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Deposition and paleo-oceanographic significance of the Late Silurian laminated and bioturbated mudstone in the English Lake District, northwest of England

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ABSTRACT: *The Late Silurian (Wenlock) laminated and bioturbated mudstones of the Lake District basin, northwest of England are genetically not different and most likely both resulted from slow and continuous sedimentation but in different bottom water conditions. The deposition of laminated mudstone took place in a density stratified basin. This density stratification produced anoxic bottom water conditions which caused preservation of fine lamination. The bioturbated mudstones display either complete or partial bioturbation, associated with horizontal burrows, indicating slow sedimentation in oxygenated bottom water conditions.*

The interbedding of bioturbated mudstone with laminated mudstone indicated periodic return of the basin to oxygenated conditions which might have caused by renewed bottom circulations and/or reduction in the supply of organic material.

INTRODUCTION

In the Lake District Basin, northwest of England, the Late Silurian (Wenlock-Ludlow) Series succession is about 6000m thick (Fig. 1) and is dominantly composed of fine-grained sediments (fine grained sandstones, siltstones and mudstones). In the succession, the laminated mudstone appears as thin interbeds with bioturbated shale (Stockdale Shale) and becomes the dominant lithology from *centrifugus* to the base of the *ludensis* graptolitic zone (Rickards, 1978) making a monotonous sequence of laminated mudstone (Brathay Flags), and again becomes interbedded with bioturbated mudstones (Middle Coldwell Beds) during the ludensis graptolite zone. Then the sedimentation of this facies was interrupted by sand turbidites (Coniston Grits) during *nilssoni* and *scanicus* graptolite zones and is present as a thin unit (< 75m) between the Lower and Upper Coniston Grits (turbidites), indicating a pause in the deposition of sandy turbidites. Coniston Grits are overlain by thin bedded siltstones and mudstones (Bannisdale Slates).

Laminated mudstone

This laminated mudstone is characterized by very fine lamination (submillimetre scale), averaging 2 to 4 laminae per millimeter. In hand specimen and polished slabs, individual laminae rarely can be distinguished, and units have a mottled appearance. In X-radiographs, even finer lamination can be identified (Fig. 2), while under a microscope, these laminae are discontinuous and irregular (Fig. 3). This lamination is caused by a regular alternation of coarser and finer sediments.

