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Origin of lamination in deep sea, fine-grained sediments

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Many mechanisms have been proposed for the origin of lamination in deep sea sediments, but without general agreement. Experiments in other environments have suggested that several different processes may operate in particle flow conditions. Those relevant to deep water conditions are briefly discussed, and a new quantitative model developed for lamina formation in fine-grained sediments on a continental margin.

SILT laminated muds are very common marine facies and occur repeatedly in geological records[1–3]. Although there have been many mechanisms suggested for their deposition, the mode of emplacement and the process of lamina formation are still not fully understood. Velocity fluctuations are, perhaps, the most commonly endorsed mechanism for the generation of lamination[2,4–6] in marine sediments. Random and regular fluctuations are found in most types of natural flows and have been given as explanations for various types of stratification in eolian dunes[7], for parallel lamination in delta plain sediments[8], and micro-lamination in tidal muds[9,10]. It has been postulated that the quasi-cyclic bursting process in turbulent boundary layers will give rise to vertical variation in the texture of sediment being deposited, thus defining a single horizontal lamina for each cycle[11,12]. For fine-grained sediments, the time scales suggested are often too short to allow a mud layer to deposit[13].

The concept of turbid layer flow has been introduced to explain the movement of mud and silt across the Californian continental shelf and down the slope[14]. One lamina would result from each of these long-period flows. Such turbid layer flows have subsequently been considered to be responsible for much of the fine-grained silt-laminated muds which are so common on outer continental margins[15,16].

A different view of the origin of lamination involves the congregational segregation of like particles near the base of a sediment-laden flow. At current velocities of 15–30 cm s^{-1}, silt and large muddy flocs, deposited from suspension, still move as bed-load; the flocs form cohesive patches increasing the rate of clay deposition from the base of the current until most of the clay is removed; silt deposition is then resumed[17]. Experimental studies in a circular flume[18] demonstrated the formation of lamination in the absence of current pulsations. During a short period of traction or rolling as particles deposit from a uniform flow, the particles show a tendency to join stationary ones of equivalent size, shape and density. A very similar picture was deduced from observations on stratification in coarser grained deposits[19].

Various authors have proposed lamina formation by the migration of bed forms[7,20–22]. Experiments with sand at shallow flow depths[23] showed the formation of laminae during the migration of low-relief ripples and in-phase waves. When sufficient sediment was present for agradation, the concentration of coarse material in the troughs buried the finer material on the stoss side of the underlying ripple. The migration of small current ripples with straight, long crests and muddy troughs has been observed to produce sand/mud laminae from a few cm to a few tens of cm in length[24]. This produced flat, slightly lenticular bedding.

Other mechanisms proposed for the formation of laminae include differential settling and diagenetic effects[25]; gyres in the tails of turbidity currents[26,27]; a series of light suspensions floating at different levels behind a single, floor hugging turbidity current[26,28]; and reflection of a turbidity current from the walls of a small basin[29]. More significantly, internal lamination and cross lamination in cores from the western North Atlantic continental margin have been considered as evidence of reworking and placer concentration by contour-following, bottom currents. The association of abundant laminae in a rise environment with contour currents has become well established[30–33].

Sediments of the Scotian margin

The silt-laminated mud facies (Fig. 1) on the outer continental margin off Nova Scotia has been shown to be dominantly of turbidite origin; the evidence includes the inference of the direction of flow from the sediment fabric, the presence of systematic grading in the depositional units and the absence of bioturbation from these units[34]. This throws considerable doubt on the hypothesis that similar facies found in other areas arise from either the action of contour currents or the flows of thin turbid layers. However, to appreciate the possible importance of turbidity currents in other environments a much clearer understanding of the depositional processes, particularly those producing silt lamination, is needed. A depositional model, as far as possible quantitative, is required.

