Sedimentary Geology, 25 (1980) 23—42

SEQUENCE OF STRUCTURES IN FINE-GRAINED TURBIDITES: COMPARISON OF RECENT DEEP-SEA AND ANCIENT FLYSCH SEDIMENTS

DORRIK A.V. STOW * and GANAPATHY SHANMUGAM **

Department of Geology, Dalhousie University, Halifax, N.S. (Canada)
Department of Geological Sciences, University of Tennessee, Knoxville, Tenn. (U.S.A.)

(Received July 5, 1978; revised and accepted August 1, 1979)

ABSTRACT

Stow, D.A.V. and Shanmugam, G., 1980. Sequence of structures in fine-grained turbidites: comparison of recent deep-sea and ancient flysch sediments. Sediment. Geol., 25: 23—42.

A comparative study of the sequence of sedimentary structures in ancient and modern fine-grained turbidites is made in three contrasting areas. They are (1) Holocene and Pleistocene deep-sea muds of the Nova Scotian Slope and Rise, (2) Middle Ordovician Sevier Shale of the Valley and Ridge Province of the Southern Appalachians, and (3) Cambro-Ordovician Halifax Slate of the Meguma Group in Nova Scotia.

A standard sequence of structures is proposed for fine-grained turbidites. The complete sequence has nine sub-divisions that are here termed T_0 to T_8. The lower subdivision (T_0) comprises a silt lamina which has a sharp, scoured and load-cast base, internal parallel-lamination and cross-lamination, and a sharp current-lineated or wavy surface with 'fading-ripples' [illegible] (= Type C ripple-drift cross-lamination, Jopling and Walker, 1968). The overlying sequence shows textural and compositional grading through alternating silt and mud laminae. A convolute-laminated sub-division (T_1) is overlain by low-amplitude climbing ripples (T_2), thin regular laminae (T_3), thin indistinct laminae (T_4), and thin wipsy or convolute laminae (T_5). The topmost three divisions, graded mud (T_6), ungraded mud (T_7) and bioturbated mud (T_8), do not have silt laminae but rare patchy silt lenses and silt pseudonodules and a thin zone of micro-burrowing near the upper surface.

The proposed sequence is analogous to the Bouma (1962) structural scheme for sandy turbidites and is approximately equivalent to Bouma's (C)DE divisions. The repetition of partial sequences characterizes different parts of the slope/base-of-slope/basin plain environment, and represents deposition from different stages of evolution of a large, muddy, turbidity flow. Microstructural detail and sequence are well preserved in ancient and even slightly metamorphosed sediments. Their recognition is important for determining depositional processes and for palaeoenvironmental interpretation.

---

* Present address: British National Oil Corporation, 150 St. Vincent Street Glasgow, U.K.

** Present address: Mobil Research and Development Corporation, P.O. Box 900 Dallas, Texas, 75221.

INTRODUCTION

Fine-grained sediments are common in recent deep-sea environments and in ancient flysch sequences. They are deposited by a variety of processes including low-concentration thick turbidity currents, thin turbid layer flows, bottom (contour) currents and hemipelagic and pelagic deposition. Partly because of their monotonous or structurally homogeneous appearance and partly because of their poor preservation potential, they have been less well studied than equivalent coarse-grained deposits. In particular, there has been relatively little work on the detailed micro-sedimentary structures of fine-grained sediments and their relationship to different processes or environments (Rupke and Stanley, 1974; Hesse, 1975; Mutti, 1977; Piper, 1978; Stow and Lovell, 1979).

Bouma (1962) was the first to propose a structural scheme for turbidites. However, he was concerned mainly with sandy turbidites and thus grouped all the fine material into the E division. The shales in the sequence in the French Alps in which Bouma first identified his five (A—E) turbidite divisions are mostly poorly preserved so that internal structures are indistinguishable. Keunen (1964) proposed a distinction of e^t (turbidite) and e^p (pelagic) within the E division; Van der Lingen (1969) and Hesse (1975) used E and F divisions. Various modifications have also been proposed to account for the whole range of coarse clastic rocks (Middleton and Hampton, 1973; Davies and Walker, 1975; Walker, 1967, 1970, 1976).

There have been relatively few attempts to determine similar structural schemes for fine-grained turbidites. Rupke and Stanley (1974) found an upward grading of the size distribution in turbidite muds overlying thin sands. They also observed slight mineralogical changes through the sequence. Skipper and Middleton (1975) proposed a different structural scheme for some shale-rich, Ordovician turbidites of the Cloridorme Formation, Gaspé, Quebec. They found a basal conglomeratic or coarse sand member, a middle argillaceous host with coarse-grained pseudonodules, and an upper siltstone/shale unit. Piper (1978) recognized a standard sequence in thick (up to 50 cm) turbidite muds overlying sands, from a laminated mud (E1) through a graded mud (E2) to an upper ungraded mud (E3). Chough (1978) and Hesse and Chough (1979) noted micro climbing ripples within a laminated turbidite sequence from the levees bounding the Northwest Atlantic Mid-Ocean Channel. Experimental work with silty sediment in a circular flume (Banerjee, 1977), has shown that silts behave as cohesionless grains and produce similar bedforms to those of sands. The rate and nature of deceleration during the experiments was found to be the key factor in producing different types of vertical structural sequences.

We have examined fine-grained (silt and clay size) sediments in three contrasting areas: the Nova Scotian Slope and Rise, including the Laurentian Fan, which comprises unconsolidated, Holocene and Pleistocene deep-sea muds; the Middle Ordovician Sevier Shale in east Tennessee; and the low-grade metamorphosed Halifax Slate of Nova Scotia which is (?) Cambro-Ordovician in age. All three areas comprise fine-grained sediments that are dominantly of turbidite origin, and in the case of the ancient rocks, of inferred deep-sea setting. In this paper we summarise previous work on the geographical setting and facies distribution for each area. We then present detailed documentation and comparison of analogous micro-sedimentary structures and propose a standard structural sequence for fine-grained turbidites.

The methods of study are described in more detail in Shanmugam and Walker (1978), and Stow (1977). More than 60 piston and gravity cores were collected from the Nova Scotian outer margin. The techniques used to study sedimentary structures in the muds and silts, included X-radiography, impregnation and thin-sectioning, and microscopic examination of core sections. Size analysis was by Coulter Counter. More than 500 m of the Sevier Shale were examined in the field for bed thickness and grain size variations. 250 stratified random samples were collected for microscopic examination. Nearly 9000 individual layers were examined for sedimentary structures using thin sections, polished slabs, acetate peels, and X-radiographs. Size analysis was also made from thin sections to corroborate field data. Detailed field measurement and photographic study were made of selected parts of the Halifax Slate.

GEOLOGICAL SETTING

The Nova Scotian Slope and Rise (from 200 to 5000 m in depth, Fig. 1A) have been the sites of thick sediment accumulation on a spreading margin since the opening of the North Atlantic in the Jurassic (Jansa and Wade, 1975). This margin has been described by Emery and Uchupi (1972) as a series of overlapping Pleistocene fans. The largest is the Laurentian Fan (Stow, 1979) which extends some 100 km farther seawards than the adjacent Rise. During Pleistocene glacial maxima, sea level was lowered by up to 120 m and this increased considerably the volume of sediment delivered to the deep ocean margin.

Coarse sands and gravels are restricted to the channel axes, while the overbank and interchannel areas are composed dominantly of muds (Stow, 1976). Two distinctive fine-grained facies are identified (Stow, 1977, 1979 a, b). A bioturbated, biogenic-rich, olive-grey mud with rare, irregular, sandy or silty layers has been deposited relatively slowly by a combination of hemipelagic settling, sandy turbidity current input and bottom current reworking. This is the dominant Holocene and (probable) Wisconsin interstadial facies. The second facies, with which the present study is concerned, comprises red-brown, silt-laminated muds (Fig. 2A) of the latest glacial period which were deposited from large, fine-grained, turbidity currents, (Stow and Bowen, 1978, 1979).

