N.B., thorough bioturbation and poorly defined bedding.

Facies E1.3 consists of relatively uniform, thin to thick intervals of mud that are poorly bedded. Some primary sedimentary structures occur including wavy, indistinct or fine parallel layering; otherwise, bioturbational mottling and indistinct burrows dominate the facies. Clay-grade material is dominant but relatively silty intervals (silt mottles, pockets and blebs) may be common, and where silt content becomes substantial, Facies E1.3 grades into Facies D1.3. Compositionally, this facies shows considerable variation, but typically consists of mixed terrigenous and biogenic components, with or without volcanogenic debris. The facies is often associated with other probable contourite deposits (D1.3 and some C1.2), hemipelagites (G2) and fine-grained turbidites (D2, E2).

Depositional process: probably bottom-current-influenced muddy contourites or hemipelagites, often with significant lateral transport.

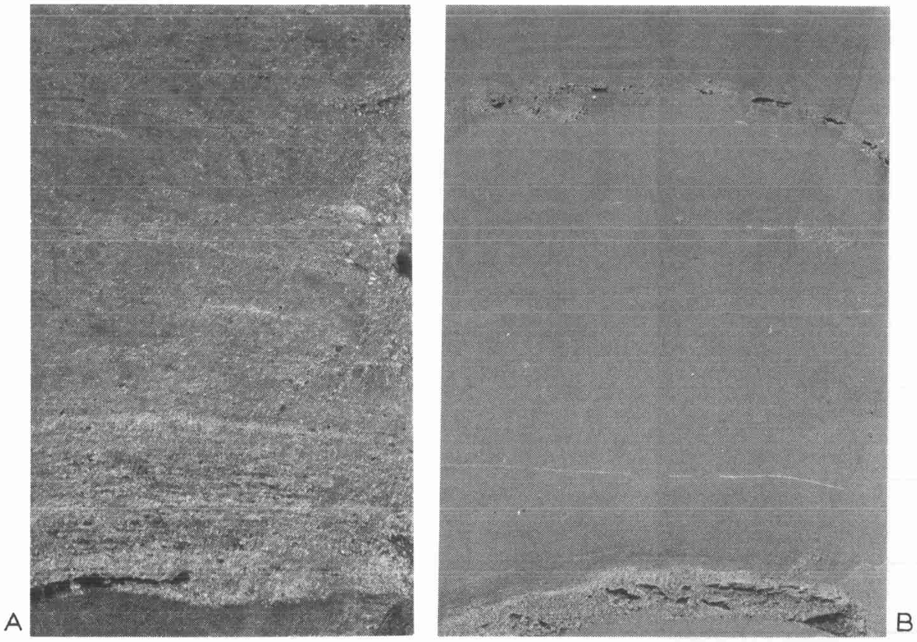


Fig. 36. Graded muds (Facies E2.1). A. Pleistocene sediments, Angola Basin, DSDP Leg 75, Site 530B. B. Pleistocene Mississippi Fan, Gulf of Mexico, DSDP Leg 96, Site 615. Core widths 7 cm. N.B., graded mud is between two prominent silt laminae.

Selected references: Stow, 1982; Stow and Holbrook, 1984; Faugères et al., 1984; Gonthier et al., 1984; Hill, 1984.

Facies Group E2, 'organized muds'

The muds and clays that show some internal organization are classified in Facies Group E2; there is, however, a complete gradation with the facies of Group E1. The constituent facies include muds, silty muds and clays in thin isolated beds or thicker layers. There are two distinctly different facies: the graded muds and the finely layered or laminated muds.

Facies E2.1 — graded muds

Recognition: well bedded, graded (often colour-graded) muds, sometimes with very thin silt laminae at the base and bioturbation towards the top (Fig. 36).

Facies E2.1 is widespread, especially in deep basinal settings, although it does occur more proximally. It can occur as single, isolated, graded beds up to thicknesses of over 1 m, or as thick repetitive successions of graded muds of variable thickness. Individual beds may show broad scoured bases and

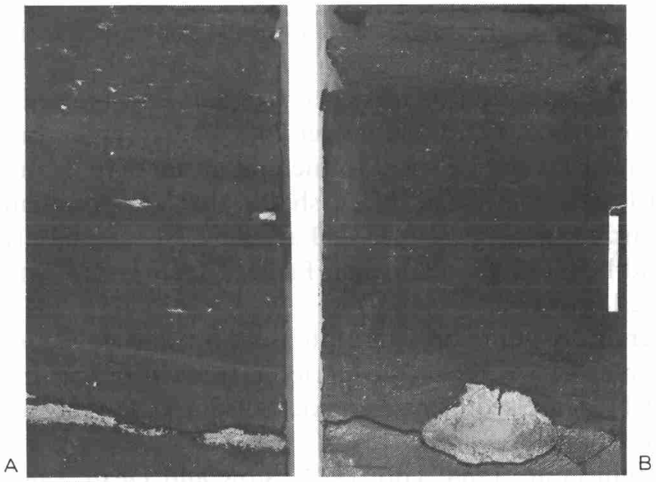


Fig. 37. Laminated muds and clays (Facies E2.2). A and B. Albian "black shales", Angola Basin, DSDP Leg 75, Site 530A. Scale bar is 2 cm. Muds and clays are organic-carbon-rich fissile, faintly laminated sediments. Light-coloured layers and nodules are pyrite.

thicker beds can sometimes be lenticular. Most beds show normal grading. Silt : mud ratios are less than about 3 : 7. Bioturbation becomes increasingly more important towards the top of many graded mud beds.

Colour or compositional grading is generally more marked than grain size grading, although beds tend to be more silty towards the base, with increasing clay content upwards if this facies is mainly terrigenous in composition. Wherever biogenic material is present, the overall texture tends to be slightly coarser. Facies E2.1 is gradational with the silt–mud turbidites (D2.3 and D2.1), and commonly occurs in association with Facies Classes F and G.

Depositional process: deposition from low and high concentration turbidity currents.

Selected references: Piper, 1978; Kelts and Arthur, 1981; Hill, 1984; Stow, 1984b; Stow and Piper, 1984a.

Facies E2.2 — laminated muds and clays

Recognition: finely laminated or fissile, often dark-coloured organic-rich muds and clays (Fig. 37).

Facies E2.2 occurs in thin to thick mud-dominated sections (up to tens of metres) in which it typically constitutes from 10 to 60% of the section. Individual beds range from 1 cm to decimetres in thickness, commonly with fine parallel lamination or distinct varves. The laminae or varves show slight colour, compositional and, or, textural variations. Bioturbation is generally absent, although small-scale localized burrowing may be evident. Clay- and fine silt-grade sediments dominate this facies and, in some cases, there are thin silt laminae.

The main composition of Facies E2.2 is mixed terrigenous and biogenic, with from 1 to 10% organic carbon, more rarely over 20%, and common but minor iron sulphides. Facies E2.2 are believed to include, in modern examples, the precursors to at least some of the 'black shales' that are prevalent throughout parts of the ancient geological record. Facies E2.2 is commonly associated with pelagic and hemipelagic sediments (Facies Class G) and with fine-grained turbidites (E2.1 and D2).

Depositional process: grain-by-grain or aggregate settling and low-concentration turbidity currents; varves related to periodic fluctuations in the influx of terrigenous and biogenic sediments; anoxic bottom waters favour the preservation of organic matter.

Selected references: Arthur et al., 1984; Hill, 1984; Stow and Dean, 1984.

FACIES CLASS F — CHAOTIC DEPOSITS

Facies Class F consists of more or less chaotic mixtures of sediments and rock types, including other deep-water facies, that, for the most part, have been subjected to large-scale downslope mass movements. We have excluded deposits resulting from in-situ liquefaction and fluidization. The thickness and shape of the deposits in this facies class is more variable than for any other class, ranging from single isolated clasts (pebbles, cobbles and boulders) to whole sections of continental slope, and from centimetres to hundreds of metres in thickness.

Two facies groups are established on the basis of the internal structure and the relationship of the deposits to adjacent beds or layers: Facies Group F1, exotic clasts; and Facies Group F2, contorted/disturbed strata.

In Facies Class F, perhaps more than is the case for the other classes, the lateral and vertical transitions from our various facies can occur over very short distances, for example, from central to marginal parts of submarine slides. Where vertical/lateral facies changes are abrupt and abundant, a researcher may choose to describe a succession only in terms of our facies groups, and describe the variability of the deposits without recourse to our facies divisions.

Facies Group F1, 'exotic clasts'

Facies Group F1 contains any block or clast of rock/sediment within a sedimentary succession that appears to have been emplaced within the sedimentary pile in isolation from any immediately adjacent deposit, that is, isolated in origin. Such exotic clasts may occur in complete isolation from, or associated with, other similar clasts (in terms of composition and, or, origin), but whatever their spatial association with other deposits, there is no binding (contemporaneous) matrix common to the clasts if they are present at the same chronostratigraphic horizon.