For fine-grained sediments it has been proposed that the rate of deposition, R, of sediment of settling velocity, w, is given by an equation of the form,

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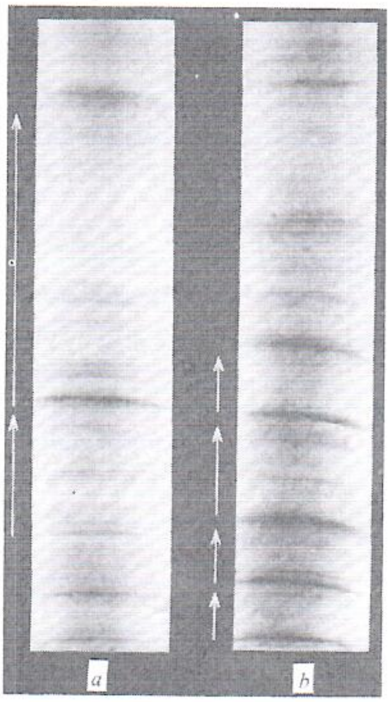

Fig. 1 X-radiograph prints of silt-laminated muds from the Nova Scotian outer continental margin. The width of the core sections is about 5 cm. The dark layers are silt laminae, and the arrows show probable graded laminated units.

$$R = \rho_s C w P \tag{1}$$

where C is the concentration of the sediment of settling velocity, w and density, ρ_s, in the flow just above the viscous sub-layer of the bottom boundary layer; P is the probability that a given particle will be deposited[35]. Data from experiments with fine, noncohesive silt[36], suggest that P is given by

$$P = \nu\left(1 - \frac{\tau}{\tau_c}\right) \tag{2}$$

where τ is the local bottom stress, $\tau_c(w)$, a critical value for the deposition of sediment of settling velocity, w, and ν is a factor to account for other influences on the probability of deposition. This is generally in line with the experiments on the deposition of cohesive material. A plot of τ_c as a function of w has been constructed[35], based on a wide range of data[36,37].

A layer of sediment of thickness q, and solid concentration λ, is therefore deposited in time T_0, where

$$\lambda \rho_s q = T_0 \sum_w R(w) \tag{3}$$

the layer consisting of contributions from the various sediment sizes (of differing settling velocities) in suspension. Sediment analysis allows us to determine λ, to identify q as a layer with particular characteristics, and to obtain from its grain size distribution, $p_s(D)$, the proportion of grains within a particular size interval. There are two cases.

For silts, w is a well defined function of D, so that equations (1), (2) and (3) can be written in the form,

$$p_s(D) = \frac{C(D) w(D) \nu T_0}{q\lambda}\left(1 - \frac{\tau}{\tau_c(D)}\right) \tag{4}$$

For muds, there is no simple relationship between the grain size obtained by analysis of the deposit, and the dynamic behaviour of flocculated particles in suspension. However, a relationship between dispersed grain size distribution and flocculated particle size distribution has been suggested[38], and is supported by our experiments[34].

An important consequence of equation (4) is that there should be no silt deposited of grain size less than some critical diameter, D_c, given by: $\tau = \tau_c\,(D_c)$.

Figure 2 shows a sequence of size analyses through a typical graded laminated unit from a Scotian margin core. Proportional summation of these analyses, or summation of a continuous series of measurements through a silt–mud couplet, a silt lamina and the overlying mud layer, produces a fairly even distribution of grain sizes.

The size distribution of the silty layers shows a small quantity of very fine material, but a distinct change in trend at some intermediate grain size. This provides a first, crude estimate of D_c, and hence the actual stress, τ, at the time of deposition (Fig. 2). It is implicitly assumed above that there are finer particles in the flow not being deposited because τ_c is too large.

The size distribution of the superjacent mud layer shows that the coarse tail begins to fall off at the same size interval with which the silt curve changes to a marked upwards trend. This point, therefore, also provides a crude estimate of τ_c. The curve decreases to zero at the modal silt size (Fig. 2). This close match between silt and superjacent mud is, clearly, strong evidence that they were deposited almost simultaneously from the same flow. The flow is one in which the larger grains are behaving as individual silt particles during the depositional phase.