The Middle Ordovician sequence of the eastern Valley and Ridge Province

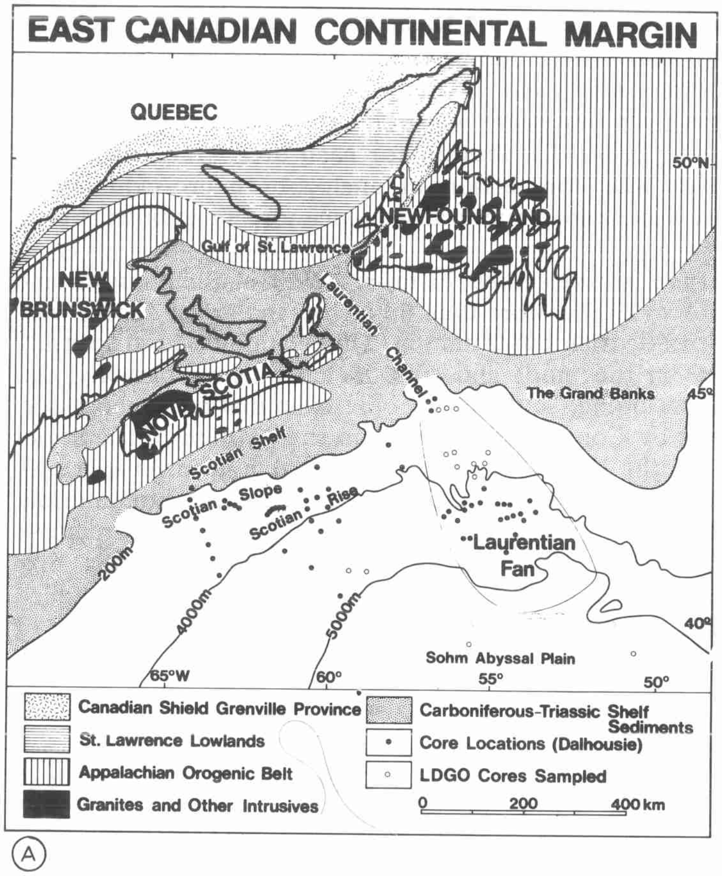


Fig. 1A. East Canadian continental margin off Nova Scotia, and location of cores used for this study.

in Tennessee consists of a thick (up to 3000 m) succession of limestones, shales, siltstones and sandstones. The basal 900 m of this was studied in detail in the Boyds Creek area (Fig. 1B) where the rocks are well exposed and the structural complications are minimal. This interval rests unconformably on the Lower Ordovician Knox Group dolomites and consists of: (1) a basal carbonate sequence (Lenoir-Whitesburg Formations) which is 47 m thick; (2) a thinly laminated calcareous, graptolitic, clay shale (Blockhouse Formation of Neuman, 1955) which is 379 m thick; and (3) a sequence of shale, siltstone, and fine sandstone (Sevier Shale) of more than 500 m thickness (Fig. 2B).

The Lenoir Limestone has been interpreted as shallow tidal to sub-tidal deposits. The Whitesburg Formation is an inferred slope deposit. Carbonate debris flow deposits have been observed in the Whitesburg Formation

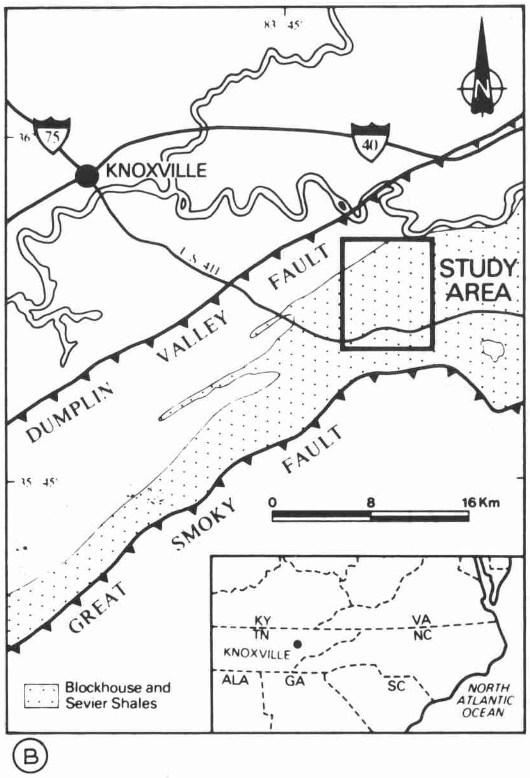


Fig. 1B. Location map showing Boyds Creek study area, eastern Tennessee, U.S.A.

exposed at Nina Section (Shanmugam and Benedict, 1978) nearly 40 km east of Boyds Creek. The overlying Blockhouse Formation is mainly composed of pelagic deposits. Conformably overlying the Blockhouse are the Sevier Shales, deposited at inferred water depths of 600—800 m or more in a basinal setting, with a source to the southeast in an area of Taconic uplift. The primary agent of deposition for the Sevier Shale was probably distal turbidity currents (Shanmugam and Walker, 1977a). Causes of subsidence and evolution of the Sevier Basin are given elsewhere (Shanmugam and Walker, 1977b; Shanmugam, 1978).

The Lower Palaeozoic Meguma Group of southern Nova Scotia (Fig. 1C) comprises a thick succession (up to 10,000 m) of sandstone, siltstone and slate that was deposited as a slope—rise—fan complex in a deep marine eugeosynclinal setting (Schenk, 1970, 1971). These rocks were folded, intruded and regionally metamorphosed during the Devonian Acadian orogeny (Poole et al., 1970). The major folds are generally open, upright and low-plunging, and a marked cleavage parallels their arcuate trend. The metamorphism varies regionally from chlorite to higher grades.

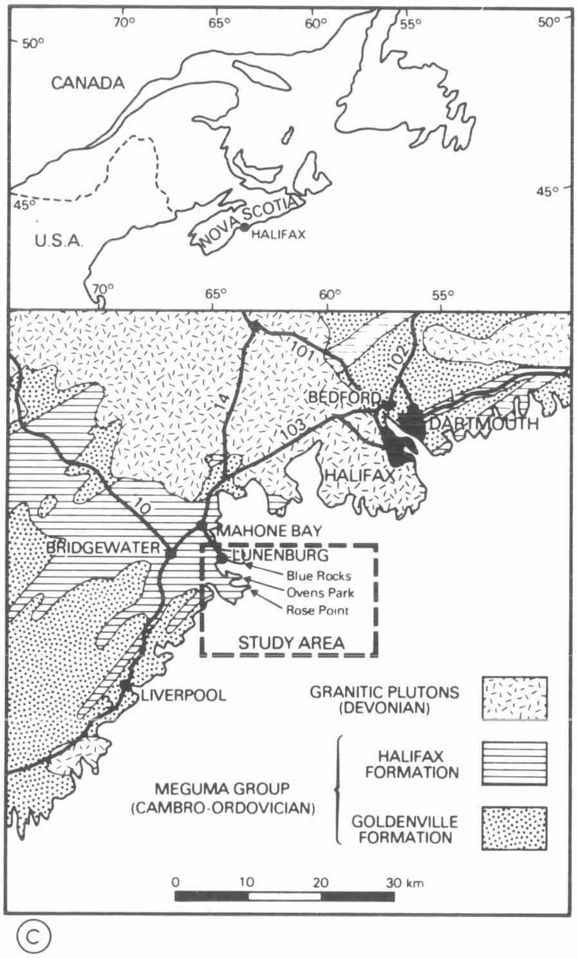


Fig. 1C. Location map showing Lunenburg study area, Nova Scotia, eastern Canada.