The texture of Facies Group F1 deposits, using the term to include any 'matrix', is extremely variable. Generally, any 'matrix' is very poorly sorted, showing a bi-modal to polymodal grain-size distribution, although there may be overall systematic textural and compositional variations laterally. Generally, the 'matrix' or enveloping sediments of the exotic (F1) clasts are commonly finer grained than the clasts of Facies Group F1. In some cases, the shale matrix may have acquired a fissility due to compaction, and in other cases, it may be pervasively sheared during tectonic deformation to leave the exotic clasts relatively undeformed (Abbate et al., 1970). Within this group, two facies are recognized: Facies F1.1, rubble; and F1.2, dropstones and isolated ejecta.

Facies F1.1 — rubble

Recognition: mostly angular to sub-angular cobbles and boulders of varying composition as lithified and, or, consolidated sediment, associated with later sediment infilling and draping (Fig. 38).

Facies F1.1 consists of a chaotic jumble of mainly angular to sub-angular cobbles and boulders, usually as a talus or scree fringing relatively steep submarine cliffs and slopes. Interstitial finer grained sediments invariably occur in ancient examples of this facies such that the matrix tends to resemble a rock flour devoid of any dynamic sedimentary structures: infilling of residual hollows between the larger clasts may be indicated by sediment draping. In modern examples of Facies F1.1, the facies occurs as rubble and is devoid of interstitial sediments or such sedimentation is of limited and patchy extent.

The clasts tend to show compressional deformation and rupturing of underlying sediments in the form of depressed bedding, small scale syn-sedimentary faults, buckling and attenuation of beds surrounding the clasts. Wherever large blocks occur, detailed sedimentary logging and mapping may be the only methods of revealing sediment draping and even the presence of an "exotic" block — faunal data also may be necessary to establish age-relationships of the rubble in this facies.

Clast composition is variable as intra- and extra-formational exotic clasts, ranging from igneous, metamorphic and sedimentary rock types. The degree of lithification present in the rubble varies considerably. Also, clasts may show internal wet-sediment deformation. Isolated, displaced clasts, or exotic blocks, are well documented from ancient successions, for example limestone blocks up to 250 m in maximum dimension from the Mesozoic Laganegro

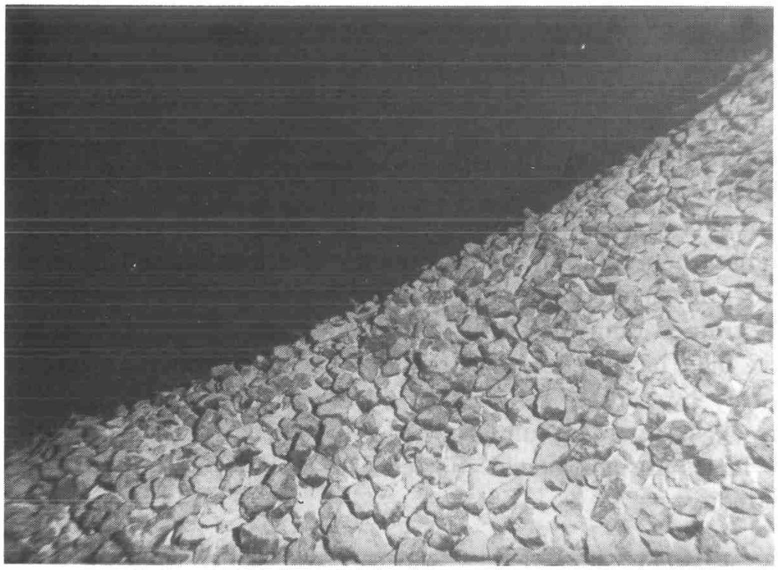


Fig. 38. Rubble (Facies F1.1). Recent, TAG area, Mid-Atlantic Ridge. Hand-held photo from side viewport of ALVIN, Dive 1247, approx. 3,000 m water depth. Talus ramp at base of a steep median valley; fault scarp exposing mainly basaltic volcanic rocks with pelagic sediments beginning to fill in the interstices. Plate kindly supplied by J.A. Karson, Woods Hole Oceanographic Institution, Mass., U.S.A. Cobble and boulder material.

Basin, southern Italian Apennines (Wood, 1981), isolated blocks up to 100 × 50 × 50 m in the Longobucco Group of southern Italy (Teale, 1985), and the so-called 'fallen-stack' of Devonian Caithness Flagstone (45 × 27 × ? m) in the late Jurassic of NE. Scotland (Bailey and Weir, 1932; Pickering, 1984a). Facies F1.1 tends to be associated in particular with Facies Group F2 and A1 deposits.

Depositional process: submarine rockfall, avalanching and sliding along glide planes and debris flow. Some large blocks travelling in debris flows may have become 'grounded', even though the rest of the flow continued farther into the basin, leaving little or no depositional record in the vicinity of the block.

Selected references: Bailey and Weir, 1932; Flores, 1955; Abbate et al., 1970; Hsu, 1974; Surlyk, 1978; Pickering, 1984a; Teale, 1985.

Facies F1.2 — dropstones and isolated ejecta

Recognition: clasts in isolation, or in groups, of substantially larger size than their 'matrix' or host sediment; host sediment commonly depressed beneath clasts (Fig. 39).

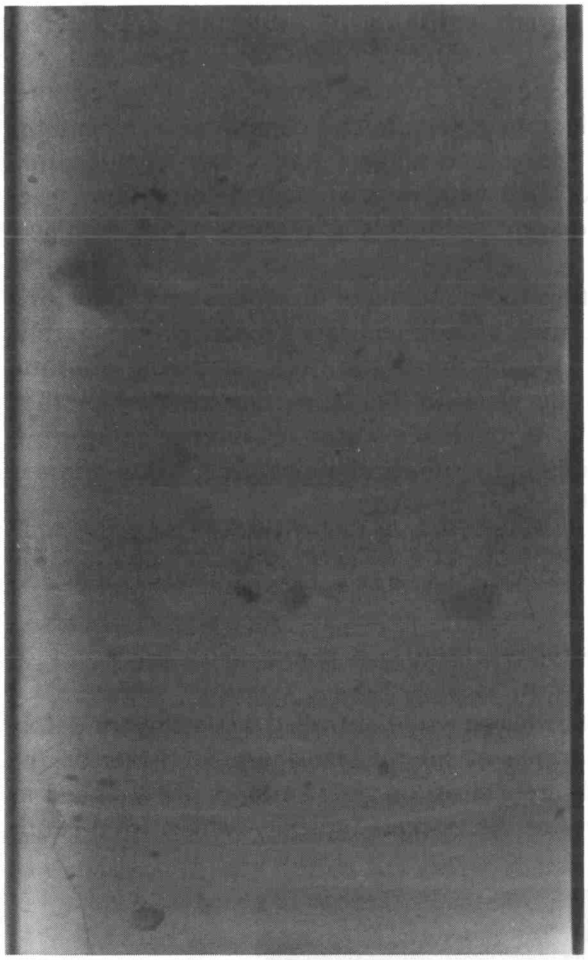


Fig. 39. Dropstones and isolated ejecta (Facies F1.2). X-radiograph of Pleistocene glacial dropstones and ambient sediments from the continental margin off Nova Scotia, North Atlantic. Core width 6 cm.

Typically, in Facies F1.2 the clasts are substantially larger in size than their 'matrix' or host sediment, occurring either in isolation, as groups, or in lumps, for example of till. Dropstones are associated with bending, penecontemporaneous rucking, and complete rupture of strata beneath them, and onlap of subsequent strata, the degree of deformation varying as a function of clast size, shape and axial orientation, and of the "host" sediment (Thomas and Connell, 1985).

The composition, shape and other attributes of the clasts are mainly a function of the source area and source area processes. For example, ice-rafted dropstones may show glacial striae, polishing or faces that are faceted. However, the recognition of such features is only supportive, and not diagnostic, evidence for identifying glaciomarine dropstones. Furthermore, volcanic ejecta will vary considerably in texture and composition depending, amongst other factors, upon the source magma and crater composition. Typically, Facies F1.2 are associated with wet-sediment deformation structures such as down-flexured adjacent sediments as a result of the emplacement processes.

Depositional process: ice rafting and dumping of clasts due to: (1) melting of ice, or (2) the sudden overturning of sediment-laden icebergs. Very rarely, dumping from seaweed rafts. Volcanic bombs are ejected during eruption processes and follow ballistic trajectories to the sea surface after which they tend to fall essentially vertically through sea water — submarine eruptive processes will be somewhat similar to subaerial types except that the sea water will provide a considerable damping effect.

Selected references: Boltunov, 1970; Ovenshine, 1970; Anderson et al., 1979; Gravenor et al., 1984; Thomas and Connell, 1985; Edwards, 1986.