Knowing the stress τ, the velocity of the current U can be estimated as $\tau = c_D \rho U^2$ where c_D, the drag coefficient, has a value close to 2.5×10^{-2} for the flow over a smooth, fine-grained surface[13]. The data from the Scotian margin cores suggest velocities in a restricted range, 9–16 cm s^{-1}. Maximum velocities for deposition of fine-grained material have been estimated, from laboratory experiments, to be in the range

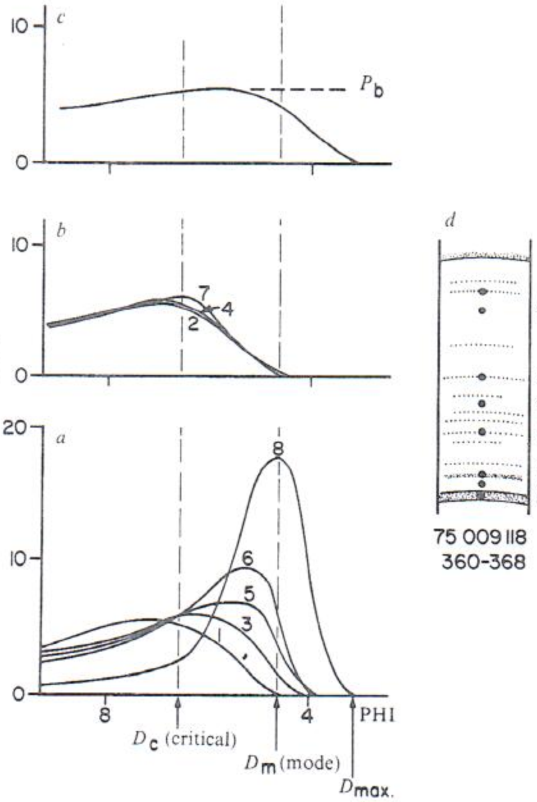

Fig. 2 Smoothed, weight-per cent, grain size curves from analyses of a, individual silt layers; b, mud layers; c, whole unit; and d, whole graded laminated unit shown as a schematic core section. The numbers beneath the core section are the core code and section depth in cm. The critical grain diameter (D_c), silt mode (D_m) and maximum silt size (D_{max}) are shown. See text for further discussion.

15–25 cm s^{-1} (refs 39–41). The present results are therefore in the right range. The very thin silt layers higher in the cores (Fig. 2), should show lower velocities, presumably, but it becomes very difficult to sample these layers to determine the detailed size distribution.

Model for depositional sorting

Within a fine-grained turbidity current there are clay flocs and silt grains having equivalent settling velocities, so that the expected deposit from a waning current would be a graded, silty mud. In most cases, however, the depositional unit is distinctly laminated as well as graded. This separation of mud and silt layers may be primarily due to depositional sorting through the boundary layer at the base of a turbidity current.

The even distribution of grain sizes in the deposits (Fig. 2) suggests an even distribution of grain sizes in the boundary layer, made up of a coarse silt mode and a fine mud tail. The coarser silt settles into the boundary layer as individual grains, while the finer silt and the mud probably settle as flocs where, $D_{\text{mode (flocs)}} > D_{\text{mode (silt)}}$, and the effective floc settling velocity is of the same order as that of the modal size of the silt[38]. The finest mud is left behind in the turbidity current.

As the sediment falls towards the bed the increasing shear in the boundary layer tends to break up the flocs[39,40] (Fig. 3). The larger silt grains continue to settle through the viscous sublayer to form a silt lamina (Fig. 4*a*). As more sediment is supplied to the top of the boundary layer the mud concentration increases, and reflocculation may occur (Fig. 4*b*)[41,42]. At some critical concentration (Fig. 4*c*) the clays are able to form aggregates large enough to overcome shear break-up and deposit rapidly through the laminar sublayer as a mud 'blanket' over the coarser silt lamina (Fig. 4*d*). This must occur rapidly as very little coarse silt is found in the mud layer. The process is then continued with the formation of another silt layer, slightly finer than the first.

Although the separation of mud and silt in this way seems to be a necessary corollary of boundary layer shear, it is not clear exactly what causes the mud to deposit so rapidly. Temporary disturbance of the boundary layer structure (by velocity fluctuations, and so on), or the partial development of a cohesive bed surface as the largest flocs manage to settle through the sublayer, are possible explanations. The increased mud concentration may affect these processes[41] or may be sufficient alone to cause mud blanketing. Experimental work with mud slurries suggests that they deposit more rapidly with increasing concentration[42].