The Meguma Group comprises two partially coeval formations, the Goldenville Quartzite and the Halifax Slate, which are identified largely on the basis of lithology. The fine-grained Halifax Formation probably represents deposition in a basin plain to outer fan environment, and in interchannel areas of the rise and slope (Fig. 2C). Some sedimentological work on the Halifax Slate has been carried out by Schenk (1970) and Harris and Schenk (1975). More detailed work is currently in progress in the Lunenburg area and preliminary results from this study are included here.

SEDIMENTARY STRUCTURES

A variety of small-scale primary and secondary sedimentary structures is observed in both the modern and ancient fine-grained sediments examined.

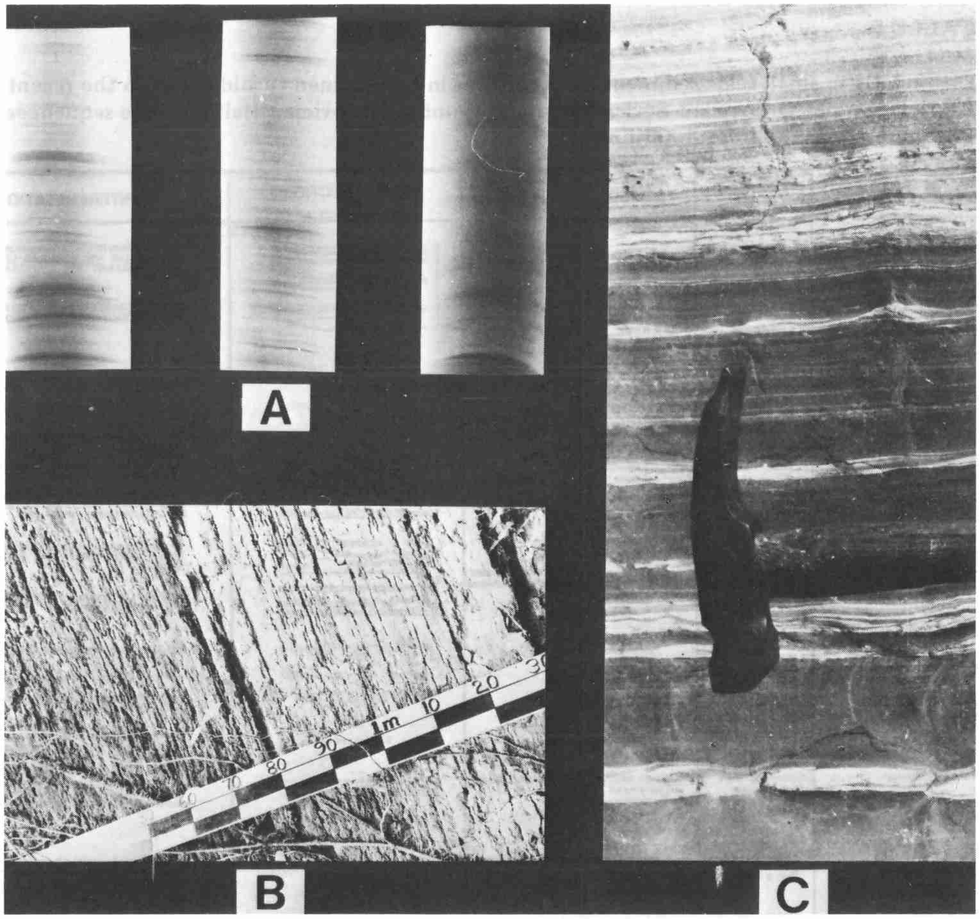


Fig. 2. Fine-grained turbidites showing thin-bedded stratification. A. X-radiograph positives of Recent Scotian Margin turbidites (cf. Fig. 1A). B. Photograph of part of Ordovician Sevier Shale (cf. Fig. 1B). C. Photograph of part of Cambro-Ordovician Halifax Formation (cf. Fig. 1C).

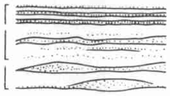
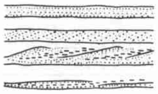
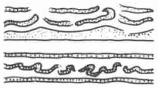
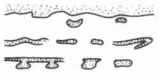
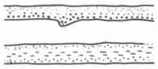
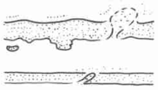
These structures are illustrated in Figs. 4—6, and are summarised in Table I. They are discussed in greater detail in the following sections. For convenience, the terms mud, silt and sand are used throughout, in place of mudstone, siltstone, sandstone, etc.

Stratification

The fine-grained turbidite facies of the Scotian margin sediments comprise regular, irregular and lenticular silt laminae (<1—10 mm) and thin sand beds (>10 mm) alternating with mud layers (Fig. 2A). Alternating grey and red

TABLE I

Characteristic small-scale sedimentary structures in fine-grained turbidites from the recent Scotian Margin, Ordovician Sevier Shale and Cambro-Ordovician Halifax Slate sequences Sketch sections and interpretation

SEDIMENTARY STRUCTURES	SCOTIAN MARGIN (RECENT)	SEVIER SHALE (ORDOVICIAN)	HALIFAX SLATE (CAMBRO-ORDOVICIAN)	SKETCH SECTIONS 40mm	INTERPRETATION
STRATIFICATION (alternating silt/sand and mud layers)					STRATIFICATION REFLECTS DEPOSITIONAL ENERGY THIN REGULAR AND IRREGULAR, LOW ENERGY, THICK IRREGULAR AND LENTICULAR, HIGHER ENERGY CORRELATION OVER 10 km INDICATES SINGLE VERY LARGE TURBIDITY FLOWS IN DEPOSTIONAL MODE
Regular	Common	Common	Common		
Irregular	Common	Present	Common		
Lenticular	Present	Present	Common		
Average thickness	1-10 mm	2-5 mm	2-20 mm		
Observed continuity	up to 10 km	up to 50 m	>50 m		
INTERNAL LAMINATION (in silt and sand layers)					TRACTIONAL MOVEMENT DURING DEPOSITION OF HORIZONTAL AND INCLINED LAMINATION CONCENTRATIONS OF HEAVY MINERALS, FORAMS AND CLAYS BY SHEAR-SORTING, "LIKE-SEEKS-LIKE" MECHANISM FADING-RIPPLES (HIGH-MEDIUM ENERGY) AND LOW-AMPLITUDE RIPPLES (MEDIUM-LOW ENERGY) DEPOSITED FROM CLAY-RICH FLOWS
Horizontal sub-horizontal	Common } may be accentuated by heavy minerals forams or clays	Common } commonly accentuated by shale laminae or shale clasts	Common		
Inclined	Rare	Rare	Rare		
Fading ripples	Rare } accentuated by clays	Rare	Common		
Low amplitude ripples	Common	?	Present		
CONVOLUTE LAMINATION (Contorted silt laminae in mud)	Present (especially related to underlying ripples)	Present	Present (especially as isolated lamina in undisturbed sequence)		INCIPIENT RIPPLE FORMATION IN MUDDY SEDIMENT OR DISTURBED FLOW REGIME ABOVE RIPPLED SURFACE LOADING OF RAPIDLY DEPOSITED SILT INTO UNCONSOLIDATED MUD
PSEUDONODULES	Present	Common	Common		ISOLATED LOAD STRUCTURES AT BASE OF THICK LAMINA EXTREME CONVOLUTION OF SILT LAMINA DISRUPTION OF SILT LAMINA BY EXTREME LOADING INTO UNDERLYING MUD
GRADING Graded laminated units (textural, mineralogical and colour grading)	Present	Present	Present	See Figures 3-6	DEPOSITION FROM DECELERATING MUDDY TURBIDITY FLOW PRODUCES GRADED LAMINATED UNIT SILT-MUD LAMINATION DUE TO DEPOSITIONAL SHEAR-SORTING SILT LAMINAE ARE MOSTLY POSITIVELY GRADED, EXCEPT FOR THINNEST, FINEST LAMINAE APPARENT NEGATIVE GRADING MAY BE DUE TO THE MIGRATION OF A LOW AMPLITUDE SILT RIPPLE OVER A MUDDY TROUGH
Graded silt and sand laminae	Common, positive Rare, negative Absent in thinnest laminae	Common, positive and continuous Rare, discontinuous	Common, positive		
NATURE OF CONTACTS (of silt and sand laminae)	Commonly sharp lower contact and moderately sharp upper contact. Both gradational upper and lower contacts are present— especially of thinnest silt laminae				COMMON SHARP CONTACTS INDICATE RELATIVELY RAPID ALTERNATION BETWEEN SILT-DEPOSITING AND CLAY-DEPOSITING MODES GRADATIONAL CONTACTS OCCUR EITHER AS A RESULT OF OVERALL VERY RAPID DEPOSITION OR MINIMAL GRAIN SIZE DIFFERENCE BETWEEN MUD AND SILT EROSIVE, DEWATERING AND INJECTION STRUCTURES INDICATE RELATIVELY RAPID DEPOSITION AND HIGH ENERGY ENVIRONMENT
Bottom structures	Scours, load-casts, flame-structures, straight or irregular base				
Surface features	Rippled, wavy, current-lineated or smooth				
SECONDARY STRUCTURES					
Mottling	Rare, including black iron-sulphide mottles	Rare	?	Visible on X-radiographs (Stow, 1977) 	BIOTURBATIONAL MOTTLING AND BURROWING IRON SULPHIDE MOTTLES (?) RELATED TO PRESENCE OF ORGANICS
Burrows	Rare, micro-burrows	Rare, including possible animal escape structures	Rare		
Mycelia	Rare	?	?	Visible on X-radiographs (Stow, 1977)	(?)
Microfaults	Rare, but common close to channel margins	Rare	Rare		FAULTING AND SLUMPING EITHER SYNSEDIMENTARY OR SECONDARY IN ORIGIN
Slumping				Slump horizons commonly 10-50 cm thick	