Facies Group F2, 'contorted / disturbed strata'

Packets of beds and layers showing gravity-controlled wet-sediment deformation and indicating some degree of lateral translation of parts or the entire sediment packet along discrete shear or glide surfaces are assigned to Facies Group F2. The thickness of the packets typically ranges from centi-

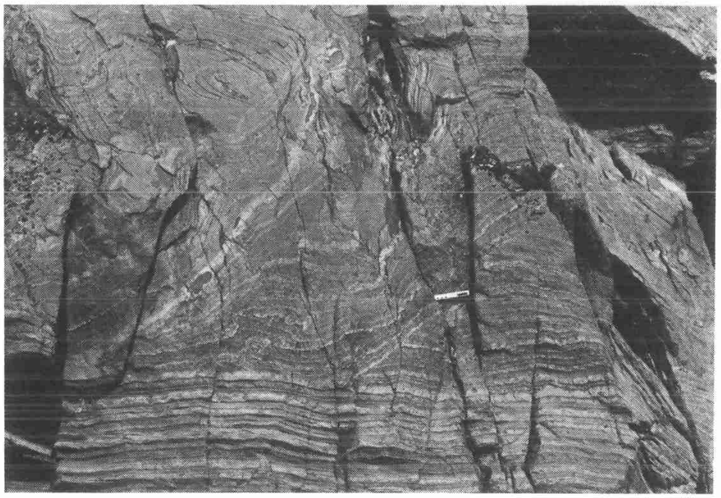

A

Fig. 40 (legend on p. 62)

metres up to hundreds of metres. Bounding surfaces range from smooth, planar and parallel-sided, to very irregular with deep erosional scours at the base of the packets. Internally, bedding varies from virtually undisturbed to extremely disturbed, and it is upon this criterion that we distinguish Facies F2.1, coherent folded and contorted strata, from Facies F2.2, dislocated, brecciated and balled strata.

B

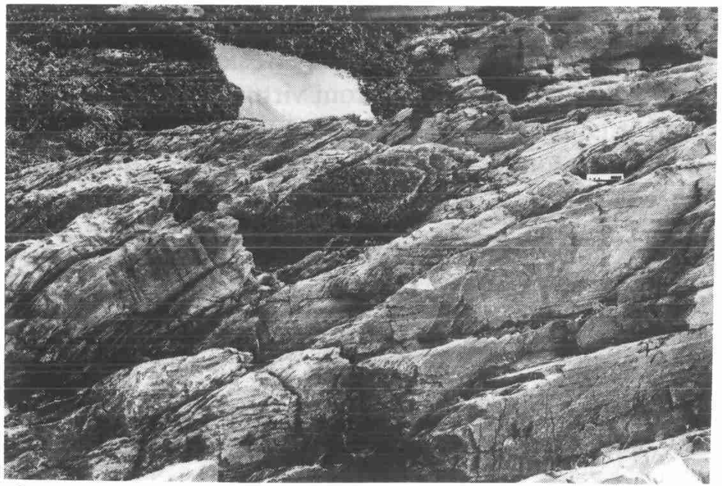


Fig. 40. Coherent folded/contorted strata (Facies F2.1). A. Late Precambrian Båsnaering Formation (Lower Naeringselva Member), Finnmark, N. Norway. 15 cm scale. Succession youngs towards top of plate. N.B., erosive surfaces cutting down to left into undeformed sediments (to right), and note continuity of most deformed strata. B. Pleistocene Mississippi Fan, Gulf of Mexico, DSDP Leg 96, Site 621. Core width 6 cm. N.B., only part of a slide unit visible, involving silts and muds. C. Late Precambrian Kongsfjord Formation, Finnmark, N. Norway. 15 cm scale towards middle right, parallel with undisturbed bedding. N.B., decollement surface cutting down to left immediately above scale, and rotational slide sense of movement along surface (slump).

Numerous examples of facies in Group F2 are documented from both modern and ancient deep-water environments, and for more detailed descriptions and interpretations the reader is referred to: *Geology of Continental Slopes*, edited by Doyle and Pilkey (1979); *Geological and Geophysical Investigations of Continental Margins*, edited by Watkins et al. (1979); *Marine Slides and other Mass Movements*, edited by Saxov and Nieuwenhuis (1982); and volumes I, II and III of, *Seismic Expression of Structural Styles*, edited by A.W. Bally (1983).

Facies F2.1 — coherent folded / contorted strata

Recognition: coherent/semi-coherent folded and contorted strata on any scale (Fig. 40).

Deposits of Facies F2.1 occur in individual layers from centimetres up to tens of metres in thickness. Facies F2.1 is folded and contorted, essentially coherent to semi-coherent, strata in irregularly-shaped layers or horizons. The orientation of the strata within this facies, generally, is extremely variable over short distances and commonly occurs at acute/oblique angles to bedding in adjacent facies. Discrete internal glide or shear surfaces may be visible and define the bounding surfaces to a Facies F2.1 deposit. Characteristically, there are dramatic changes in layer thickness along strike. Upper and lower bounding surfaces vary from smooth, planar, to very irregular.

Internal structure, bed thicknesses and grain sizes of this facies are very variable. There may be a consistent sense of overturning in any folded strata, and locally such folds may be of relatively constant wavelength and amplitude. Typically, it is the coarser grained beds and laminae that have preserved their lateral continuity in this facies, whereas the silt-, mud- and clay-rich sediments tend to show "flow" accomodation structures around the coherent strata. Facies F2.1 often passes laterally and vertically, either gradationally or abruptly, into Facies F2.2.

In ancient rocks, the scale of many Facies F2.1 layers/horizons often precludes an appreciation of their vertical and especially lateral dimensions. In present-day continental margin and other deep-marine environments, this facies is recognized on the basis of deep and shallow seismic profiling, long-range sidescan sonar and deep-sea drilling techniques. In seismic profiles, horizons and layers of this facies typically occur either as acoustically unstratified sediments and, or, chaotic acoustic horizons. Sidescan profiling tends to reveal this facies as irregular hummocky topography on the sea floor and basin slopes. In drilled and recovered cores, this facies is suggested by frequent reversals of bedding dip, stretched, attenuated, sheared, faulted (usually seen as microfaults), folded and overturned strata.

Depositional process: mainly gravity-induced sediment sliding and slumping in which the sediment shear strength is exceeded; some in situ, shock-induced deformation due to earthquakes, tsunamis etc..

Selected references: Moore, 1961; Laird, 1968; Lewis, 1971; Ricci Lucchi, 1975b; Roberts et al., 1976; Woodcock, 1976, 1979a, b; Clari and Ghibaudo, 1979; Doyle and Pilkey, 1979; Watkins et al., 1979; Pickering, 1982a, 1984b, 1986; Saxov and Nieuwenhuis, 1982; Bally, 1983.

Facies F2.2 — dislocated, brecciated and balled strata

Recognition: internally dislocated, brecciated and balled strata in layers of variable thickness (Fig. 41).

Facies F2.2 is gradational from F2.1. This facies is typified by very brecciated and balled strata in a chaotic jumble of fragments, in layers of varying thickness but generally thinner than for Facies F2.1. Layer shape is highly variable from parallel-sided to very irregular and lensing. Typically, the layers consist of a relatively fine-grained 'matrix' with fragments of original bedding and laminae in lens-like angular to well rounded pieces. Facies F2.2 usually is an intraformational deposit with relatively uniform