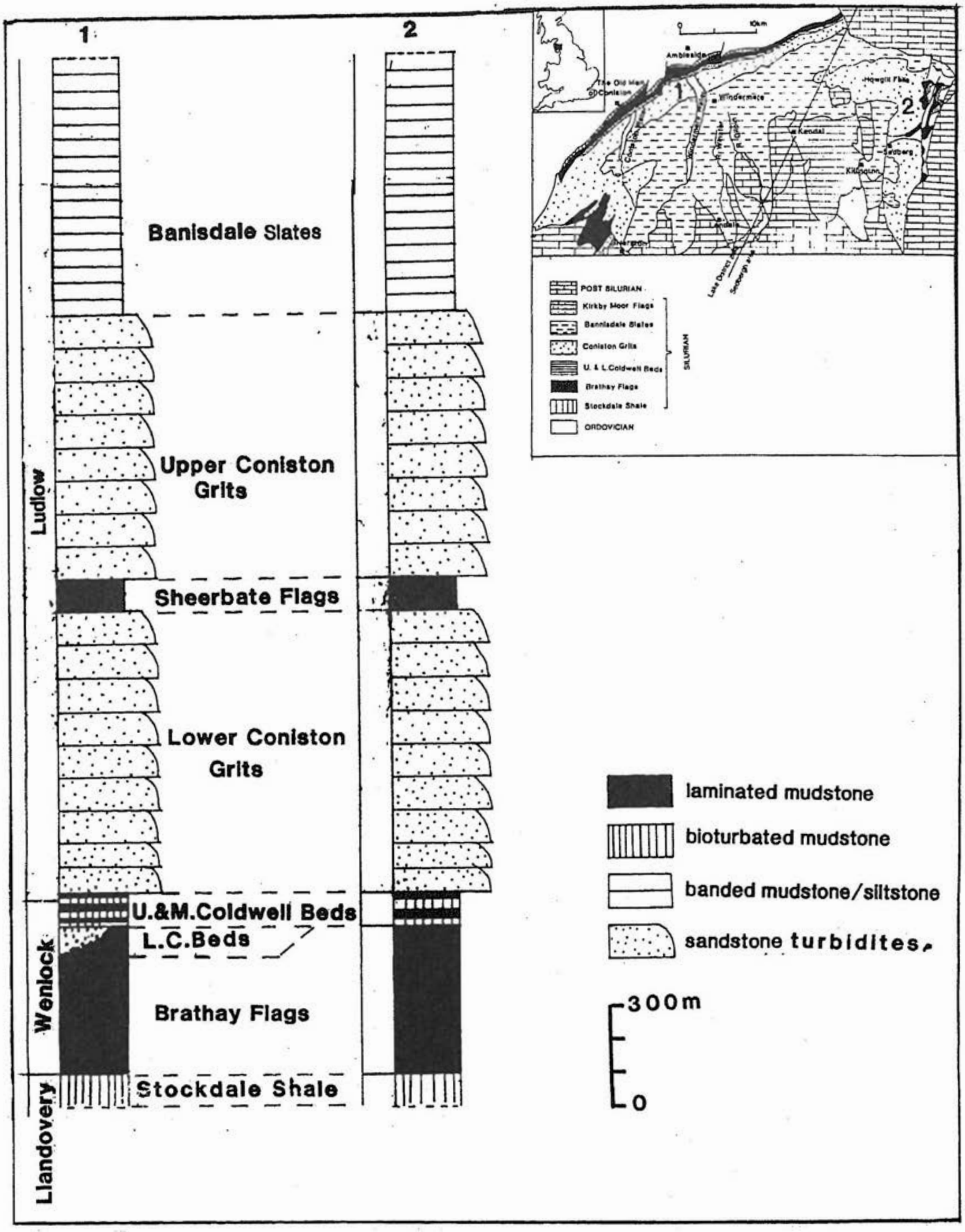

Fig. 1. General Wenlock-Ludlow lithostratigraphic sucession in the Lake District; 1. Southern Lake District, 2. Howgill Fells (after Rickards, 1978).

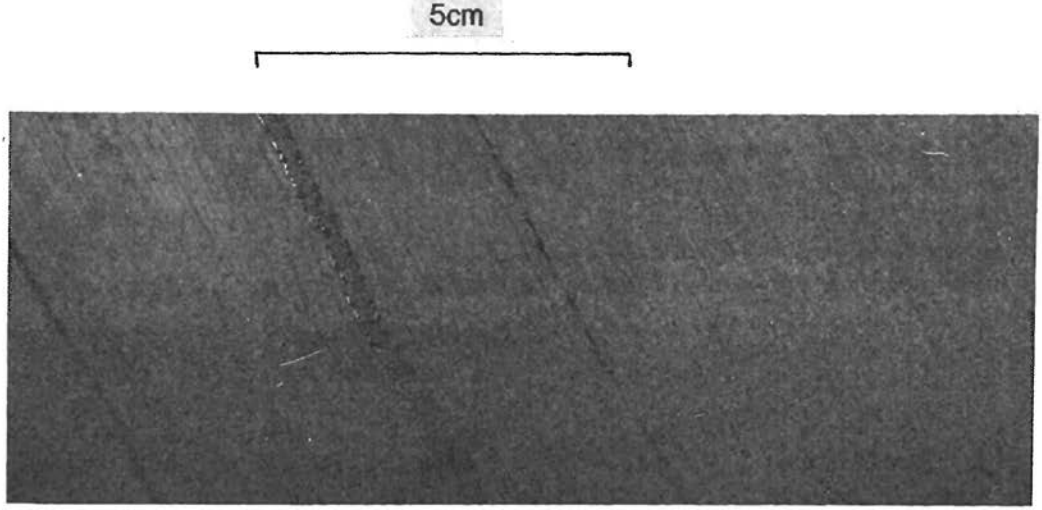

Fig. 2. X-radiograph of the laminated mudstone facies showing very fine varve-type lamination (from Bratagy Flags, Brathay Quarry, Lake District, Grid Reference SD35780161).