layers and homogeneous mud bedding are also present. Some of the thicker silt/sand layers can be correlated for over 10 km between adjacent levee cores on the Laurentian Fan. Long distance correlation of the thin silt laminae was not observed.

The Sevier Shales exposed in the Boyds Creek section are characteristically uniform in megascopic bedding thickness, which ranges from 20 to 50 mm (Fig. 2B). Individual beds can be traced for up to 50 m along the outcrop. Most beds are composed of several internal laminae, similar to those of the Scotian margin, which may be regular (with parallel borders) or irregular. They are commonly 2—5 mm thick and are traceable over several metres.

Shales with thin (1—10 mm) silt laminae are the dominant lithology of the Halifax Formation in Lunenberg County, Nova Scotia (Fig. 2C). They are interbedded with thin to thick sandstone beds (20 mm to 3 m). Individual silt laminae are laterally continuous and have been traced for over 50 m although they are often distinctly lenticular. Elongate silt lenses vary between 1 and 10 mm in thickness with an apparent periodicity of about 10 cm.

Internal horizontal and cross-lamination

The thicker silt laminae in Scotian margin cores commonly show either horizontal or inclined internal lamination. In some cases a few mm of cross-lamination is developed at the base of the layer and is then overlain by horizontal lamination. Either horizontal or cross-lamination may extend throughout a 5—10 mm layer. The tops of some thick laminae are wavy and have the appearance of Type C ripple drift cross-lamination (Jopling and Walker, 1968). They are here termed 'fading ripples' since they fade out laterally into muddy troughs. Migration of the coarse silt ripples over the muddy troughs produces a somewhat irregular or lenticular interlamination of silt and mud. A third type of cross-lamination is that of very low-relief, long-wavelength ripples whose migration produces thinly interlaminated and very slightly inclined mud/silt layers. This is similar to the lamination produced experimentally by McBride et al. (1975) in sands, although the mechanism may not be the same.

Very similar micro-structural features are observed in both the Sevier Shale and the Halifax Slate, although a complex intercalation of different types of layers makes resolution of these structures difficult. Irregular, lenticular interlamination of mud and silt is common in the former sequence; fading ripples at the tops of thin, horizontally laminated layers are observed throughout the Halifax, and appear in beds mostly 5—30 mm thick.

Convolute lamination and pseudonodules

Various examples of convolute or contorted silt laminae are common on microscopic examination of the Scotian margin cores, although they are not easily detected on X-radiographs. They may be developed directly above the wavy upper surface of thick laminae where they appear to be due to incipient ripple formation in muddy sediment (Keunen, 1953; Sanders, 1960) or to disturbed flow conditions (Allen, 1977). They also occur as isolated, irregular or wispy silt laminae which may be due to current drag or to loading effects (Davies, 1965).

Convolute lamination of both types is found in the Sevier Shale and

Halifax Slate. In the latter, single, convolute silt laminae within undisturbed, horizontally laminated mud/silt sequences are laterally continuous over 15 m and more.

Dispersed silty lenses or pseudonodules are observed in both the modern and ancient sediments examined. Several causes seem possible: they may result from the extreme convolution of silt laminae; from disruption and loading of a silt layer into the underlying, semiconsolidated mud; or as a result of burrowing disturbance. In some cases they are clearly related to loading at the base of a thick silt lamina or bed.

Grading

Most silt laminae in the Scotian margin cores, except for the very finest, exhibit positive grading when viewed under the microscope. Doubly graded laminae are also seen, while apparent reversed-grading is rare. The red and grey alternating laminae commonly show a distinct colour gradation from darker grey at the base through reddish grey to greyish red. There is a relatively sharp colour break within each grey/red couplet, and a still sharper one between adjacent couplets. This gives the whole sequence a varved appearance.

Graded silt laminae are also important structures in the Sevier Shale and range in thickness from 2 to 6 mm. Both continuous and, more rarely, discontinuous grading have been noted. Visual observation of laminae in the Halifax Slate suggests that positive grading is common, especially in the thicker layers.

Nature of the contacts

In all three sequences, the nature of the top and bottom contacts of individual silt laminae are various. They may have very sharp upper and lower contacts, or a sharp lower and fully gradational upper contact. Most of the thin laminae fall between these two extremes having a sharp lower and moderately sharp upper contact. The very thin laminae have gradational margins; and the advancing silt limb of a low-amplitude ripple has a gradational lower contact with the muddy trough and a sharp upper margin. In the narrow width of piston core sections the upper limb of this type of ripple may be misinterpreted as a single, reversely graded, silt lamina.

Both straight and irregular bases of silt laminae are observed, the latter showing scouring, load-casting and mud injection (flame) structures. Silt pseudonodules may develop and, more rarely, mud chips are included in the lower portion of the silt layer. Oriented mud clasts have been found in the Sevier Shale. The surfaces of silt laminae can be wavy (fading ripples), or may show distinct current lineations. Microscopic examination of these lineations in the Scotian margin silts show that they result from slight variations of texture and composition.

Secondary structures

Secondary structures identified in the Scotian margin cores include bioturbational mottling and burrowing, mycelia and microfaults. Bioturbational disturbance is not common, except in a narrow zone (about 5—10 mm thick) at the tops of sedimentation units. Isolated dark iron sulphide mottles and (?) iron sulphide filled cracks (mycelia) are rare. Minor faults, between 5 and 20 cm in length, offset the laminae on either side by 5—10 mm. They are most probably related to sediment slumping at channel margins, although a synsedimentary origin cannot be ruled out.

