Palaeoecology of graptolitic black shales

By S. HENRY WILLIAMS and R. BARRIE RICKARDS

Lower Palaeozoic black shales were deposited in a variety of environments, including open oceans and shallow, near-shore areas. Some resulted from relatively rapid turbidite deposition, while others were formed slowly as a soft, anoxic ooze. Bioturbation is occasionally present, while associated paler lithologies sometimes contain dark "flakes" which were flocculated organic material or "rip-up clasts" of unconsolidated sediment. Detailed study of deep-water sequences reveals rapid lateral variation in thickness, implying an undulating sea floor in abyssal environments. Currents during the deposition of black shale are often indicated by aligned graptolites. These may also have winnowed unconsolidated graptolitic sediment to form laminae with closely packed, uniformly sized rhabdosomes. This offers an alternative to the commonly preferred explanation of "mass mortalities" which would result in a variably sized assemblage, although this can also often be established. While changes in sea level were responsible for major lithological changes, small-scale lithological alternations were probably related to fluctuations in oxygen levels controlled by current strength and density of organic material.

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A substantial literature exists on black shale of the Upper Paleozoic and of the Mesozoic to Recent, which has been greatly boosted by the economic potential of such sediments as hydrocarbon source rocks (see Dunham 1961; Schlanger & Jenkins 1976). The palaeoecology of these has been studied in great detail, most of them being considered to represent sedimentation in enclosed, oxygen starved basins up to several hundred kilometers wide (Hallam & Bradshaw 1979; Deggens & Stoffer 1980; Schlanger & Jenkins 1976). Although some Lower Palaeozoic black shales were no doubt formed in such environments, many are integrally related to shallow water and sub-aerial deposits, such as the Upper Ordovician of the Oslo Region (Brenchley & Newall 1980) and the Snowdon Volcanic Group of North Wales (Fitch 1967), while others are of great lateral extent and must have been deposited in open oceans (Fig. 1). Perhaps the best known example of this type is the Moffat Shale Group of southern Scotland which is now considered to have been deposited in the Lower Palaeozoic Iapetus Ocean and subsequently formed into a series of imbricate thrust slices above a subduction zone (McKerrow *et al.* 1977). No open ocean black shale environments exist at the present time and it has been suggested (Berry & Wilde 1978) that such conditions may only exist when ocean circulation is reduced. This was probably the case in the early Palaeozoic when the climate was relatively uniform and there was no ice cap in the northern Polar area. During the late Ordovician, glacial conditions clearly existed in Gondwanaland, which have been most frequently documented from North Africa (e.g. Beuf *et al.* 1966; Bennacef *et al.* 1971). This led to widespread regression and probably increased oceanic circulation. Destombes (1976, and following discussion) considered the glaciation to have begun in the Hirnantian and possibly to have extended into "lowest Silurian", depending on the position relative to the South Pole.

If present day sequences are compared, black shales are seen to accumulate under anoxic conditions with a slow "rain" of fine sedi-

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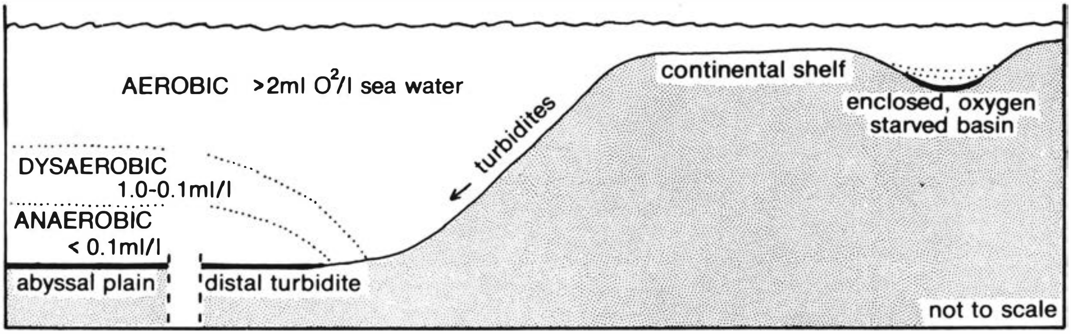


Fig. 1. Idealised profile showing possible sites of formation of graptolitic shale. Names and definitions of oxygen levels from Rhoads & Morse (1971).