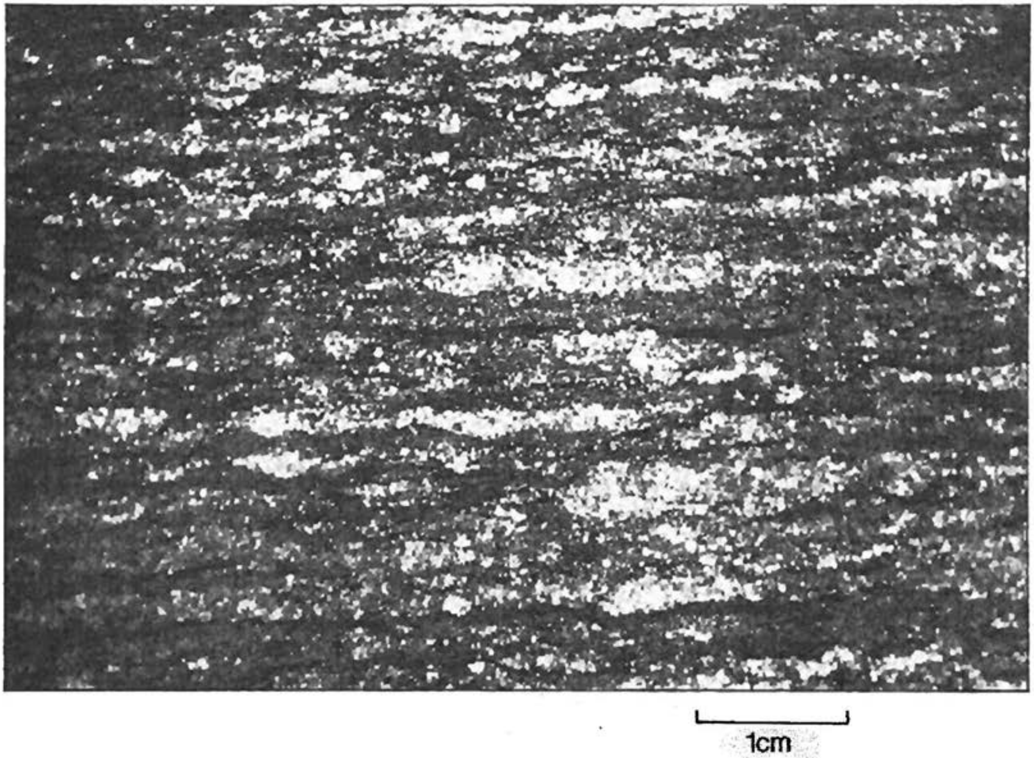

Fig. 3. Photomicrograph of the laminated mudstone facies showing discontinuous and irregular nature of the laminae (from Brathay Flags, Brathey Quarry, Lake District, Grid Reference SD35780161).

The coarser laminae consist of silt-size detritus, dominantly quartz and feldspar grains with subordinate carbonate and mica. These sediments are segregated into lens-shaped bodies and occur as aggregates. These aggregates have various shapes, including ovoid, cylindrical, rounded, and ellipsoidal with the latter being the most common. They rarely exceed 0.25mm in thickness and 2mm in length. The individual grains in the aggregate structure are angular to subangular. Grading in the individual silt laminae occasionally may be seen but there is no obvious grading from lamina to the overlying clay lamina.

The finer laminae consist of clay and carbonaceous material and are relatively thinner than the silt laminae. These finer laminae also occur as aggregates and continuous laminae. The carbonaceous material generally occur as thin films (<50 micron) between silt and clay laminae (Fig. 3). These films rarely continue laterally for a few centimeters, with pinching and swelling outlines and mutual truncations in places. This irregularity may result from differential compaction. The abundance of carbonaceous material varies greatly from place to place.

Bioturbated mudstone

This facies occurs with in the *ludensis* and *nilssoni* graptolite zones and is interbedded with laminated mudstone facies (Fig. 4). In field this facies can be distinguished from the interbedded laminated sediments by its massive and phacoidal weathering but is difficult to identify bioturbation and biogenic structures megascopically. However, polished slabs, X-radiographs and thin sections show a high degree bioturbation which have destroyed or modified primary sedimentary structures. Based on degree of bioturbation and primary sedimentary structures, at least four subfacies can be recognised.

Subfacies a: This subfacies is characterised by complete and thorough bioturbation which has obliterated all sedimentary structures (Fig. 5). Identification of burrows is very difficult because the mixing of the sediment is thorough, but rarely small patches of slightly coarser sediments can be seen in polished slabs and thin sections which probably represent burrow fillings.

Subfacies b: This facies is characterised by high degree of bioturbation with rare sedimentary structures. Most of the burrows are horizontal, filled with dark grey sediment and clearly visible on the polished section (Fig. 6). *Zoophycos* and *Chondrites* are the most common burrows. The proportion and diameter of the chondrite burrows increase upwards, together with a change in the sediment from grey to greenish grey.

Subfacies c: This subfacies is characterised by black, laminated mudstone at the base, followed upwards by grey highly bioturbated mudstone at the top. The black and laminated mudstone show a few tiny chondrites burrows filled with greenish sediments and a few large *zoophycos* burrows, dug downwards from the partially laminated, grey mudstone units. The top bioturbated mudstone shows clusters of *chondrites* burrows which are filled with darker sediments (Fig. 7).