In the Sevier Shale probable animal escape burrows are seen, as well as thin muddy zones at the tops of sedimentation units, which show evidence of micro-burrowing. Rare slump horizons and sandfilled vertical burrows are noted in parts of the Halifax Slate.

SEQUENCE OF STRUCTURES

Repetition of the characteristic Bouma (1962) sequence of structures is not immediately obvious in the fine-grained sediments examined, although they are mostly of turbidite origin. Much of the sediment is composed of alternating silt and mud layers of varying thickness and structures (probable Bouma D and E division), and shows no clear evidence of individual sedimentation units. However, in about 30% of the sections examined we have been able to identify separate units, with the characteristic structural sequences described below. Analysis of these sequences and comparison of those observed by other workers leads us to propose a standard sequence of structures for fine-grained turbidites.

Scotian Margin

Graded laminated units (Piper, 1972) have been identified in the Scotian margin cores. They are from 1 to 10 cm thick (mostly 2—5 cm) and show an upward decrease in the number and thickness of silt laminae. Size analyses of individual silt laminae through one unit reveal an upward decrease in modal grain size and sorting. The interlaminated mud shows less evidence of a similar gradation. Slight mineralogical and compositional changes are also noted, there is a decrease in the percentage of heavy minerals and foraminifera, and an increase in coccoliths, micas and organic carbon upwards through the unit (Fig. 3).

Fig. 4 shows 6 typical units. Each has a relatively coarse, thick basal silt lamina which ranges from about 8 mm thick, with scoured base, micro cross-lamination and fading ripple surface (Fig. 4A), to less than 1 mm thick (Fig. 4E). Successive silt laminae may be prominent (Fig. 4B), thin and wispy (Fig. 4D) or barely visible except in X-radiographs (Fig. 4E). In some cases the silt layers are much more diffuse so that only the basal lamina has a

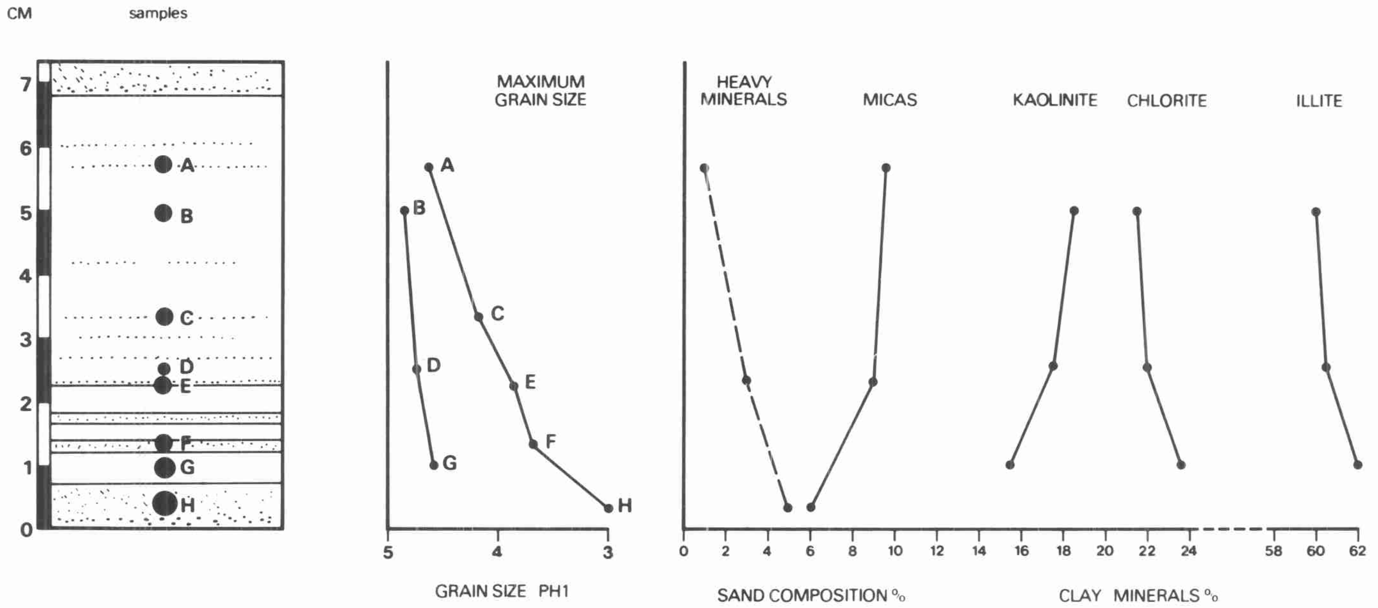


Fig. 3. Textural and mineralogical grading through graded-laminated unit in recent Scotian margin sediments. Very small samples were taken from the layers indicated for grain size analysis using a Coulter Counter. Larger samples were taken for mineralogical determinations.

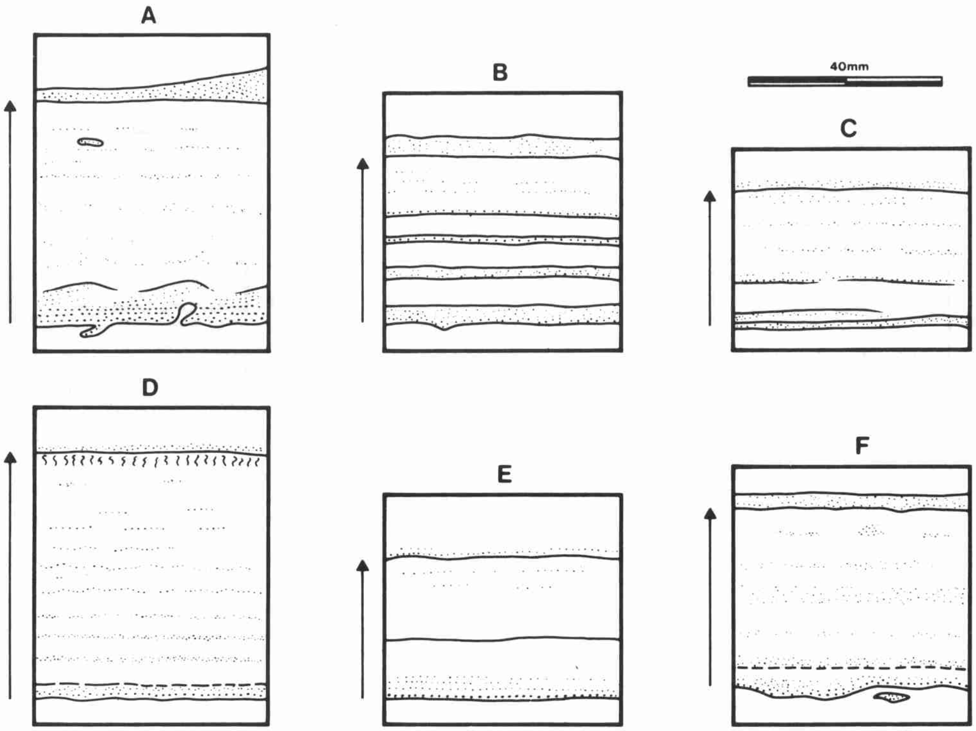


Fig. 4. Six characteristic sedimentation units in recent Scotian margin turbidites (shown by arrows). Sketch sections from microscopic/X-radiographic core study.

sharp bottom. Colour gradation from greyish to reddish may be present in any of these sequences (Fig. 4E), and micro-burrowing near the top is most common in the finely laminated units. Type A unit tends to occur closest to the channel axes and type E farthest away.

Sevier Shale

Shanmugam and Walker (1978) have recognised seven type sequences in the Sevier Shale. However, it is difficult in ancient sediments to define individual units, and some of the sequences they defined probably represent multiple depositional events. Fig. 5 is a reinterpretation of their data showing five typical structural sequences within probable sedimentation units.