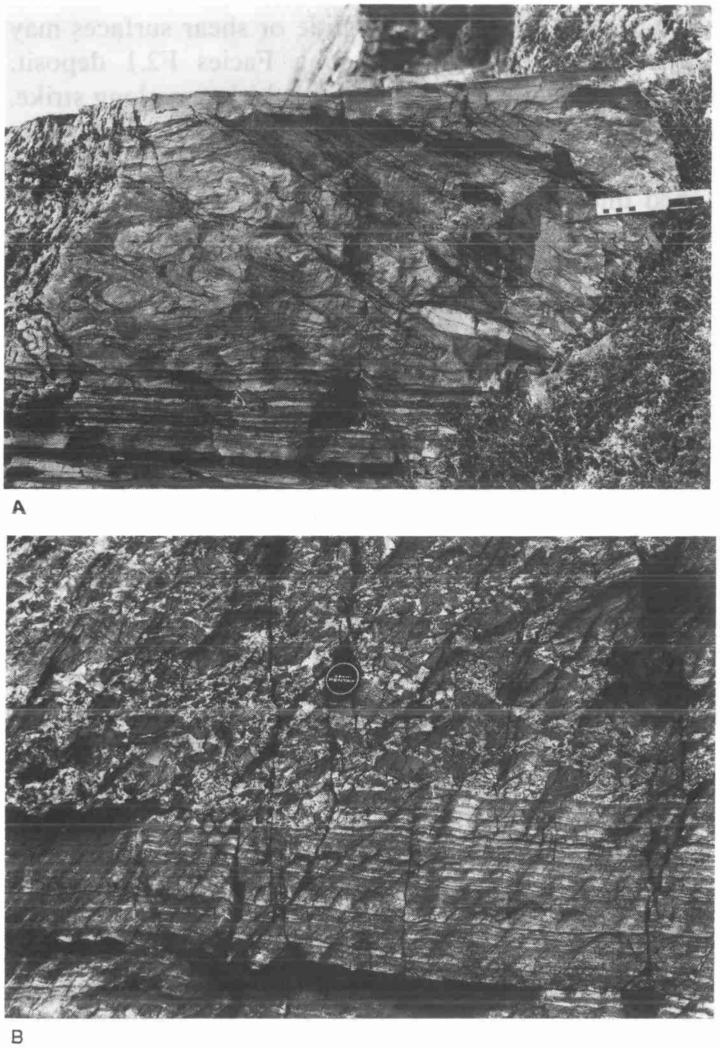


Fig. 41. Dislocated, brecciated and balled strata (Facies F2.2). Late Precambrian Båsnaering Formation (Naeringselva Member), Finnmark, N. Norway. A. Scale 15 cm; N.B., balled strata within slide unit and normal bedding beneath. B. Camera lens cap for scale; N.B., brecciated strata, with under-cutting into undisturbed strata beneath.

composition for any given layer. A crude ghost stratigraphy may be present and commonly many of the fragments are folded/contorted as isolated prolapse structures and single folds on a scale of decimetres.

The layers of balled strata, so named because of the roundness of the fragments, are the most common variant of Facies F2.2. Typically, bounding surfaces are smooth although layer thickness is variable along strike. Relict bedding is visible as plastically deformed bundles of laminae/beds, or as 'wisps' within an almost 'homogenized' layer. Layers of balled strata may pass laterally through a zone of pervasively microfaulted sediment into Facies F2.1 over short distances.

The brecciated variants of Facies F2.2 are characterized by abundant poorly imbricated/unordered, elongate, angular to subangular intraformational fragments, usually of fine-grained sands, silts, muds and clays, in layers of the order of decimetres thick. Upper and lower surfaces tend to be irregular. Undercutting of partially eroded sediments may be visible at the base of one of these layers, while upper surfaces may show sediment draping. Commonly, brecciated strata are associated with liquefaction and fluidization structures such as water escape pipes.

Depositional process: mainly gravity-induced sediment sliding with more pervasive internal deformation of the slide sheets than for Facies F2.1; some in-situ liquefaction and fluidization.

Selected references: as for Facies F2.1.

FACIES CLASS G — BIOGENIC OOZES, HEMIPELAGITES AND CHEMOGENIC SEDIMENTS, < 5% TERRIGENOUS SAND AND GRAVEL

This facies class comprises various non-terrigenous sediments that are often closely associated with siliciclastic facies in the deep sea. These pelagic, hemipelagic and chemogenic sediments are ubiquitous throughout the world's oceans, and are widely recognized in both modern and ancient environments. Most of Facies Class G have been deposited either by the slow settling of material through the water column in the absence of substantial bottom currents, or by direct chemical precipitation. However, many of the processes that are proposed for the accumulation of some of these sediments require current-induced advective processes that replenish suspended sediments, nutrients and other chemicals to the sedimentation column. Three distinctive facies groups can be distinguished on the basis of differing composition: G1, biogenic oozes; G2, hemipelagites; and G3, chemogenic sediments.

Pelagic sediments (Facies Group G1) accumulate in the open ocean, and primarily consist of skeletal parts of planktonic organisms, together with some minor amounts of very fine silt and clay, much of which has reached the open ocean by eolian transport. The proportion of terrigenous material may be increased by the preferential dissolution of the biogenic fractions (such that a true record of the primary depositional composition is not preserved). Almost total dissolution results in a pelagic clay (less than 25% biogenics; often less than 1%) which we have described as Facies E1.2 (varicoloured muds).

Hemipelagic sediments accumulate on continental margins and in other settings near to terrigenous sediment sources. They consist of indigenous biogenic material (greater than 5%), with silt and clay-grade terrigenous detritus, at least 40% of which is silt-sized. Both pelagites and hemipelagites accumulate slowly, therefore they tend to be thoroughly bioturbated except where organic productivity rates are low to absent as in anoxic basins.

Other minor facies groups that occur principally in the pelagic realm of the deep sea include the purely chemogenic sediments (Facies Group G3), composed almost entirely of authigenic minerals such as ferro-manganese nodules and phosphorites. While we acknowledge that this group of sediments represents an important part of the spectrum of deep marine sediments, in the same way as does the carbonate sediments, they are not dealt with further in this paper since they are outside the scope of this study. However, any extension of our classification scheme to accomodate such deposits could place these sediments in Facies Class G.

The chief distinguishing features of the pelagites and hemipelagites includes: (1) evidence for low to very low rates of sediment accumulation and continuous bioturbation (except in anoxic basins); (2) an absence of primary sedimentary structures or other evidence of sustained current-controlled deposition; (3) an essentially uniform composition within any given succession that may show a regular cyclicity related to climatic or other controls; and (4) a variable biogenic component, mainly of planktonic tests, a very fine-grained, often far-transported, terrigenous component, and commonly a significant authigenic fraction.

Facies Group G1, 'biogenic oozes and arls'

Facies G1.1 — biogenic oozes

Recognition: greater than 75% calcareous/siliceous biogenic material in layers of variable thickness, no primary sedimentary structures, bioturbation often pervasive (Fig. 42).

Biogenic oozes are most typical of the open ocean basins far from a terrigenous source. Some important syntheses are to be found in the volume by Hsü and Jenkyns (1974), and Cook and Enos (1977), and in papers by Arrhenius (1963) and Jenkyns (1986).

One of the chief characteristics of the pelagic oozes is their very slow rates of accumulation, commonly from less than 1 mm to 10 mm/1000 years, although this can be an order of magnitude higher under zones of upwelling. They are usually, therefore, thoroughly homogenized by bioturbation, and devoid of any primary current-induced structures. A variety of burrow types may be preserved with different assemblages or ichnofacies, dependent upon varying environmental factors such as water depth, grain size, rate of

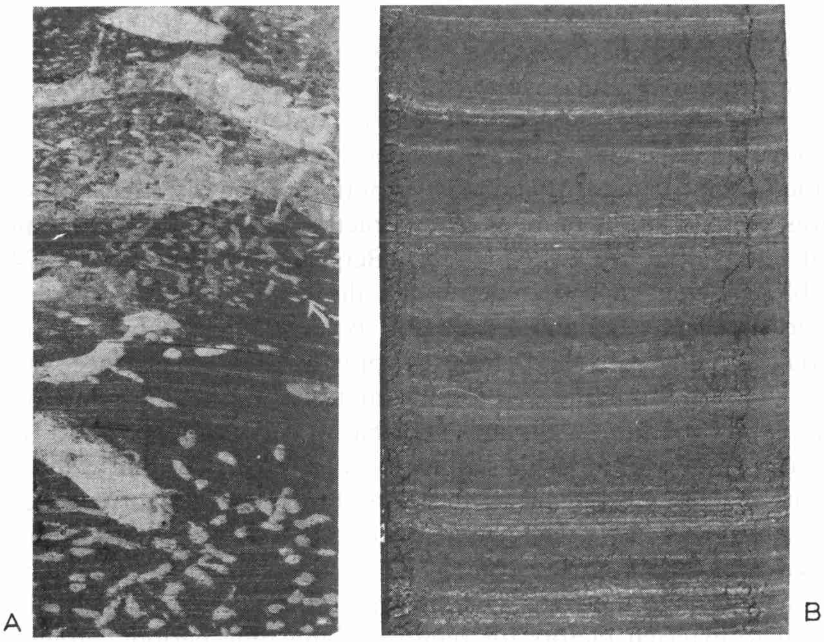


Fig. 42. Biogenic ooze (Facies G1.1). A. Plio–Pleistocene diatomaceous ooze (dark-coloured) with burrows of nannofossil — foraminiferal ooze (light-coloured), Walvis Ridge, SE Atlantic, DSDP Leg 75, Site 532. Core width 5 cm. B. Pleistocene finely laminated (varved) diatomaceous ooze, Guaymas Basin slope, Gulf of California, DSDP Leg 64, Site 480. Core width 7 cm.

sediment accumulation and redox conditions (Seilacher, 1967; Werner and Wetzel, 1982). Some of the main diagnostic trace fossils are *Zoophycus, Chondrites, Planolites, Scolicia, Trichichnus, Teichichnus* and *Lophoctenium*. Several tiers of trace fossil assemblages are commonly superimposed on one another (Werner and Wetzel, 1982).