Subfacies d: This facies is characterised by regular alternations of laminated and partially bioturbated mudstone (Fig. 8). The laminated mudstone is dark grey while bioturbed mudstone is greenish grey. Bioturbation is represented by tiny burrows of *chondrites*.

DISCUSSION AND INTERPRETATION

Origin of the laminated mudstone

Fine lamination in deep marine environments have numerous and diverse origins. They could

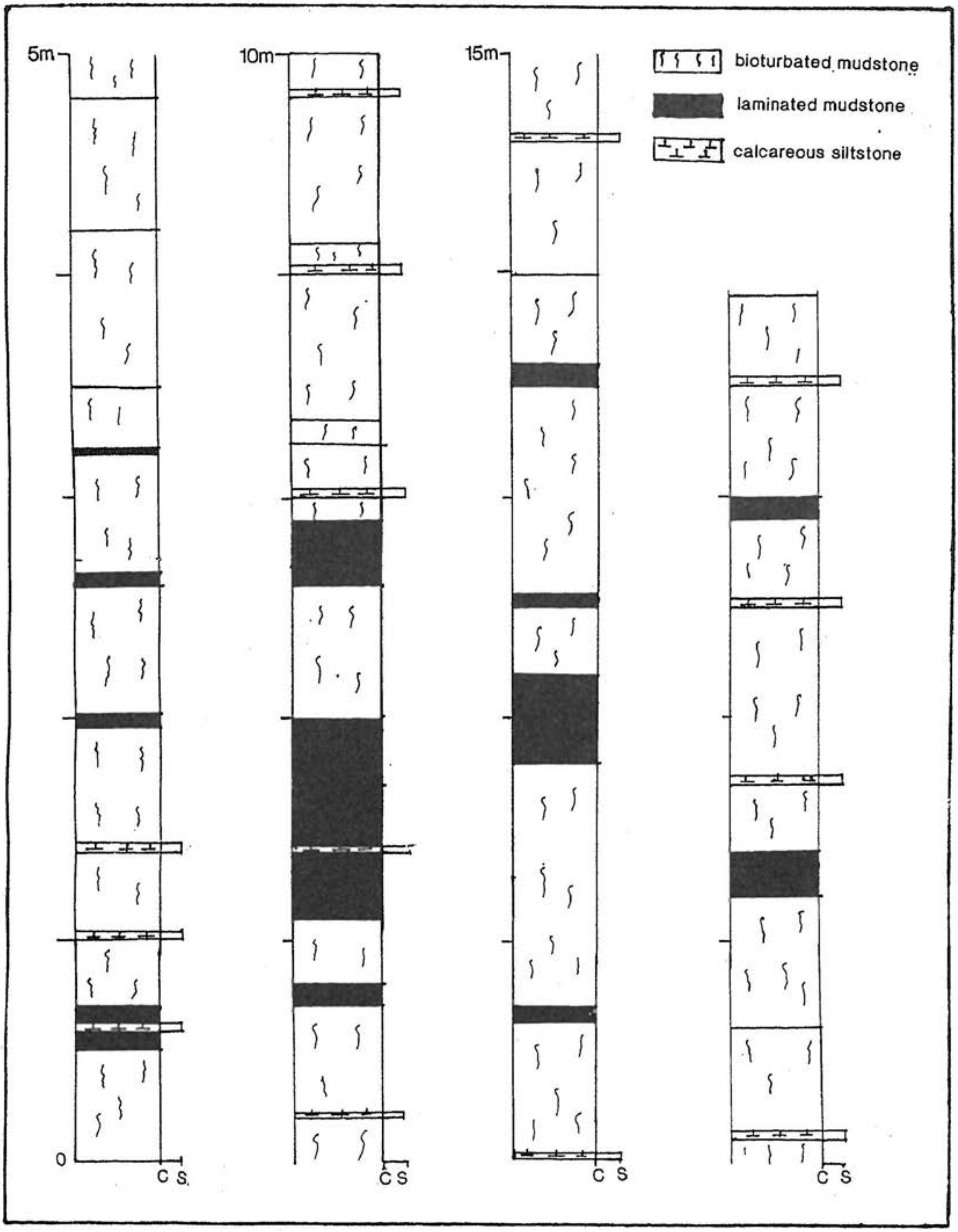

Fig. 4. Sedimentary log of the Middle Coldwell Beds, comprising bioturbated and laminated mudstones (measured near Brathay Quarry, Lake District, Grid Reference SD36100115).