Type A has an alternation of graded silt laminae and clay layers with the thicker, coarser silt laminae towards the base and thicker clay layers with fine silt laminae near the top. Grain-size grading through the unit is similar to that for Scotian margin sediments. Type B is a normally graded layer from

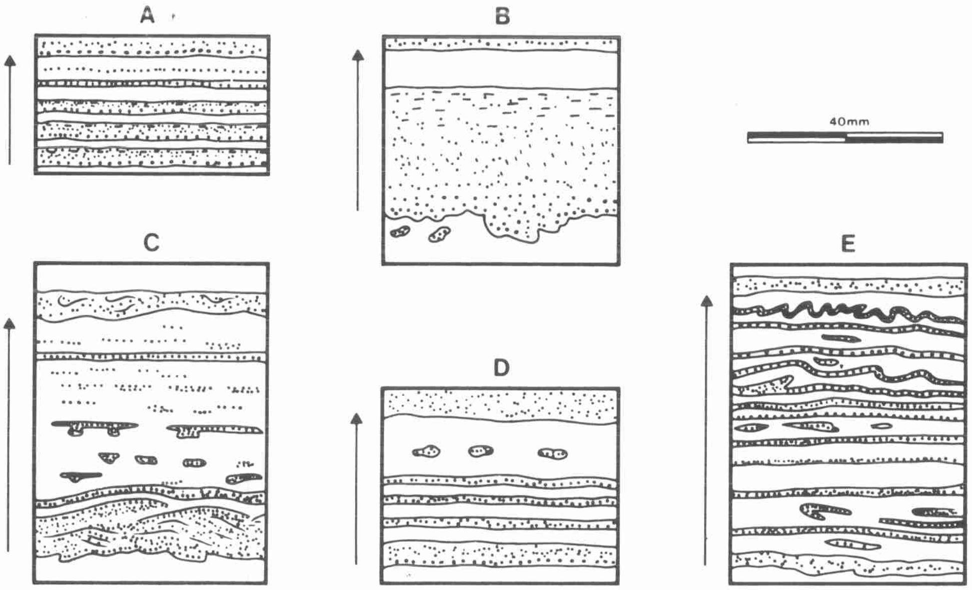


Fig. 5. Five characteristic sedimentation units in Ordovician Sevier Shale turbidites (shown by arrows). Sketch sections from thin sections and polished slabs.

fine sand or silt at the base (which shows loading and flame structures), through partly graded, laminated, silty clay, to a topmost unlaminated and ungraded clay layer. Type C is characterized by a lower cross-laminated zone with minor flames, a middle pseudonodule zone and an upper parallel laminated zone; while type D has a pseudonodule zone overlying parallel laminated silt and clay layers. Type E sequence consists of alternating silt and clay layers with a lower zone of silt lenses and an upper zone of convolute laminae.

Halifax Slate

Fig. 6 shows photographs of typical sedimentation units from the fine-grained parts of the Halifax Slate. The sequences in types A, B and C all begin with a thick, fading-ripple silt or thin sand layer at the base. The arrangement of silt and mud laminae in the overlying zone varies as shown, with a less laminated, clay rich zone near the base (A), in the middle (B) or at the top of the sequence (C).

In some cases the basal lamina does not show development of fading ripples at its surface but passes directly into a graded laminated sequence (D). In other cases only the graded laminated unit is present (E). This may comprise distinct fine silt laminae or more diffuse silty layers. Low-amplitude ripples similar to those found in the Scotian margin cores are present at

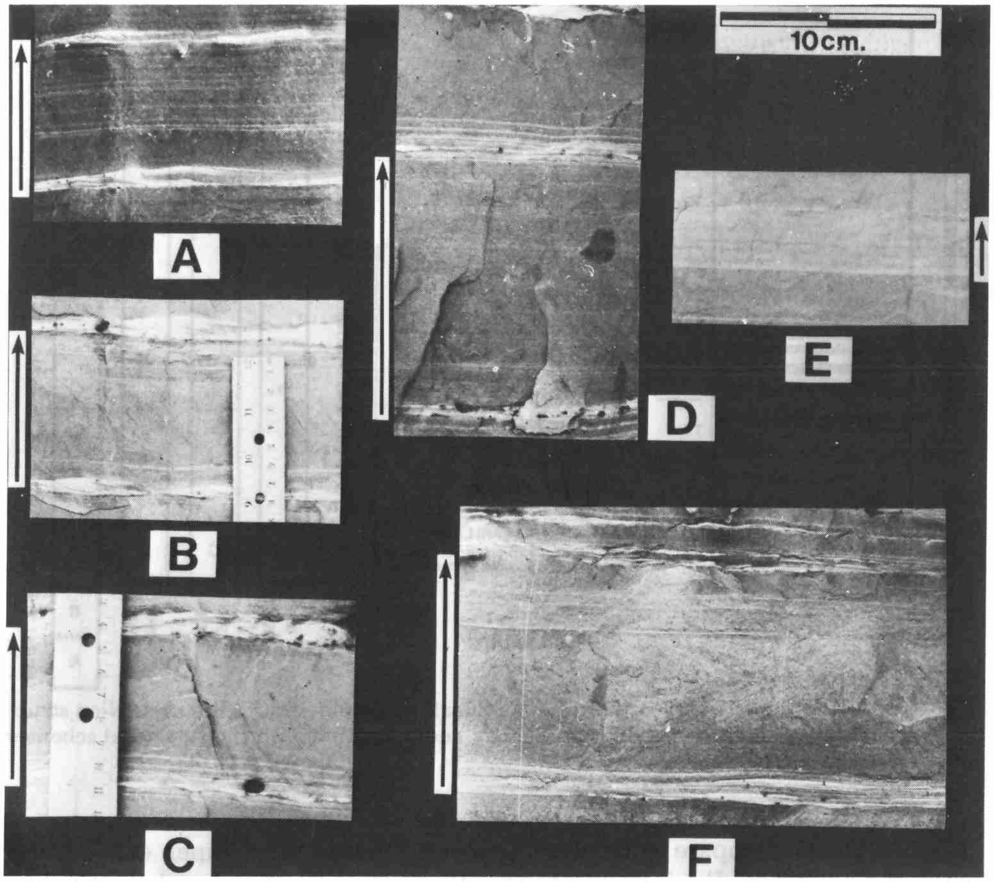


Fig. 6. Six characteristic sedimentation units in Cambro-Ordovician Halifax Formation turbidites (shown by arrows). Photographs of smooth rock surfaces in the field.

the base of type F sequence, which also shows lenticular or thin, wispy laminae near the middle of the unit.

Standard structural sequence

Analysis of the type sequences observed in the three regions studied and comparison with structural schemes proposed by other workers reveals a fairly consistent pattern of structures in fine-grained turbidite units. By consideration of the structures found in apparently more 'proximal' (higher silt/mud ratio) and more 'distal' (lower silt/mud ratio) regions, we may deduce the same pattern.