ment. The black colour is often, but not always, due partly to the presence of pyrite rather than carbon, which rarely exceeds a few percent (Hallam 1980). Determination of the carbon origin by geochemical means is difficult or impossible in Lower Palaeozoic British rocks due to subsequent alteration (A. Thickpenny, pers. comm.). Byres (1979) described general and detailed sections from two black shale sequences in the Upper Devonian and Upper Cretaceous of the United States, both of which were apparently formed in enclosed basins up to 150 m deep. He summarises ideas on the formation of laminated muds in Recent sediments, concluding that although most laminated fine silts and shales are products of low energy environments, some may have been deposited by relatively rapid turbidity currents, such as the Phyllopod Bed of the Burgess Shale which has clearly graded units (Piper 1972). The lamination of black shales, caused by variation in sediment supply, is destroyed or partially destroyed (Rickards 1964) when bioturbation is present. Normal oxygenation in the ocean surface water is about 7 ml O^2 /l sea water; this can be lowered to about 2 ml/l with little effect on marine communities (Byres 1979). The terms "dysaerobic" and "anaerobic" were defined by Rhoads & Morse (1971); dysaerobic conditions occur with 0.1–1.0 ml/l which can support a simple infauna such as small polychaetes and aschelminths but no shelly fauna, while anaerobic conditions, below 0.1 ml/l, are toxic to all life. Although sediments formed under dysaerobic conditions are partially bioturbated the burrows are only up to 2 mm diameter and lamination is commonly preserved.

Rickards (1964) described and illustrated sectioned slabs from the Silurian of the Howgill Fells, northern England, which he considered to have been deposited by distal turbidites, the evidence being graded bedding on a microscopic scale and lateral passage into proximal turbidites. The lithologies were later studied briefly by Piper (1975); he gave no conclusive suggestions on the formation of black graptolite mudstone but suggested that graptolite preservation was favoured by rapid burial. Rickards (1964, text-fig. 2) clearly showed that the graptolitic mudstone was soft at time of deposition and that current strength was low, due to the existence of rare upright orthocone cephalopods. These occur rarely in graptolitic shales of both Wenlock and Ludlow age in northern England and of Ashgill age in the Oslo Region. Rickards also showed that the change from black to pale lithology was a simple one with few sedimentary changes and almost no change in total mineralogy, save for extra S, Fe and As in the black shales (see also Spencer 1966). He concluded that increase in current strength caused aeration of bottom waters, decreasing the preservation of carbon and primary pyrite and permitting the existence of benthic organisms. He also noted, both in 1964 and later (Rickards 1978; Ingham & Rickards 1974), that the presence of narrow carbonaceous