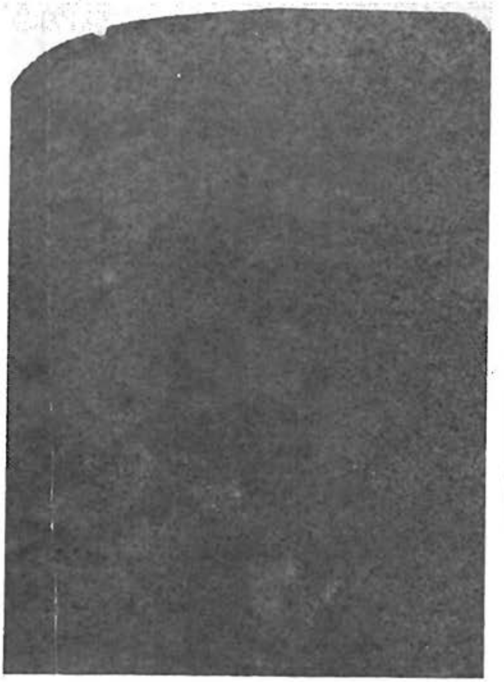

Fig. 5. Photograph of polished slab of the bioturbated mudstone (subfacies a) showing thorough bioturbation as indicated by poorly sorted and swirling texture (from Middle Coldwell Beds, near Brathay Wuarry, Lake District, Grid Reference SD36100115).

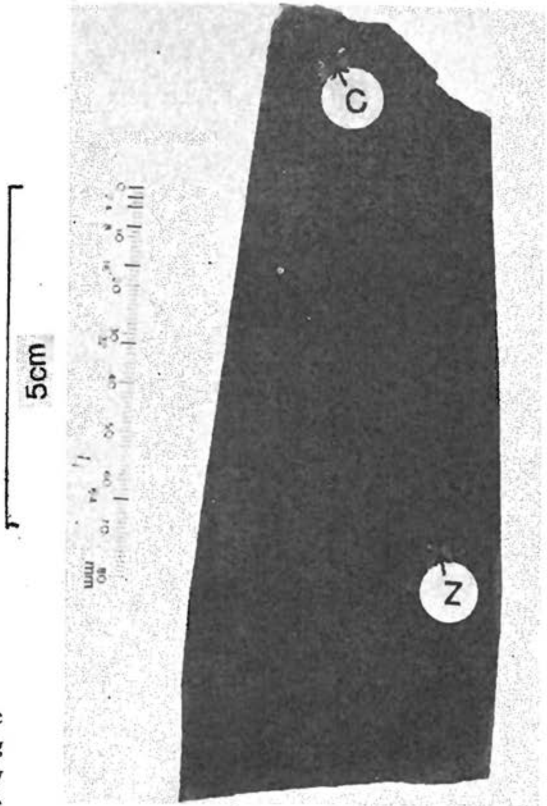

Fig. 6. Photograph of polished slab of the bioturbated mudstone (subfacies b) showing high degree bioturbation and partially preserved sedimentary structures. Note, horizontal burrows of *Zoophycos* trace fossil (from Middle Coldwell Beds, Lake District, Grid Reference SD36100115).

be the result of one of the combinations of more than one of the following mechanisms: (i) turbidity currents, (ii) contour currents, (iii) seasonal variation in the sediment supply, and (iv) deposition in density stratified water conditions (Hulsemann & Emery, 1961; Calvert, 1965; Reineck & Singh, 1972; Piper, 1978; Stow & Bowen, 1980; Stanley, 1983).

Turbiditic origin: Fine lamination formed by turbidity currents can be correlated with the Bouma (1962) Td division and Piper's (1978) E1 unit. The characteristic feature of this lamination is a progressive vertical decrease in grain size, thickness and frequency of the laminae. But here the laminated mudstone shows neither a progressive vertical decrease in coarseness, thickness and frequency nor a gradual transition to the overlying mudstone unit. Thus, it is unlikely that this facies was deposited by turbidity currents.