This standard sequence is shown in Fig. 7. The complete unit is about 7 cm thick and can be divided into nine sub-divisions which are here termed

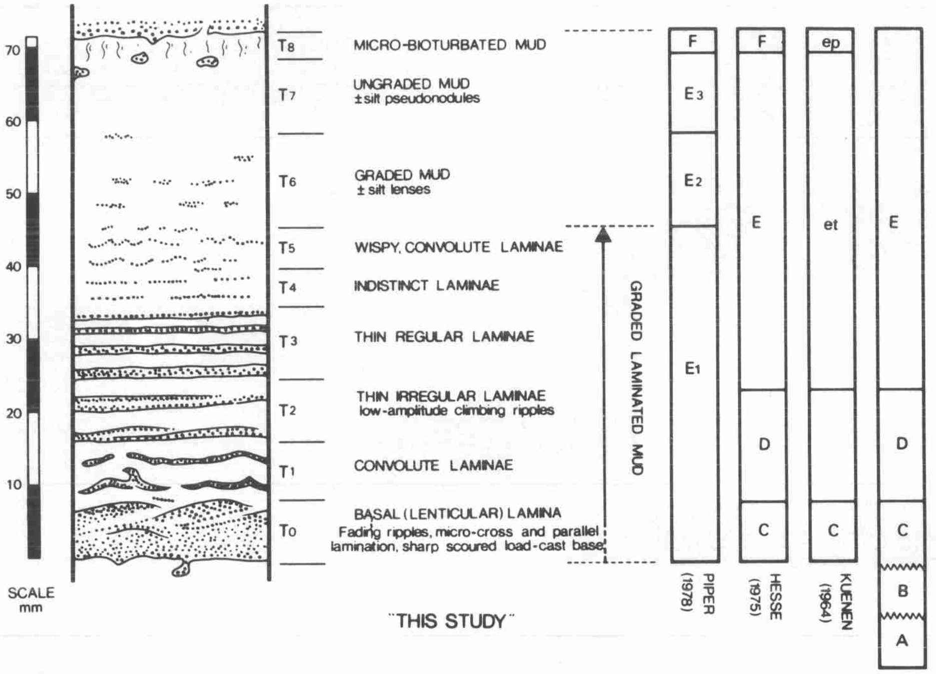


Fig. 7. Standard sequence of structure in an 'ideal' fine-grained turbidite unit. Nine structural divisions are identified as T_0 through T_8 and compared with the structural schemes of other authors.

T_0—T_8. These compare with the E_1—E_2—E_3 divisions of Piper (1978) and with the (?C) DE divisions of other authors (Fig. 7). The basal (lenticular) silt lamina (T_0) is the thickest (about 8 mm) and coarsest (coarse silt—very fine sand) with a sharp, irregular base that shows scouring, load-casts and mud-injection structures. Internally it may show horizontal or cross-lamination that passes upwards into fading ripples. The upper surface is sharp or gradational and wavy or current lineated.

The basal lamina is the lowest sub-division of a graded laminated unit through which the grain size and thickness of silt laminae decrease upwards, concomitantly with slight mineralogical changes. The overlying, dominantly muddy sub-division (T_1) contains thin silt laminae which thicken immediately in front of the subjacent fading ripple crest, or which are convoluted 'in-phase' with the ripples. These are overlain by a low-amplitude climbing ripple sub-division (T_2), thin regular laminae (T_3), thin indistinct laminae (T_4) and thin wispy or convolute laminae (T_5). Silt laminae are not present through the three topmost sub-divisions, graded mud (T_6) with patchy fine silt lenses, ungraded homogeneous mud (T_7) with rare coarse silt pseudonodules, and bioturbated mud (T_8) with micro-burrowing and silt pseudonodules.

DISCUSSION

Each sedimentation unit with its positive grading and standard sequence of structures represents deposition from a single, large, fine-grained turbidity current. Physical analysis of the textural properties of the Scotian margin sediments has led to the suggestion that these muddy turbidity flows are very thick, have very low sediment concentrations, and move downslope at velocities of around 10—15 cm/s (Stow and Bowen, 1979). 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 increased shear in the bottom boundary layer (Stow and Bowen, 1978).

The sedimentary structures observed, then, are presumably related to the hydrodynamic regime of low velocity, muddy, turbidity flows. Internal lamination in the basal layer and migrating ripple lamination indicate periods of tractional movement during deposition of the coarser silt grains. The structures within this layer may be controlled in part by the nature of flow deceleration (Banerjee, 1977). Most of the sequence is believed to be deposited directly from suspension. Silt ripples with muddy troughs are deposited from turbidity flows containing a high proportion of clay-sized material. Some of the convolute silt laminae may represent incipient ripple formation in a muddy environment; others are perhaps due to slight silt loading into unconsolidated muddy layers. The more homogeneous mud zone at the top of the unit comprises the finest silt and clay which was not sorted so effectively into silt and mud laminae because of its uniformly fine grain size.

Many of the units observed are only 2—5 cm thick and do not show the full sequence of structures. The upper parts of the sequence (T_4—T_8) are dominant away from the channel axes on levees and interchannel areas, and in the outer fan and abyssal plain environment. The lower parts of the sequence (T_0—T_4) occur closer to the channels and on fan lobes. Repetition of these partial sequences results in successions dominated by thick, lenticular, silt/sand laminae ('high-energy' near-channel); thin, regular, silt and mud laminae in otherwise homogeneous muds ('low-energy', abyssal plain). This is similar to the facies distribution of mud turbidites suggested by Piper (1978); and is analogous to the distribution of partial Bouma sequences described by Walker (1967) and others. Hemipelagic and contourite muds are often intercalated with fine-grained turbidites in the low and medium-energy depositional environments (Stow, 1979a, b).

Other important controls on the exact nature of the sequence deposited include the grain size composition of the material, and the concentration and velocity of the flow. Perturbations in the structural sequence may also result from variation in the nature of the bed surface (cohesive, granular or rippled) velocity fluctuations and the previous history of the underlying layer. The significance of these controls might usefully be determined by future experimental work with fine-grained sediment flows.

CONCLUSIONS

(1) A standard sequence of structures has been recognized in both ancient and modern fine-grained turbidites. The complete sequence has nine sub-divisions which are here termed T_0 to T_8. These are equivalent to the topmost C and DE divisions of Bouma (1962), and result from deposition during the passage of a large, muddy, turbidity flow.

(2) The term 'fading-ripple' is introduced as a useful description of Type C ripple-drift cross-lamination (Jopling and Walker, 1968), which is commonly observed at the upper surface of the basal silt lamina (T_0) in the standard sequence. Very low-amplitude and relatively long-wavelength climbing ripples (referred to as low-amplitude ripples) are described from the T_2 sub-division. These are similar to the low-relief bedforms produced experimentally in sands (McBride et al., 1975).

(3) The complete sequence (T_0—T_8) is rarely found. However, different parts of the sequence are commonly repeated in different zones of the slope/base-of-slope/basin plain environment. Recognition of these partial sequences should aid palaeoenvironmental interpretation.

(4) Although the Sevier Shale has undergone considerable compaction and the Halifax Slate, low grade metamorphism, the microstructures observed in these rocks are directly comparable to those found in piston cores from the modern deep-sea Laurentian Fan. Microstructural detail and sequence have a better preservation potential than, say, textural or mineralogical character.

(5) Many of the individual micro-structures described (e.g. heavy mineral cross-lamination), as well as the abundantly laminated nature of these fine-grained turbidites, have been considered charactertistic of contourites by other authors. Careful analyses of sedimentary structures and recognition of partial sequences should help in distinguishing between fine-grained turbidites and contourites (see Stow and Lovell, 1979).

ACKNOWLEDGEMENTS

The Sevier Shale study was supported by grants from National Science Foundation (to Ken Walker), Geological Society of America (G.S.) and Sigma Xi (G.S.). G.S. wishes to express his gratitude to Ken Walker for his supervision and co-operation. The Laurentian Fan and Halifax Slate studies were supported by National Research Council and Imperial Oil grants to David J.W. Piper while D.A.V.S. was in receipt of a Canadian Commonwealth Scholarship. D.A.V.S. would also like to thank Mahmood Alam and David Piper for their help with field work on the Halifax Slate, and for useful discussions. J.P.B. Lovell is thanked for useful criticism of the manuscript.

REFERENCES

Allen, J.R.L., 1977. The possible mechanics of convolute lamination in graded sand beds. J. Geol. Soc. London, 134: 19—31.

Banerjee, I., 1977. Experimental study on the effect of deceleration on the vertical sequence of structures in silty sediments J. Sediment. Petrol., 47: 771—783.