The grain size of pelagic oozes is largely dependent upon the composition of the biogenic components. Coccolith plates are very small (clay-size), whereas some foraminifera-rich or diatom-rich oozes may have a mean grain size that is in the silt range. The terrigenous fraction is largely clay-grade. Full grain size analyses of pelagic oozes are rarely conducted, especially since the hydraulic equivalence of biogenic particles is poorly understood, hence interpretation of the grain size distribution is extremely speculative.

Pelagic oozes are composed predominantly of the tests of planktonic organisms (greater than 75%), either calcareous (coccoliths, foraminifera, pteropods and nannoplankton) or siliceous (radiolaria, silicoflagellates), or a mixture of both (Berger, 1974). The other components (Lisitzin, 1972) may include very fine-grained terrigenous material (principally quarz, feldspars and clay minerals), volcanogenic minerals (e.g., palagonite and derived clay minerals), authigenic minerals (e.g., phosphates, barite, zeolites, ferromanganese nodules and coatings), and rare extra-terrestrial material. Under normally oxic conditions, the organic carbon content is extremely low, but under anoxic conditions pelagic black shales can contain up to and over 20% organic carbon (Isaacs, 1981; Arthur et al., 1984).

The characteristics, composition and distribution of the different types of pelagic oozes depend on a number of interacting variables that are not discussed at length (but see Lisitzin, 1972; Berger, 1974; Broecker, 1974). These variables include: the water depth and the location of the carbonate compensation depth (CCD); the source and type of terrigenous/volcanogenic material, together with the sediment-supply process(es); surface water productivity and the supplying of biogenic material; surface currents and bottom circulation patterns; climate and basin physiography; and the physio-chemical conditions. Pelagic sediments are perhaps more affected by this spectrum of variables than is the case for turbidity currents and contourite deposits, because pelagic grains: (1) consist of biogenic carbonate and, or, silica both of which are soluble in sea water; and (2) they settle relatively slowly through the water column and are buried very slowly, thus being exposed to external factors for relatively long time periods, either in the water column or on the sea floor. The actual processes of settling as single grains or as larger flocs and pellets are discussed in more length in papers by, for example, Gorsline (1984) and McCave (1984).

Depositional process: very slow accumulation of calcareous/siliceous material by settling of single grains or aggregates through the water column.

Selected references: Arrhenius, 1963; Lisitzin, 1972; Berger, 1974; Broecker, 1974; Hsü and Jenkyns, 1974; Jenkyns, 1986; Isaacs, 1981; Werner and Wetzel, 1982; Arthur et al., 1984; Gorsline, 1984; McCave, 1984.

Facies G1.2 — muddy pelagic ooze (arl)

Recognition: 25–75% biogenics and mainly clay-size terrigenous material in layers of variable thickness, devoid of primary sedimentary structures with common bioturbation (Fig. 43).

There is a continuum of facies from biogenic ooze with greater than 75% biogenic material to pelagic clay with less than 25% biogenics (our Facies E1.2). Muddy biogenic oozes or arls (see terminology of Stow and Piper, 1984c; and Dean et al., 1985) are a relatively common intermediate sediment type, with attributes that are transitional between an ooze and a clay. They differ from true hemipelagic sediments in possessing a dominantly clay-sized rather than silt-sized terrigenous component, and in being mainly an open ocean rather than continental margin facies. Layers of this facies lack primary sedimentary structures but, often, show pervasive bioturbation.

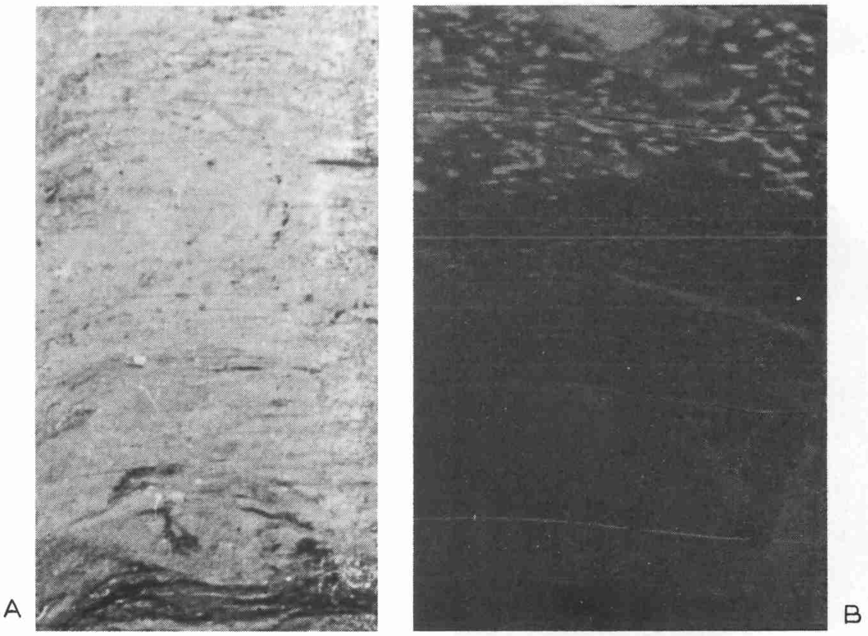


Fig. 43. Muddy pelagic ooze (arl) (Facies G1.2). A. Plio–Pleistocene muddy calcareous ooze, Aegean Sea, DSDP Leg 42, site 378. N.B., bioturbational mottling. B. Plio–Pleistocene muddy siliceous ooze with *Chondrites* burrows, Angola Basin, DSDP Leg 75, Site 530B. Core widths approx. 5 cm.

Depositional process: mainly very slow accumulation by settling, with dissolution or dilution of biogenic material. Clays may have been transported to the sea surface by wind.

Selected references: as for biogenic oozes; Stow and Piper, 1984c; Dean et al., 1985.

Facies Group G2, 'hemipelagites'

Facies G2.1 — hemipelagite

Recognition: 5–75% biogenic, with greater than 40% of the terrigenous component as silt-grade material, as layers of variable thickness, devoid of primary sedimentary structures, commonly pervasively bioturbated (Fig. 44).

Hemipelagic sediments are more typical of marginal oceanic settings where there is a ready supply of terrigenous material. In published descriptions of sedimentary successions, they are frequently referred to as "background" sedimentation, normal, ubiquitous or interbedded facies, and are often not described in any detail although they may constitute the greater part of a given succession. At high latitudes, for example in the Arctic Ocean

Fig. 44. Hemipelagite (Facies G2.1). Pleistocene hemipelagite with large *Zoophycos*-type burrows, Angola Basin, DSDP Leg 75, Site 530B. Core width 7 cm.

and Baffin Bay, ice-rafting is a major contributary source of the fine-grained hemipelagic sediments.

Amongst the voluminous literature that simply refers to hemipelagic sediments in a cursory manner, some authors have attempted to document the facies characteristics in rather more detail. Particularly useful descriptions of modern hemipelagites include those of Rupke (1975) and Stanley and Maldonado (1981) from the western and eastern Mediterranean, respectively; Stanley et al. (1972) and Hill (1984) from the Nova Scotian margin;

Moore (1974) and Kolla et al. (1980) from the Indian Ocean, and various contributions by Gorsline and colleagues (e.g., Gorsline, 1978, 1981) from the basins of the Californian Borderland.

Although more difficult to identify in ancient rocks, there have been a number of papers describing possible hemipelagites from slope and basinal environments (e.g., Hesse, 1975; Piper et al., 1976; Ingersoll, 1978; Hicks, 1981; Pickering, 1982b). Such facies are commonly homogeneous and structureless, with poorly defined bedding if at all present — where it may be accentuated by burial and diagenesis. There are no primary, current-induced, sedimentary structures such as lamination or erosional contacts, although a depositional lamination may be preserved under anoxic conditions (e.g., Isaacs, 1984; Thornton, 1984).

Under normal oxic conditions, however, bioturbation is ubiquitous and pervasive, often resulting in a completely homogenized sediment with a mottled aspect. Burrow traces may be preserved, with the same major trace fossil assemblages represented as for the pelagic oozes described above. Similarly, these depend upon water depth, grain size, accumulation rate and redox states (Werner and Wetzel, 1982; Wetzel, 1984). Iron sulphide filaments (mycelia) and mottles are also common features of hemipelagic deposits.

Texturally, hemipelagic sediments are silty clays with from 1 to 15% sand-grade that is mainly of biogenic origin. They are poorly sorted and show no systematic grading apart from that associated with the compositional cyclicity discussed below. The shape of the grain size cumulative curves (Rivière, 1977) appears almost uniform or logarithmic, although there may be irregularities due to a typical biogenic input or rare exotic terrigenous material (e.g., ice-rafted debris).