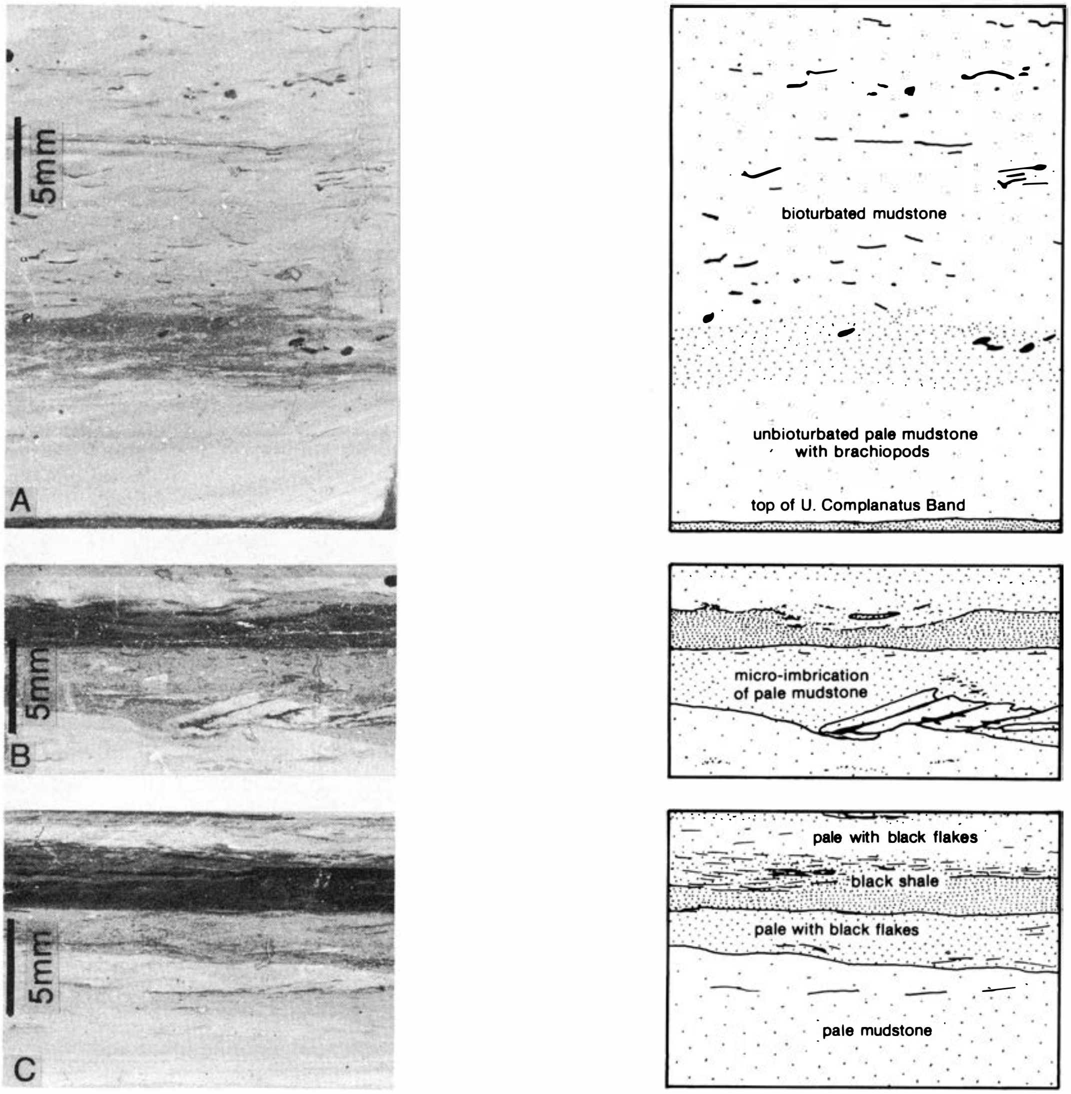


Fig. 2. Sectioned slabs from the Upper Hartfell Shale at Dob's Linn with explanations. A. Strata above the upper Complanatus Band. B. Micro-imbrication just below the lower Complanatus Band. C. Strata at the same level as B, showing black flakes above and below a thin black shale band.

bands in an otherwise pale sequence was due to increased influxes of carbonaceous material (also see Wilson 1954) from a planktonic source. This caused anoxic bottom conditions with a corresponding increase in pyrite formation and preservation of graptolites.

Detailed work at Dob's Linn, southern Scotland, shows that the lithological reversals in the Upper Hartfell and low Birkhill Shale Formations are to some extent characterised by different features from those described by Rickards (1964), although there are certainly some similarities in the Llandovery black shales in the *atavus* to *argenteus* levels. The pale grey mudstone is occasionally bioturbated by horizontal burrows a few millimetres in diameter (Fig. 2A), but these are never present in the black shale. Rickards (1964) considered that black shale lamination was due to variation in density of carbonaceous material and that bioturbation