Discussion

The correlation between silt and mud layers suggests deposition from the same flow, separation arising from a particular value of the bottom stress, τ. If velocity fluctuations were playing a part, silt would presumably be deposited during the strong pulses, and mud during relatively quiet periods. Although this would assist the mud deposition from the boundary layer in the present model, it is not essential to the basic argument. Previous suggestions for the role of velocity fluctuations are in terms of deposition from the flow as a whole, in which case the composition of the whole current must fluctuate with velocity (otherwise the coarser silt would deposit very rapidly during the quieter periods) and no particular correlation would be expected between the size distributions in the mud and silt layers.

In addition, the mud layer would represent low settling velocities and consequently relatively long depositional time scales. The settling velocity of the modal size in the mud layers (Fig. 2) is an order of magnitude less than that of the silt mode. The result would be analogous to that for tidal currents[13]; it takes a long time to deposit a mud layer several mm thick.

The suggestion that lamination is due to a series of thin, turbid flows, one for each lamina[15,16], does not explain the overall grading of a unit. However, many laminated, fine-grained sediments do not show any obvious gradation and a more significant objection may be the very long time scales required to deposit a laminated unit, not consistent with the absence of bioturbation.

The possible role of contour currents in the formation of laminated, but ungraded, sediments is harder to assess. Most of the existing literature is concerned either with the reworking of the sediments by steady currents or deposition from slowly moving, nepheloid layers. However, current measurements, close to the sea bed on the upper-continental rise south of Cape Cod, Massachusetts[43], have shown that although there is a mean westwards flow along the contours at 5 cm s^{-1} the current pulsates in strength flowing at up to 40 cm s^{-1} to both east and west. The most obvious periodicity in the velocity variations is of the order of 30 d.

If the current varies greatly in strength the resulting sediment dynamics may be similar, except in direction, to those associated with a turbidity current. As far as small scale processes are concerned, a waning contour current would be indistinguishable from a waning turbidity current and the lamination mechanism proposed here would be equally applicable.

Two general comments might be made, the size ranges and concentrations measured in nepheloid layers[35] suggest very slow rates of deposition. The importance of winnowing can be assessed directly by comparing the size distribution of a mud layer with that of the silt layer immediately below. A strong correlation between these distributions, as in the data presented here, suggests that material has not been removed by winnowing.

There is, however, direct evidence in the cores that other mechanisms, in addition to shear sorting, are important at some phase of the depositional sequence. In the lowest silt layers in some of the units there is structural evidence for some lamina formation within the graded laminated units by the migration of low-relief bed forms. This probably results from the migration of the coarse silty ripple crest over a muddy trough, and may involve a short amount of tractional transport and sorting. However, this is apparently restricted to the lowest parts of units, and is not seen in the finer silt and clay sizes, consistent