Contourite origin: Fine lamination can also be formed by bottom currents. These currents flow along the slope, rework and segregate the sediments into coarser and finer laminae. Such laminae generally are laterally discontinuous, irregular in shape (lensoid and wavy) and show current induced characteristic features (ripple

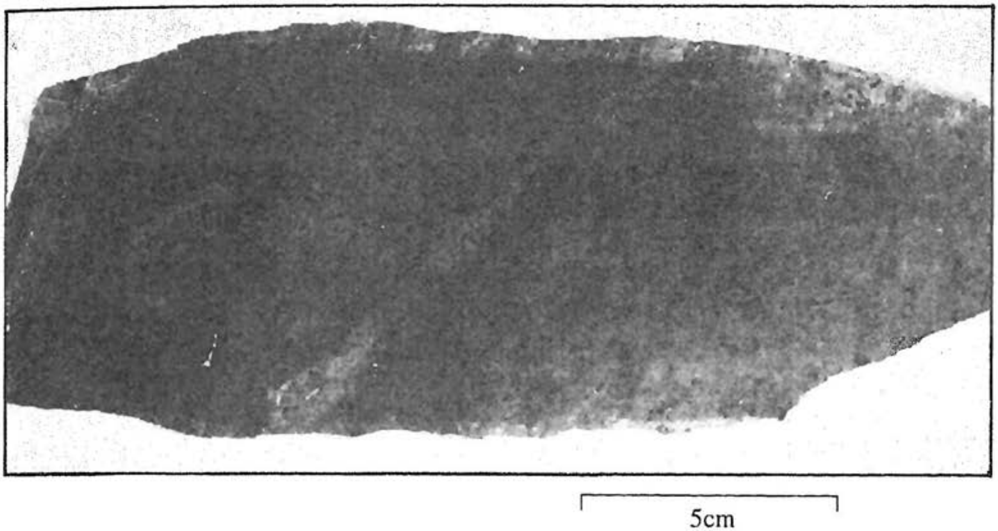

Fig. 7. Photograph of polished slab of the bioturbated mudstone (subfacies c) showing a gradual change from lamination (lower) to bioturbation (upper) (from Middle Coldwell Beds, Lake District, Grid Reference SD36100115).

Fig. 8. Photograph of polished slab showing alternations of laminated and bioturbated mudstone (from Middle Coldwell Beds, Lake district, Grid Reference SD36100115).

and cross lamination; Piper, 1978; Stow, 1979). Some of the features observed in this laminated mudstone facies (discontinuous and irregular nature of the laminae, truncation of finer laminae and segregation of coarse sediments) may indicate bottom reworking by bottom hugging nepheloid flow. It is unlikely that there are contourites, because in small and topographically restricted basins, like the late Silurian Lake District Basin, such contour currents are seldom generated.

Seasonal variation in sediment supply: Lamination can also be produced by seasonal variation in the sediment supply which consists of a regular alternation of sediment layers from different sources. The characteristic feature of such lamination is the lack of systematic variation in the grain size and thickness of laminae. This type of lamination is more readily preserved in anoxic bottom water conditions (Hulsemann & Emery, 1961). It is unlikely that this mechanism was responsible for the deposition of the laminated mudstone of the Lake District Basin, because there is no discernible difference in the composition of coarser and finer laminae (terrigenous vs biogenic). The difference is textural rather than compositional. However, the finer laminae are slightly organic-rich, and may have formed in situ, possibly in the form of bacterial mat (Schieber, 1986).

Suspension in a stratified water basin: Stanley (1983) proposed a model involving the role of stratified water masses in the formation of fine lamination. Under such conditions the density interfaces act temporarily as barriers and prevent immediate particle settling (depending on the strength of the density interfaces). According to this model, when a gravity flow encounters a sharp density interface, part of it detaches as turbid as a layer and moves along the density interface and the sediment then is released as flocs from suspension cloud. These flocs disaggregate, coarser particles settling first followed by finer sediment and thus forming a couple of laminae (Slow & Bowen, 1980).

Deposition of the Late Silurian laminated mudstone of the Lake District Basin

Various interpretations have been proposed for the deposition of laminated mudstone. Cummins (1959a), from his work on the Nantglyn Flags (characterised by regular alternation of laminated and uniform mudstone layers) of Wales, interpreted these lamination as the result of the compaction of the mottled structures produced by benthonic organisms, and the sediments initially being delivered to the basin by minor turbidity currents. Warren (1963) described laminated sediments identical to those of the Nantglyn Flags (Cummins, 1959a) from the Hawick region, Southern Upland of Scotland and suggested that these lamination resulted from the entrapping of pelagic organisms by drifting clouds of fine turbidite sediments. Rickard's (1964) work on the graptolitic mudstone of the Howgill Fells, Lake District, suggests that the sediments were supplied by low density, non-eroding turbidity currents and the lamination were destroyed by burrowing organisms, reasoning that the bottom water was aerated due to these tumidity currents. Llwellyn (1965), in his work on the same graptolitic mudstones of the Howgill Fells, Lake District, gave a similar interpretation to Cummins (1959), "compaction of faecal pellets"; these pellets being produced by benthic organisms. Archer (1981), from her work on the Devilsbit/Keeper Hill inlier Late Wenlock, (South Central Ireland), interpreted these laminated sediments as contourites, reasoning that the presence of internal laminae indicates current activity during deposition. Based on field studies on the Jemtland Formation in northeast Maine (Silurian) and an experimental flume study, Carey and Roy (1985) considered that the intermittently laminated shale is similar to that described by Piper (1978) as interval E1 in the mud turbidite model, and interpreted that "they were deposited from silt and clay-rich flows that were essentially unidirectional". Kemp (1987) working on the Silurian rocks in the Southern Uplands of the Scotland, interpreted the laminated sediment (identical to the Nantglyn Flags of Wales) as a hemipelagic or background sediment and suggested that the fine lamination probably formed in response to repeated algal blooms which may have been annual. Tyler and Woodcock (1987), and Dimberline and Woodcock (1987), working on the laminated mudstone of the Nantglyn Flags in Central Wales offer a broadly similar interpretation.