Apart from the mixed biogenic/terrigenous aspect of hemipelagites, it is difficult to generalize further about their composition. The biogenic input may be slight or dominant, calcareous or siliceous depending upon surface productivity, CCD, etc. It is commonly of mixed planktonic and in-situ bathyal benthic species. The terrigenous components are mostly uniform in any given area of an ocean and display very gradual compositional trends towards the source area(s). The nature of hemipelagites varies considerably throughout the geologic record and in modern oceans, depending on the tectonic, climatic, source area and oceanic physio-chemical conditions. There may be minor amounts of far-transported wind-blown and ice-rafted terrigenous detritus, reaching substantial proportions of the total sediment composition in some cases.

Depositional process: relatively slow accumulation of biogenic and terrigenous material by vertical settling, with substantial contribution from land run-off, some lateral transfer by weak mid- and bottom-water currents

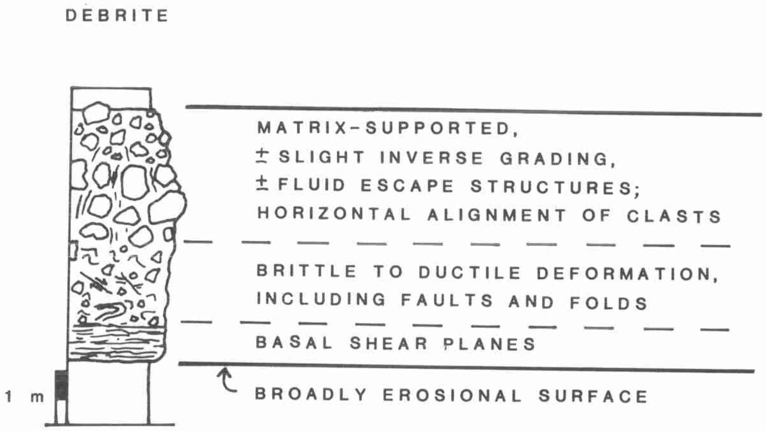


Fig. 46. Schematic facies model for debris-flow deposits (debrites). After Thornton (1984).

with Woodcock (1979 b), we adopt the use of the term "slide" for all downslope mass movement involving translations whereas the term "slump" is reserved for a slide with a rotational component; i.e., restricted to the "downward slipping of a mass of rock or unconsolidated material of any size, moving as a unit or as several subsidiary units, usually with backward rotation on a more or less horizontal axis parallel to the slope from which it descends" (Sharpe, 1938). Thus, a slump is only one of several types of slide. Coates (1977) defines a slide as downslope mass movement "with displacements along recognized shear surfaces where the ruptured mass moves with some semblance of unitary motion."

Woodcock (1979b) emphasizes the problems of recognition of slides, especially where slide masses are large relative to the amount of exposure. Kelts and Arthur (1981) list the following criteria for the probable identification of slide deposits in DSDP cores as (relevant to recognition of slides where there is limited onshore outcrop): sheared, stretched, or highly microfaulted beds, folded or overturned layers, and frequent reversals in dip of bedding.

Debris flow model (Fig. 46)

Facies A1.1, A1.2, and A1.3 involve mixed lithologies, with relatively hard cobbles, boulders, pebbles and soft silt–mud clasts set in a sandy or muddy matrix: such deposits vary in thickness up to several metres or tens of metres. In the last decade, a large amount of research has been undertaken to explain the origin of pebbly muds and muddy sandstones (Johnson, 1965, 1970; Rodine and Johnson, 1976; Enos, 1977; Middleton and Southard, 1984) and, in many cases, such beds are ascribed to debris flow processes. Also, Facies C1.1 and D1.1 are very muddy and disorganized, and may be explained by the debris flow model.

'Cohesive' debris flows derive particle support mainly from buoyancy and the cohesiveness of a sediment–water matrix with sufficient strength to carry the particles. Deposition is brought about by freezing of the flow, accounting for the uniform distribution of the clasts within a mud or sand–mud matrix after sedimentation. These flows in almost all cases are laminar and, as early as 1922, Jeffery demonstrated that a crude fabric may exist as clast imbrication/alignment of clasts (see also Hiscott and James, 1985).

The absence of grading, stratification and recognizable fabric in Facies Group A1 suggests that the clasts were deposited en masse. Inertial clast interactions do not appear to have been a dominant process; otherwise, inverse grading might reasonably be expected. Thus, some form of matrix strength and buoyancy probably were the most significant processes supporting the clasts immediately prior to deposition. Many disorganized gravel facies described in the literature appear to contain very little mud, so that pure cohesive strength is not a viable principal support mechanism (Lowe, 1976a, 1982). A mud–water slurry constituting as little as 5% by volume of the flow can provide buoyant support and lubricate the clasts (Rodine and Johnson, 1976), but cannot supply total support (Hampton, 1972; Lowe, 1982). The remaining clast support probably is provided by a combination of dispersive pressure (Takahashi, 1981) and excess pore-fluid pressures (Pierson, 1981).

Lowe (1982) believes that in many cases the largest clasts are not actually suspended within the mud–water matrix, but remain in contact through rolling, sliding and intermittent bouncing downslope, and that such flows tend to be clast-supported with as little as 5% clay–water matrix.

In many cases, olistolith horizons (olistostromes) have been attributed to debris flow processes. For example, the Licha Melange of Pliocene age in eastern Taiwan contains pebbly mudstones as well as sandstones and ophiolitic blocks in a disturbed scaly-mudstone matrix, and Page and Suppe (1981) interpret the olistoliths as the result of submarine sliding and mass flow in a fore-arc basin. Olistostromes often are associated with sediment slides and, indeed, deposits may show features of both slide and debris flow processes. Clearly, olistostromes may be defined as Facies F1.1 (isolated exotic blocks) or as Facies A1.3 (exotic clasts/blocks within a mud matrix that rafted those clasts via essentially laminar flow processes as a debris flow to the depositional site). Since the terms "olistolith" and "olistostrome" have genetic overtones, we prefer to descriptively define the deposits and to avoid the use of such terms in our facies scheme.

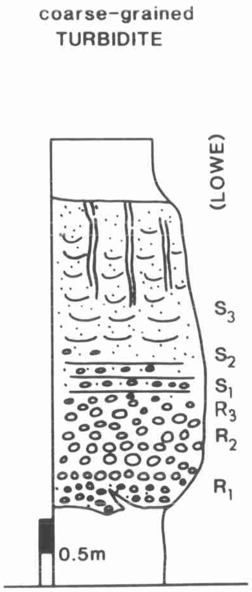


Fig. 47. Schematic facies model for coarse-grained turbidity-current deposits. See text for explanation. Divisions are labelled after Lowe (1982).

Clearly, caution should be exercised in deciphering the origin of melanges in terms of processes such as debris flow with olistostromal material, or slides, once tectonism has partially to severely altered/over-printed the primary sedimentary fabric and structures. Recently, Cowan (1985) identified four types of melange and discussed their possible origin, including muddy debris flow processes, slides and mud diapirism or similar processes involving the migration and intrusion of mobile mud-rich sediment. Cowan (1985) and Pickering (1986) describe good examples of layers containing blocks/clasts within finer grained matrices, showing incipient to thorough disruption and fragmentation, either gravity-driven and, or, shear-zone (often thrust) related. The problem of melanges and olistostromes, and their origin, while not an integral part of this study, should be appreciated since many deep-water sedimentary successions contain such enigmatic deposits.

Coarse-grained turbidite facies model (Fig. 47).

The fundamental depositional processes for the coarse-grained facies model can be divided into those in which grains or clasts are deposited individually and those in which collective grain deposition occurs (Lowe, 1982). The coarser grain-size pupulations can be maintained in suspension by support mechanisms such as turbulence, dispersive pressure, buoyancy and hindered settling. These support mechanisms are concentration-dependent, such that sediments coarser than coarse-grade sand will only be transported in large amounts by high-concentration flows.

The coarse-grained facies model is a composite of many of the facies of our Classes A and B, each represented by one of the divisions of the idealised sequence R1, R2, R3, S1, S2 and S3 (Lowe, 1982). Deposition may have involved grain interaction (dispersive pressure) and pore fluid escape (liquefaction/fluidization processes) after long-distance sediment transport by high concentration turbidity currents. The gravel sizes may form one or more of the following divisions: R1, coarse gravel showing traction structures; R2, inversely graded gravel layer; and R3, normally graded gravel layer. The coarser-grained sands may produce: S1, traction structures, generally plane- and cross-lamination resembling plane beds and dune-like bedforms, respectively; S2, as thin horizontal layers with inverse grading (Hiscott and Middleton, 1979); and S3, structureless or normally graded layers, often with water escape structures, formed mainly under conditions of rapid deposition from suspension (Lowe, 1982).