Bouma, A.H., 1962. Sedimentology of Some Flysch Deposits. Elsevier, Amsterdam, 168 pp.

Chough, S.K., 1978. Morphology, Sedimentary Facies and Processes of the North West Atlantic Mid-Ocean Channel Between 61° and 52°N, Labrador Sea. Thesis, McGill University, 167 pp.

Davies, I.C. and Walker, R.G., 1974. Transport and deposition of resideminted conglomerates: the Cap Enrage Formation, Cambro-Ordovician, Gaspe, Quebec. J. Sediment. Petrol., 44: 1200—1216.

Davies, H.G., 1965. Convolute lamination and other structures from the lower coal measures of Yorkshire. Sedimentology, 5: 305—325.

Emery, K.O. and Uchupi, E., 1972. The Western North Atlantic. Am. Assoc. Pet. Geol. Mem., 17: 532 pp.

Harris, I.M. and Schenck, P.E., 1975. The Meguma Group. Soc. Econ. Paleontol. Mineral. (Eastern Section), Field Trip. Marit. Sediments, 11: 25—46.

Hesse, R., 1975. Turbidites and non-turbiditic mudstones and Cretaceous flysch sections of the Eastern Alps and other basins. Sedimentology, 22: 387—416.

Hesse, R. and Chough, S.K., 1979. Deposition of parallel-laminated muds from the viscous sub-layer of low-density turbidity currents. Sedimentology, in press.

Jansa, L.F. and Wade, J.A., 1975. Geology of the continental margin off Nova Scotia and Newfoundland. Geol. Surv. Can. Pap., 74-30 (2): 51—106.

Jopling, A.V. and Walker, R.G., 1968. Morphology and origin of ripple-drift cross-lamination, with examples from the Pleistocene of Massachusetts, J. Sedimentol. Petrol., 38: 971—984.

Keunen, Ph.H., 1953. Graded bedding, with observations on Lower Palaeozoic rocks of Britain. Verh. K. Ned. Akad. Wet. Afd. Nat., 20: 1—47.

Keunen, Ph.H., 1964. Deep-sea sands and ancient turbidites. In: A.H. Bouma and A. Brouwer (Editors), Turbidites, Developments in Sedimentology, 3, pp. 3—33.

McBride, E.F., Shepard, R.G. and Crawley, R.A., 1975. Origin of parallel near-horizontal laminae by migration of bed forms in a small flume. J. Sedimentol. Petrol., 45: 132—139.

Middleton, G.V. and Hampton, M.A., 1973. Sediment gravity flows: mechanics of flow and deposition. In: Turbidites and Deep-Water Sedimentation, G.V. Middleton and A.H. Bouma (Editors). SEPM Short Course, Anaheim, pp. 1—38.

Mutti, E., 1977. Distinctive thin-bedded turbidite facies and related depositional environments in the Eocene Hecho Group (South-Central Pyrenees, Spain). Sedimentology, 24: 107—131.

Neuman, R.B., 1955. Middle Ordovician rocks of the Tellico-Sevier belt eastern Tennessee. U.S. Geol. Surv. Prof. Pap., 274-F: 141—177.

Piper, D.J.W., 1972. Turbidite origin of some laminated mudstones. Geol. Mag., 109: 115—126.

Piper, D.J.W., 1978. Turbidite muds and silts on deep sea fans and abyssal plains. In: D.J. Stanley and G. Kelling (Editors), Submarine Canyon and Fan Sedimentation. Dowden, Hutchinson and Ross, Stroudsburgh, Pa.

Poole, W.H., Sanford, B.V., Williams, H. and Kelley, D.G., 1970. Geology of Southeastern Canada, In: R.J.W. Douglas (Editor), Geology and Economic Minerals of Canada. Geol. Surv. Can., Economic Geology, Rept. No. 1., pp. 227—304.

Rupke, N.A. and Stanley, D.J., 1974. Distinctive properties of turbiditic and hemipelagic mud layers in the Algero-Balearic Basin, western Mediterranean Sea. Smithsonian Contrib. E. Sci., 13: 40 pp.

Sanders, J.E., 1960. Origin of convoluted laminae, Geol. Mag., 97: 409—421.

Schenk, P.E., 1970. Regional variation of the flysch-like Meguma Group (Lower Palaeozoic) of Nova Scotia compared to recent sedimentation off the Scotian Shelf. Geol. Assoc. Can., Spec. Pap., 7: 127—153.

Schenck, P.E., 1971. Southeastern Atlantic Canada, northwestern Africa and continental drift. Can. J. Earth. Sci., 8: 1218—125.

Shanmugam, G., 1978. Subsidence analysis of shelf and basinal sequences of the Middle Ordovician in east Tennessee. Geol. Soc. Am. Southeastern Section Meeting, Program with Abstracts. 10: p. 197.

Shanmugam, G. and Benedict, III, G.L., 1978. Fine-grained carbonate debris flow, Ordovician basin margin, Southern Appalachians. J. Sediment Petrol., 48: 1233—1240.

Shanmugam, G. and Walker, K.R., 1977a. Small scale sedimentary structures in the Middle Ordovician Sevier Scale, eastern Tennessee. Geol. Soc. America, Southeastern Section Meeting, Program with Abstracts, 9: 183—184.

Shanmugam, G. and Walker, K.R., 1977b. Deep-water sedimentation and tectonics in the Middle Ordovician Sevier Shale, Tennessee. Bull. Am. Assoc. Pet. Geol., 61: 828—829.

Shanmugam, G. and Walker, K.R., 1978. Tectonic significance of distal turbidites in the Middle Ordovician Blockhouse and Lower Sevier Formations in east Tennessee. Am. J. Sci., 278: 551—578.

Skipper, K. and Middleton, G.V., 1975. The sedimentary structures and depositional mechanics of certain Ordovician turbidites, Cloridorme Formation, Gaspe Peninsula, Quebec. Can. J. Earth Sci., 12: 1934—1952.

Stow, D.A.V., 1976. Deep-water sand and silts on the Nova Scotian continental margin. Marit. Sediments, 12: 81—90.

Stow, D.A.V., 1977. Late Quarternary Stratigraphy and Sedimentation on the Nova Scotian Outer Continental Margin. Thesis, Dalhousie University, 361 pp. (unpublished).

Stow, D.A.V., 1979a. The Laurentian Fan: deep-sea fan models, fine-grained sediment distribution and hydrocarbon exploration. AAPG-SEPM Program with Abstracts.

Stow, D.A.V., 1979b. Distinguishing between fine-grained turbidites and contourites on the Nova Scotian Outer Continental Margin. Sedimentology, 26: 371—387.

Stow, D.A.V. and Bowen, A.J., 1978. Origin of Lamination in deep-sea fine-grained sediments. Nature, 274: 324—328.

Stow, D.A.V. and Bowen, A.J., 1979. Physical model for the transport and sorting of fine-grained sediment in turbidity currents. Sedimentology, in press.

Stow, D.A.V. and Lovell, J.P.B., 1979. Contourites: their recognition in modern and ancient sediments. Earth-Sci. Rev., 14: 251—291.

van der Lingen, G.J., 1969. The turbidite problem. N. Z. J. Geol. Geophys., 12: 7—50.

Walker, R.G., 1967. Turbidite sedimentary structures and their relationship to proximal and distal depositional environments. J. Sediment. Petrol., 37: 25—43.

Walker, R.G., 1970. Review of the geometry and facies organisation of turbidites and turbite bearing basins. In: J. Lajoie (Editor), Flysch Sedimentology in North America. Geol. Assoc. Can. Spec. Pap., 7: 219—251.

Walker, R.G., 1976. Facies Models 2. Turbidites and associated coarse clastic deposits. Geosci. Can., 3: 25—36.