Detailed examination of these sediments during this study indicates that deposition of laminated mudstone took place in a density stratified basin. The sediments were supplied to the basin floor through very low density and low velocity gravity flows; analogous to the bottom nepheloid layers of Gorsline (1981) and lutite flows of McCave (1972). These flows were not powerful enough to penetrate through the density interface and thus were detached completely as turbid layers at the density interfaces within the water column and spread along the density interfaces (Drake, 1971; Stanley, 1983) (Fig. 9). Subsequently the suspended sediments within this detached turbid layer were flocculated (Kranck, 1975, 1980; McCave, 1984) which by finer sediments forming monotonous sequences of laminated mudstone.

DEPOSITION OF THE BIOTURBATED MUDSTONE

In ancient fine grained sequences, primary sedimentary structures and textures are more reliable criteria to distinguish mud turbidites from hemipelagites and to envisage sedimentary processes. However, fossil assemblages, clay mineral composition, carbonate content, organic carbon content and colour can also be used for such studies. (Griggs, et al., 1969; Piper, 1973; Rupke & Stanley, 1974; Hesse, 1975; Stow & Piper, 1984). In addition to these criteria, biogenic sedimentary structures are useful indicators of depositional mechanisms (Howard, 1978).

A careful examination of polished slabs, X-radiographs and thin sections, suggests that

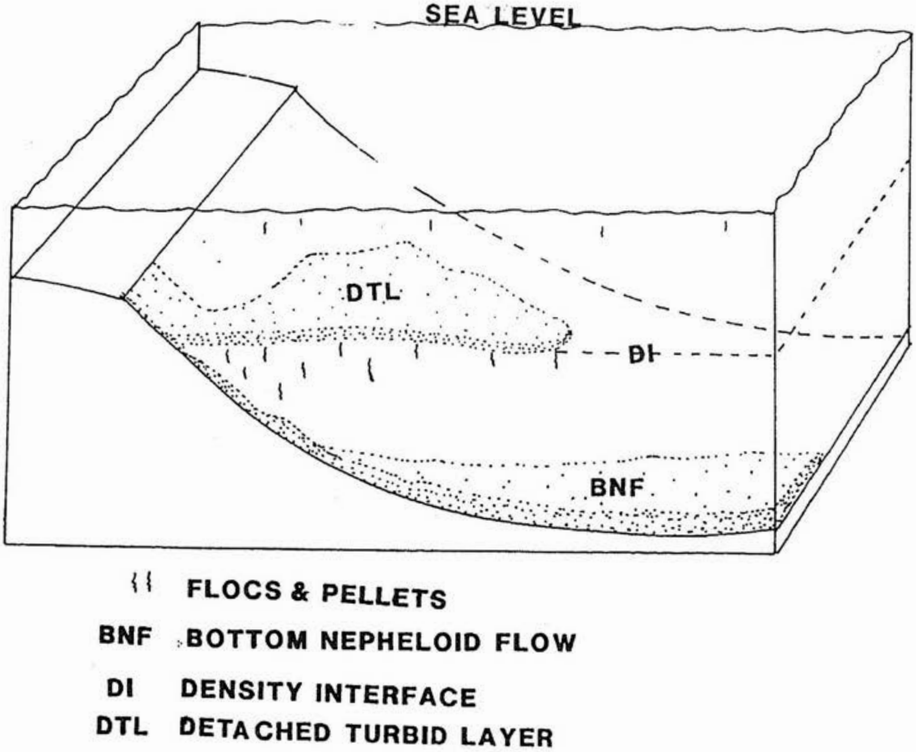

Fig. 9. Schematic model illustrating probable origin of laminated mudstone of the Brathey Flags.

the bioturbated mudstone of the Lake District was deposited by slow and continuous sedimentation in oxygenated bottom water conditions. This is reflected by thorough and complete bioturbation (subfacies a) as the rate of bioturbation equals or exceeds that of sedimentation (Howard, 1978). Thus the animals had enough time to rework the sediments several times. Partially preserved primary sedimentary structures, together with horizontal burrows (subfacies b) also indicate slow and continuous sedimentation in relatively oxygen-deficient bottom water conditions which may have allowed only low oxygen tolerant animals to survive and move around.