The stratified gravels form from clasts that have rolled, bounced and saltated under the influence of an over-riding high-velocity flow (Winn and Dott, 1977; Lowe, 1982). Winn and Dott (1977) argued that the confinement of flows in channels could allow flows to reach velocities sufficient to move 20–30 cm clasts by traction. The a-axis parallel to flow fabric, reported by these researchers, appears inconsistent with purely tractional processes. In fact, large scale traction bedforms tend to occur rarely in these deposits because of the build-up of dispersive pressure as clasts become concentrated at the base of a flow (Fisher, 1971; Walker, 1975a), leading to successive freezing of traction carpets.

Inverse grading and clast imbrication in gravels (Facies A2.2) suggest that the clasts were free to move relative to each other and that they were deposited under the dominant influence of clast–clast interaction. High clast concentrations, poor sorting and coarse-grain sizes are necessary for the development of a dense clast dispersion (Middleton, 1970; Walker, 1975a). Flow deceleration and clast fall-out are too rapid to allow bed-load traction, and concentration of the clasts towards the bed leads to the development of a traction carpet in which clast–clast interaction is important. The traction carpet is supplied and driven by the overlying turbulent flow. Deposition occurs by mass freezing once the flow velocity decreases to a point where the dispersion cannot be maintained. Inversely graded gravels result from such depositional processes. Turbulence in the higher part of these complex sediment gravity flows, and the degree of grain segregation, will determine the extent to which a massive or normally graded interval occurs above the inversely graded gravel. The upper part of the inversely to normally graded gravels may have been deposited directly from suspension without passing through a high-concentration dispersion phase. Inversely to normally graded gravels are transitional between inversely and normally graded gravels.

Normally graded gravels (Facies A2.3) occur when sediment fall-out reaches a critical point where neither traction nor the maintenance of a traction carpet is possible. Instead, deposition is directly from suspension. Normal clast grading is a result of vertical and lateral size segregation within a flow (Walker, 1965). Size segregation is controlled by the distance travelled by a flow together with the degree of freedom of movement for the clasts within that flow (i.e., relative flow concentration as suggested by Walker, 1977). Abruptly graded beds indicate only a crude separation of the coarsest clasts from the others, while beds that show distribution grading have achieved a high degree of size sorting. Fluid turbulence is, however, probably only one of several clast-support mechanisms, as very high velocities are required to suspend cobbles by turbulence alone (Komar, 1970; Davies and Walker, 1974; Winn and Dott, 1977). Buoyancy and hindered settling due to the highly concentrated nature of the flows are probably contributary factors.

For the graded–stratified gravels (Facies A2.4), suspension sedimentation of cobbles/pebbles to give normally graded gravels leaves a flow relatively enriched in fine pebbles, sand and mud, with particle support largely provided by fluid turbulence. The flow may: (1) continue downslope prior to becoming unsteady and depositing its load elsewhere; (2) rework the upper layers of the normally graded gravel to produce a thin cap of tractional deposits; or (3) continue to deposit above the normally graded gravel. In the latter case, the initial phase of deposition will be from a tractional bedload of mainly fine pebbles and sand. This will produce horizontal, oblique or cross-stratification with common amalgamation and scour structures (e.g., Aalto, 1976; Mutti and Ricci Lucchi, 1972; Hubert et al., 1970; Rocheleau and Lajoie, 1974).

Deposition at the base of a high-concentration turbidity current from a traction carpet of mainly fine pebbles and sand produces the stratified pebbly sands of Facies A2.5 (Hein, 1982). In some cases, the stratification may be produced by sequential freezing of basal traction carpets; this process produces distinct, inversely graded stratification bands (Hiscott and Middleton, 1979, 1980). Intense clast interaction also is responsible for the emplacement of inversely graded pebbly sands (Facies A2.6). If the depositional surface migrates upwards gradually, an homogeneous, structureless, or slightly inversely graded pebbly sand results (Lowe, 1976a; Hein, 1982).

However, spasmodic upward migration gives rise to several superimposed inversely graded units, in a bed otherwise characterized by normal or poorly defined grading (Hiscott and Middleton, 1979).

The normally graded pebbly sands (Facies A2.7) result from suspension sedimentation from high-concentration turbidity currents. As flow velocity declines, sediment fall-out rate increases and a traction carpet can no longer be maintained. Sand and pebbles settle out of suspension and the type of normal grading is determined by the original sediment size distribution and the effects of flow turbulence in the flow overlying the sedimenting layer.

The graded stratified pebbly sands (Facies A2.8), in common with the graded–stratified gravels (Facies A2.4), are considered as transitional between the less ordered pebbly sands and the sands of Facies Class B. The lower graded pebbly part of the beds results from suspension sedimentation with fall-out rates sufficiently great to inhibit the development of traction structures. The stratified component may be considered as analogous to the Bouma divisions in sands. Thus, the graded stratified pebbly sands are transitional between Facies Classes A and B. As yet, there is no generalized Bouma-like sequence applicable to the pebbly sands, despite attempts to establish just such a sequence (Aalto, 1976; Hein, 1982). Furthermore, it is not known if pebbly sands and other sand facies grade into each other.

Medium-grained turbidite model (Fig. 48)

The medium-grained facies model corresponds to the typical or 'classic' Bouma sequence, and represents the depositional model for most of our Facies Class C and parts of Classes B and D (there being some overlap between the three 'turbidite models' — coarse-, medium- and fine-grained models). The five divisions are well known: Ta, essentially structureless or graded basal sand division; Tb, upper flow regime parallel-laminated sand; Tc, cross-laminated and convolute-laminated sand and silt; Td, lower flow regime parallel-laminated fine-grained sand, silt and mud; and Te, essentially structureless mud, possibly with abundant bioturbation (Bouma, 1962; Kuenen, 1964; Walker and Mutti, 1973; Hesse, 1975).

Considerable research into the theoretical and experimental aspects of turbidity currents has been undertaken over the last few decades, for example, the work of Kuenen (1951, 1965, 1966a, b), Bagnold (1962), Middleton (1966a, b, 1967a), Komar (1969, 1972, 1973, 1985), Pantin (1979), Southard and Mackintosh (1981), Parker (1982), Paola and Southard (1983), and Bowen et al. (1984). Although most of this research has been directed towards the sandy turbidity currents and their deposits, there has been some investigations of finer-grained turbidity currents (see below). Hydrodynamic processes in the upper and lower flow regimes are matched with the divisions

1978; Kelts and Arthur, 1981; Stow and Piper, 1984). Recently, Chough et al. (1984) recognized a sequence of structures in fine-grained sediments above the Td division of the Bouma sequence, namely: E1, laminated mud (often laminated and graded); E2, graded mud; E3, homogeneous mud (ungraded mud of Piper, 1978); E4, convolute mud (deformed E1, E2 and E3); F1, bioturbated mud; F2, bioturbated mud with authigenic pyrite; and G, indistinctly laminated mud. Chough et al. (1984) attribute a turbiditic origin to the E1–E4 divisions, while the F and G divisions are interpreted as due to very slow settling from other bottom currents (e.g., contourites) and pelagic settling.

The T0–T8 sequence can be interpreted hydrodynamically as resulting from a single large resedimentation event that deposited progressively finer grain size populations, giving rise to different sedimentary structures as the flow velocity, competence and capacity decreased. A complete sequence is very rarely deposited and partial sequences are the rule (top-absent, base-absent and middle-absent etc.). Physical analysis of the textural properties of the Scotian margin sediments (Stow, 1977) has led to the suggestion that the muddy turbidity currents that deposited such sequences were very thick, had very low sediment concentrations, and moved downslope at velocities of about 10–15 cm/s (Stow and Bowen, 1980). Waning current velocities during the passage of a single flow explain the grading and structural sequence. The alternation of silt and mud laminae is believed to be the result of depositional sorting of silt grains from clay flocs due to shear in the bottom boundary layer (Stow and Bowen, 1980).

Facies models for deposition beneath permanent/semi-permanent currents (Fig. 50)

Deep marine bottom currents driven by winds, internal waves and tides, or thermohaline circulation are relatively well documented processes in modern ocean basins and yet their deposits in ancient deep water successions are rarely recognized. However, two distinctive types of facies may be defined: (1) reworked sediments, especially common in deep-water channels; and (2) contourite deposits. In addition, bottom currents are probably responsible, in part, for the distribution of fine-grained hemipelagic facies.