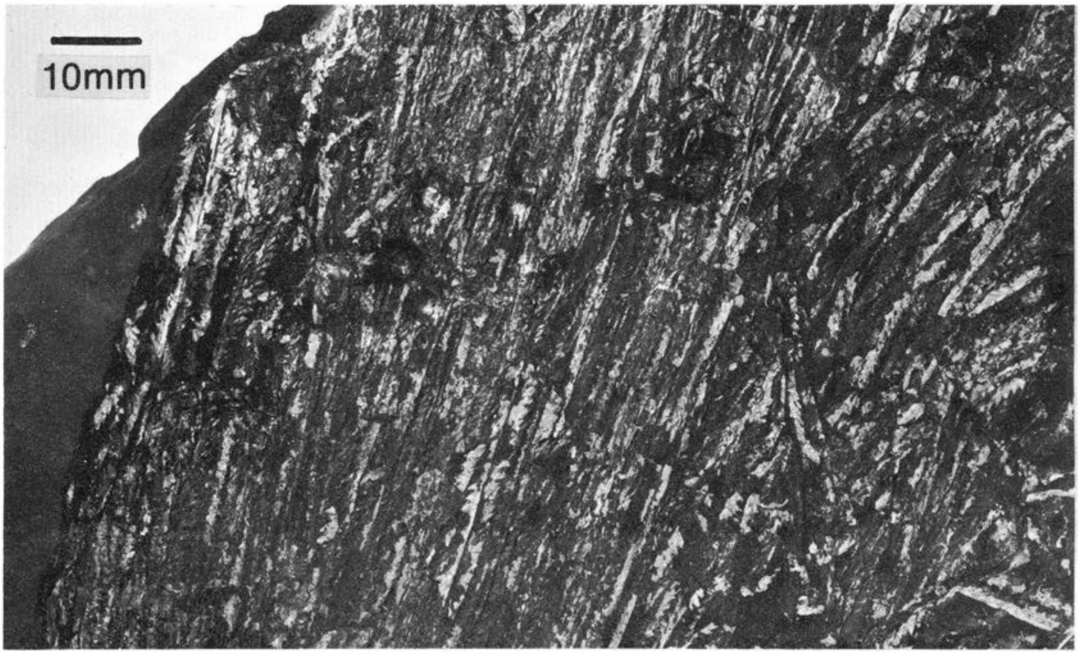


Fig. 3. Lamina of winnowed and aligned extensiform didymograptids with almost no sediment. Lower Didymograptus Shale (Lower Ordovician), Tøyen underground station excavations, Oslo. Coll. B.–D. Erdtmann. Pal. Mus. Oslo, PMO 109.141.

destroyed banding, rather than creating it by the compression of faecal pellets as suggested by Jones (1954). This conclusion was borne out by Byres (1979). It therefore seems likely that the black graptolitic bands of the Upper Hartfell Shale represent anoxic conditions, while the paler mudstones with occasional small, horizontal burrows were deposited under dysaerobic conditions. In addition, the lithological boundaries are commonly complex with scattered flakes of black material at both the upper and lower boundaries with the pale mudstone (Fig. 2B); these also occur in the *sedgwickii* Zone in the Lake District. Micro-tectonic, syn-sedimentary structures also occasionally occur at these boundaries (Fig. 2C). The micro-faulting and micro-imbrication probably indicate unstable deposition on a gentle slope, although some syn-sedimentary micro-faulting may be due to dewatering effects. There are two possible explanations for the black flakes present in pale mudstone; either they are remnants of scattered carbonaceous material which drifted over the area but was insufficiently dense to cause totally anoxic conditions, or they represent syn-depositional erosion of black material which has been reburied soon after to prevent decomposition. In the Howgill Fells the latter certainly applies in the *maximus* Subzone where black flakes up to several centimetres across themselves yield *R. maximus,* yet occur with thin beds of black shale also yelding *R. maximus.*

The Upper Ordovician Lower Tretaspis Shale of the Oslo Region, Norway demonstrates lithologies intermediate between true black shale and dark grey mudstones and silts (Williams & Bruton, in press). The base of the Lower Tretaspis Shale, which is marked by a phosphorite, represents a deepening of the sedimentary basin and gives a sharp contrast with the underlying limestone-shale alternations of the Upper Chasmops Limestone. Bioturbation is present throughout much of the unit and is locally coarse with burrows up to 10 mm in diameter. The finer bioturbation is similar to that recorded by Rickards (1964) from black shales overlain by non-carbonaceous material with rare trilobites and brachiopods. The bioturbation figured by him (Rickards 1964, pl. 16) appears close to that illustrated by Piper & Brisco (1975, fig. 12a) from a Tertiary abyssal plain mud core taken during DSDP research. The presence of bioturbation need not, however, indicate oxygenerated conditions in the black shale as present day organisms may burrow for some depth into anoxic sediment. Occasional darker bands occur throughout the paler sequence in the upper part of the Lower Tretaspis Shale, several possessing carbonaceous flakes at their bases. These clearly represent the situation where carbonaceous material was insufficiently dense to cause anoxic conditions or deposition of true black shale. The presence of a relatively abundant shelly fauna in both the dark shale and nodular limestones, together with increased bioturbation and limestone deposition towards the top, clearly indicates formation of a dark, carbonaceous shale in a relatively shallow and shallowing, near shore environment. Rickards (1964: 422–3) considered that the presence of pyritised graptolites preserved in relief indicated more fully anoxic conditions than those which are preserved in the flattened state. Work in the Oslo Region clearly indicates, however, that this hypothesis is not entirely correct as the most highly pyritised and best preserved three-dimensional specimens occur in the higher, paler lithologies of the Lower Tretaspis Shale, often associated with dense bioturbation.