Subfacies c indicates slow and continuous sedimentation with increasing oxygen levels in the bottom water. Slow sedimentation is evident from *zoophycos* burrows dug down into the dark laminated mud unit presumably of food (Wetzel, 1984). The gradual transition from laminated to bioturbated mudstone is due to a gradual increase in the level of dissolved oxygen in the bottom water. This increase in the oxygen levels might be the result of a reduction in the influx of organic matter or increase in bottom circulations.

Subfacies d also seems to be the result of slow and continuous sedimentation with fluctuations in dissolved oxygen content in bottom waters. Short term oxygenation in the bottom water be produced by turbidity currents (Hulsemann & Emery, 1961), but the lack of grading, or scoured surfaces in the non-laminated, partly bioturbated interbedded mudstone, indicates that turbidity currents are unlikely as a source of oxygen. One possible explanation could be temporal fluctuations in the position of the dysaerobic-anaerobic boundary within the water column (Rhoads & Moore, 1971) which may have been caused by variations in the supply of organic matter.

Palaeo-oceanographic significance

The finely laminated mudstone (submillimetre scale) of the Lake District basin, in the northwest of England are characterised by lack of systematic variation in the grain size and thickness of laminae, and regular alternation of coarser (terrigenous silt) and finer (clay and carbonaceous material) sediments, indicative of quiet and low energy conditions (non-turbiditic origin). Preservation of such laminae indicates an absence of benthic organisms which in turn suggests oxygen deficiency in the bottom waters (anoxic conditions). The anoxic condition for the first time seems to have prevailed in the Llendovery Series (Early Silurian) represented by the appearance of thin bands of laminated mudstone interbedded with pale grey, bioturbated mudstone (Stockdale shales). The interbedding of the laminated mudstone with bioturbated mudstone (Fig. 4) indicates periodic oxygenation of the bottom waters. A complete resumption of the anoxic conditions took place at the beginning of Wenlock Series, as represented by the deposition of the laminated mudstone (Brathay Flags). The laminated mudstone of the Brathay Flags is ovelain by a sequence of bioturbated and laminated mudstone alternations (Middle Coldwell Beds). This again indicates periodic oxygenation and deoxygenation (Fig. 10). Complete anoxic conditions prevailed in the earliest part of the Ludlow Series, as represented by a monotonous sequence of laminated mudstone (Upper Coldwell Beds). The laminated mudstone of the Upper Coldwell Beds are overlain by fine to medium grained sandstone turbidites (upper and lower Coniston Grits) with intervening laminated mudstone (Sheeted Flags). The lack of bioturbation in the overlying mudstone units on the sandstone turbidites and the preservation of lamination in the laminated mudstone of the Sheeted Flags suggest persistence of the anoxic conditions upto the late Ludlow Series (Late Silurian).

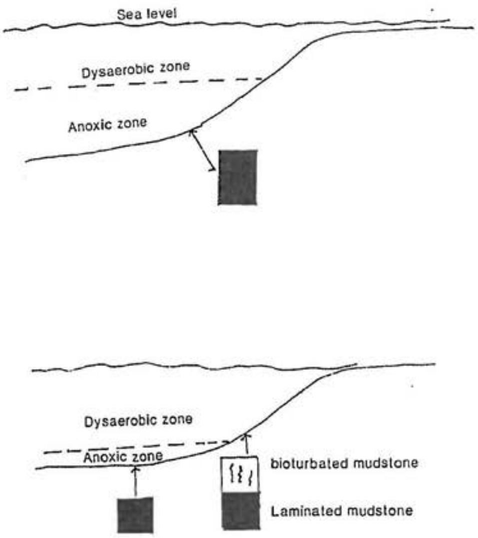

Fig. 10. Schematic model illustrating alternations of bioturbated and laminated mudstones of the Middle Coldwell Beds, probably controlled by fluctuations in dysaerobic-anoxi boundary.

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