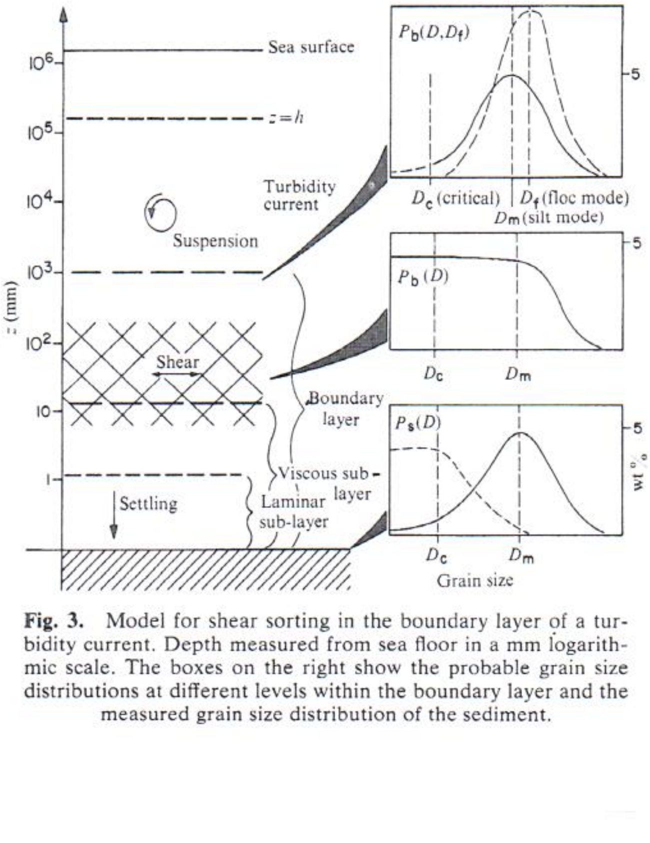

Fig. 3. Model for shear sorting in the boundary layer of a turbidity current. Depth measured from sea floor in a mm logarithmic scale. The boxes on the right show the probable grain size distributions at different levels within the boundary layer and the measured grain size distribution of the sediment.

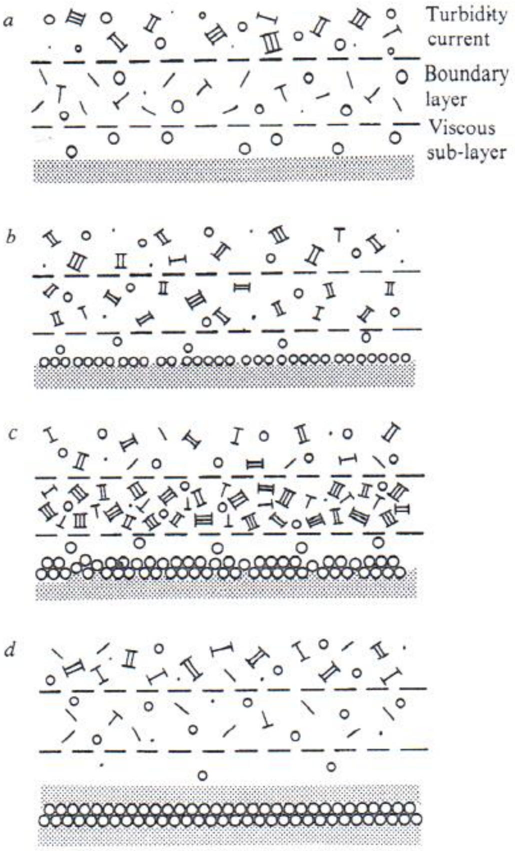

Fig. 4 Schematic representation of silt (○, silt grains various sizes) and mud (I, II, III, clay flocs various sizes) deposition through the boundary layer of a turbidity current. See text for discussion.

with the idea that these sizes do not normally move as bedload.

The primary mechanism for laminae formation seems to be the depositional sorting by the increased shear at the bottom of the bottom boundary layer. The destruction of the flocs leads to differential settling suggested by equation (4) producing a clean, silt layer. The continual accumulation of fine material during this phase eventually leads to a rapid deposition of a mud layer; the absence of the coarser silts from this layer indicates that the process is rapid. The rate of deposition of a unit is then primarily controlled by silt deposition whose settling characteristics should be reasonably well described by equation (4). The time for deposition of turbidite units 2–4 cm thick in the Scotian margin cores is therefore estimated to be of the order of 2–4 days. However, to deposit the mud component of the unit at settling velocities appropriate to modal size of the mud would imply time scales of a month or more, even if the bottom stress vanishes.

One of the interesting features of this depositional sorting process is, therefore, the suggestion that the depositional rate from the turbidity current is proportional to the modal size of the silts, the clay flocs falling out being of equivalent settling velocity. The depositional processes as a whole are therefore much more rapid than would be anticipated using any model that views the deposition of the mud layer as a separate process, characterised by the size distribution of the mud alone.

The type of mechanism may well apply to other environments where fine-grained sediments are deposited from slowly moving flows. It should result in the regular silt/mud lamination particularly common in deep sea sediments.

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