Evidence such as graptolites cutting bedding (Briggs & Williams 1981) support earlier conclusions that the black shale was very soft during deposition. It is possible that there was no true sediment-water interface but merely a transition zone, in which case syn-depositional erosion seems unlikely in some cases. However, evidence of current activity during black shale deposition is given by aligned graptolites at many localities (Fig. 3); at Dob's Linn these are especially common in the Anceps Bands of the Upper Hartfell Shale. Further indications of current activity and a possible irregular sea bed are shown by rapid lateral variation in metabentonites and thicknesses of pale shale units. Contrary to what would be expected, the thin metabentonites at Dob's Linn are rarely laterally continuous for any distance. This is well

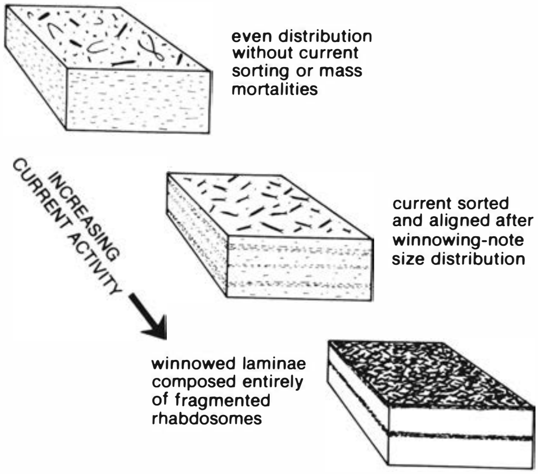
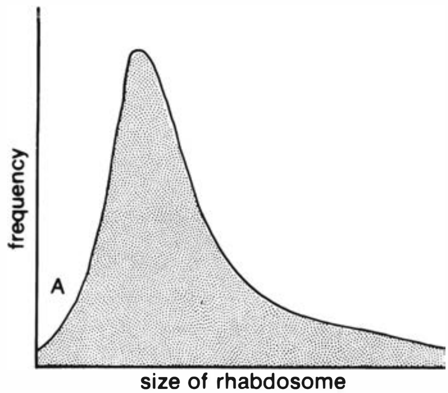


FIg. 4. Postulated effects of current activity of graptolitic shale with syn-depositional erosion and re-deposition following winnowing.

illustrated by the lower Complanatus Band which contains a metabentonite near the top in the Main Cliff section, although this is absent while the thickness of intervening pale grey mudstone increases in the Linn Branch section some 70 cm along strike. The thickest Anceps Band, B, is also affected by such lateral change; it is only 17 m thick on the Main Cliff but increases to 19 cm some 120 m along strike in the Linn Branch section (Williams 1982). In addition a thin metabentonite is present towards the top of Band B in the Linn Branch which is absent on the Main Cliff, while the top boundary of the black shale in the Linn Branch is gradational although on the Main Cliff it is sharp with a thin orange lamina directly below. It is possible that this orange band and the overlying black lamina are greatly thinned (eroded?) representatives of the metabentonite and overlying black shale in the Linn Branch. In the Lake District Hemsley (pers. comm.), has shown that bentonites can be reworked and even cut out altogether despite the generally low energy environment.

There is no doubt that further detailed study of the black bands in the Upper Hartfell Shale would reveal additional changes similar to the great lateral variation in thickness of the Anceps Bands recorded by Williams (1982, text-fig. 3). This variation is original and represents either non-deposition or syn-sedimentary ero-



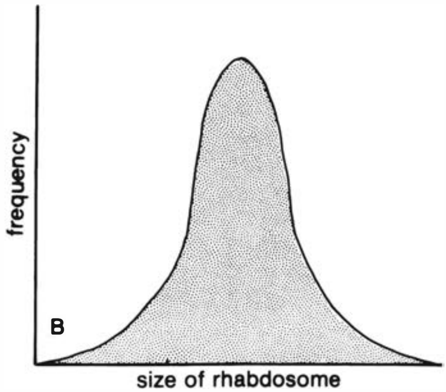


Fig. 5. Qualitative graphs showing: A. Expected size distribution of graptolite rhabdosomes (cf. Curry 1982 for Recent brachiopods). B. Distribution commonly found on bedding laminae, due to current sorting of rhabdosomes.