In deep-water canyons and channels, more or less constant bottom currents, in addition to reworking by powerful by-passing turbidity currents, probably contribute to the distinctly "fluvial" characteristics and facies observed in these environments (e.g., McGregor et al., 1982; Damuth et al., 1983; Valentine et al., 1984). Large-scale dune cross-stratified bedforms (Facies B2.2) and smaller-scale, finer-grained cross-stratified sands (some Facies C2.3 and D2.2) may represent reworking of bottom sediments by

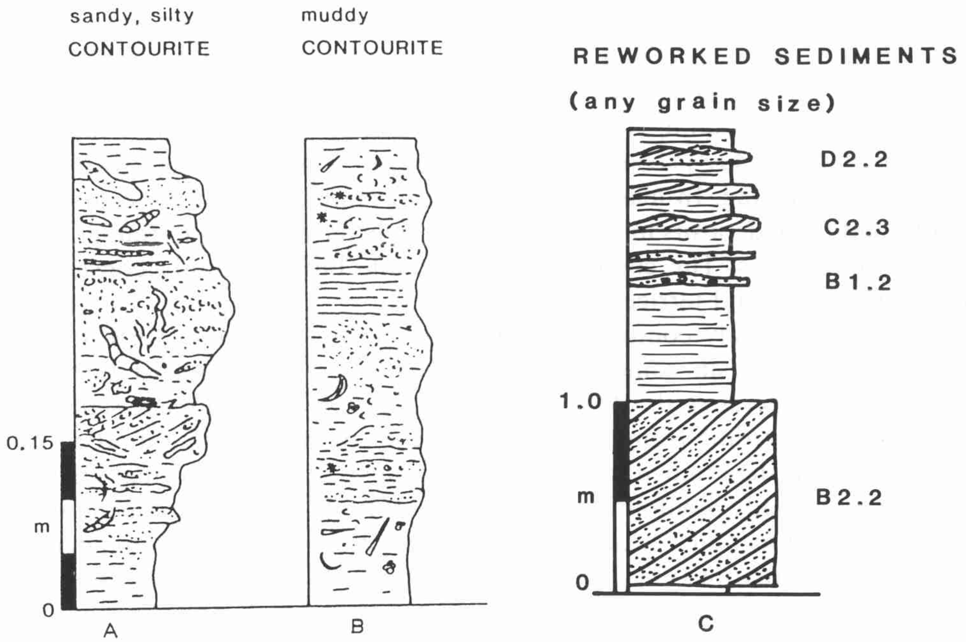


Fig. 50. Schematic facies models for: A. sandy to silty contourites; B. muddy contourites; and C. reworked sediments (any grain size). See text for explanation.

various permanent/semi-permanent currents, including non-depositing turbidity currents, mainly in canyons and channels. Such reworked sediments occur as thin to thick, usually isolated, sediments within channel deposits and not as integral parts of larger resedimented beds. Sediments showing these features are well documented from ancient successions (e.g., Mutti, 1977; Scott and Tillman, 1981; Hein and Walker, 1982).

Contour current deposits (contourites) may be considered in terms of two discrete facies models: (1) muddy contourites, and (2) sandy contourites. Facies models for these types have been developed from Tertiary to Recent contourite drifts in the deep sea (Stow and Lovell, 1979; Stow, 1982), but it has proved particularly difficult to recognize ancient contourites with any degree of certainty (e.g., Anketell and Lovell, 1976; Lovell and Stow, 1981). *Muddy contourites* (some Facies E1.2 and D1.3) are fine-grained, mainly homogeneous, structureless, and thoroughly bioturbated and only rarely show irregular layering, lamination and lensing. They are poorly sorted silt- and clay-sized sediments with up to 15% sand fraction. They range from finer-grained homogeneous muds to siltier mottled silts and muds, and their composition varies with the primary source material but is most commonly mixed biogenic and terrigenous sediments. Muddy contourites most closely resemble hemipelagites. The *sandy contourites* occur as thin irregular layers (less than 5 cm thick), that are either structureless and thoroughly bioturbated or with some primary horizontal/cross-lamination preserved. Normal and inverse grading with sharp to gradational bed contacts may be developed. Grain size is commonly fine sand, rarely medium sand, with poor to moderate sorting. In many cases, the mean grain size is in the coarse silt grade, and these deposits may be more accurately termed 'silty to fine-grained sandy' contourites. The composition is variable but commonly consists of mixed biogenics and terrigenous components.

Muddy and sandy contourites commonly occur together in vertical "sequences" that are, in some respects, analogous to the standard turbidite sequences (Faugères et al., 1984; Gonthier et al., 1984). A complete sequence shows inverse grading from a fine homogeneous mud, through a mottled silt and mud, to a fine-grained sandy contourite facies, and then normal grading back to a muddy contourite. The grain size changes and concomitant changes in sedimentary structures and composition probably are related to long-term fluctuations in the mean current velocity, on the order of 2,000–10,000 years for a 50-cm sequence.

The effects of winnowing and reworking by bottom currents can result in contourite facies with different characteristics. Thin, irregular, poorly sorted, structureless, mixed-composition, iron-manganese coated, coarse-grained

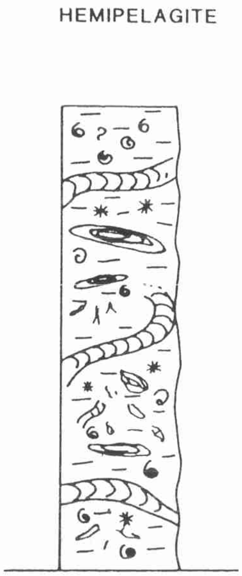


Fig. 51. Schematic facies model for hemipelagic deposits (hemipelagites). See text for explanation.

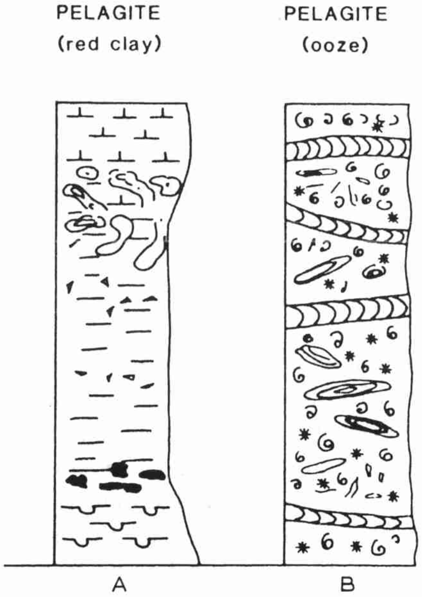


Fig. 52. Schematic facies models for pelagic deposits (pelagites): A. for open-ocean red clays; and B. for oozes. See text for explanation.

sand and *gravel-lag contourites* (some Facies B1.2) are formed by the winnowing and removal of all fines from an earlier coarse-grained sediment by powerful bottom currents. The reworking of sandy turbidites, more or less in situ, can result in bottom-current-modified turbidite sands, believed to be common on continental slopes and rises. In the central part of ocean basins, bottom currents are known to construct large sediment drifts of almost pure pelagic biogenic material (Stow and Holbrook, 1984; Kidd et al., 1984). Such biogenic contourites often are very similar to the pelagites. Finally, it is important to stress that contourites sensu stricto are the result of contour-parallel permanent/semi-permanent currents and that in ancient successions it is generally impossible to accurately reconstruct the palaeogeography and associated sediment dispersal patterns. Therefore, in ancient successions the term contourite is best applied in a descriptive sense without necessarily inferring the precise palaeogeography.

Pelagite and hemipelagite facies models (Figs. 51, 52)

Hemipelagites are compositionally very similar to muddy contourites and also appear homogeneous, essentially structureless and thoroughly bioturbated. However, they do not show any evidence of current control during deposition, probably have a somewhat different ichnofacies and show no vertical 'sequence' of facies or textures (Hesse, 1975; Cook and Enos, 1977; Hill, 1984) — such deposits occur mainly in our Facies Classes E and G.

Two contrasting pelagite facies models are shown in Fig. 52, one for oozes (Facies Group G1) containing more than 75% biogenic material, and one for red clays (Facies E1.2) that commonly have less than 25% biogenics. Neither of these models are considered in detail here, but see Jenkyns (1986), Hoffert (1980) and Thiede et al. (1981).

SUMMARY

Our classification scheme for deep-water siliciclastic sediments contains 40 formally defined facies contained within 15 conceptually distinct facies groups, subsumed within 7 facies classes. We do not claim that this scheme is exhaustive, however, we believe that it is comprehensive of the vast majority of sediments found in both modern and ancient deep-sea environments. The classification scheme is primarily descriptive, although we interpret the facies in terms of depositional processes. Therefore, even if our understanding of sedimentation mechanisms changes, the poignancy of our scheme, as a descriptive tool, will not suffer.

The above facies models may be considered in combination or in isolation when interpreting the origin of a particular deposit. For example, Stanley (1982) has documented a vertical sequence of structures in beds from 3 to 30 m thick in which a chaotic "slump" facies grades into disorganized small-pebble and granule-rich muddy sand (debris flow), and finally into the classic Bouma (1962) sequence. Such "welded slump-graded sand couplets" (Stanley, 1982) emphasize the complex interaction of sediment transport and deposition processes/products and show the artificiality of defining discrete facies models that are mutually exclusive.

In order to fully describe modern and ancient deep-water siliciclastic systems, a detailed facies study must be accompanied by a facies-association and sequence analysis. This scheme of facies merely provides the building blocks with which a complete picture of depositional environments may be constructed.

ACKNOWLEDGEMENTS

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