sion. In the Howgill Fells (Rickards 1970, Ingham & Rickards 1974) syn-sedimentary erosion may well have winnowed thicker black shale sequences, distinctly more pyritous, into hollows on the sea floor, and the positions of these have been accurately plotted. The second hypothesis is therefore preferred as this would also explain the distribution of evenly-sized, current orientated rhabdosomes of two or three species on certain laminae and other bedding planes consisting entirely of fragmented rhabdosomes with no sediment (Figs. 3, 4). Both features are here considered to be products of winnowing; the uniform size distribution could have been produced either as the dead graptolites sank to the bottom in a gentle current, or by syn-depositional erosion of the soft sediment and subsequent sorting during redeposition in hollows. The latter is preferred as a uniform presence of graptolites near the surface would have produced a uniform faunal composition on the bedding planes if sorting occurred during sinking. The winnowing of soft sediment also appears to explain layers consisting solely of fragmented graptolites; this was presumably the product of more intense current activity during which all the enclosing sediment was removed. Occasionally such beds can be 4 mm thick and consist of graptolites and a small number of remnant sand grains and (entrapped?) mica flakes.

If graptolite preservation was not biased in favour of mature colonies one would expect far more juveniles than other growth stages (Fig. 5), as found in Recent marine invertebrates (e.g. brachiopods, see Curry 1982). The presence of bedding planes covered with siculae and juveniles in the low Birkhill Shale and many horizons in the Silurian of the United Kingdom indicates that preservation of juveniles is perfectly feasible and that their absence is likely to be due to sorting. Both this and other horizons with densely packed graptolites are unlikely to be due to mass catastrophies caused by such factors as upwelling of anoxic water (e.g. Berry & Wilde 1978) as this would more often result in a complete range of growth stages. It should be pointed out that if a continuous sequence of black shale is studied in detail, although graptolites occur most commonly at discrete horizons they occur sporadically throughout. However, because of the ease of splitting along planes with abundant specimens, most are collected from such horizons and give the impression that they are almost restricted to such laminae. This often gives the incorrect impression of "mass mortalities" separated by non-fossiliferous intervals.

Many conodonts and one scolecodont have been found in Upper Ordovician black shale at Dob's Linn but only one conodont from the pale mudstone; this is either collection failure, which seems unlikely as the black conodonts are more easily seen in the pale lithology, or an original distribution or preservational feature. In the last case, the conditions affecting preservations of graptolites presumably also applied to conodonts. Inarticulate brachiopods are common in many black shale sequences. At Dob's Linn they also occur at two horizons in the pale mudstone. Specimens in and just above the upper Complanatus Band (Williams & Lockley 1983) are well preserved and in uniformly laminated strata (i.e. not *in situ*). Others between Anceps Bands B and C occur as "nests" of broken fragments in a pyritic, bioturbated interval. Trilobites occur together with fragments of bivalves and nautiloids in an interval just below the Extraordinarius Band (J. K. Ingman and N. H. Trewin, pers. comm.); the Dob's Linn trilobite represents a new blind dalmanitid genus and is clearly a deep water form but not *in situ* (J. K. Ingham, pers. comm.). Algal remains (?) occur in the black shale; these are to be expected if the black shale has a partially algal origin and it is surprising that so few examples of algae in black shales have been recorded. The enigmatic form *Dawsonia*, tentatively assigned to the Ordovician crustacean *Caryocaris* Salter by Rolfe (1969: R316) without comment may be of algal origin due to its similar preservation and original "crocus" flower shape.

At the base of Birkhill Shale is an unfossiliferous interval some 12 cm thick which is mottled and heavily weathered, especially in the lowest part. The different weathering properties indicate a different composition but lithological sections have failed to reveal any clear structures. It is not apparent whether the mottling is an original feature such as bioturbation (although the laminae appear intact) or an irregular distribution of organic material, but the interval does appear to be browner than the overlying black, graptolite-yielding strata. Similar strata occur in Spengill in the Howgill Fells. The Extraordinarius Band is also dark brown rather than black, with a graptolitic unit of only 2 or 3 mm thick. Such brown material may prove important in elucidating the exact formation of black shale as when preparing etchings of graptolites the brown shale/limestone often results in a brown, algal (?) debris, rather than a black one.

McKerrow (1979) and Leggett (1980) have both summarised large-scale processes in British Lower Palaeozoic successions and conclude that change in lithology is directly related to sea level. Although it is clear that certain major events (such as the general regression in the top Ordovician) are related to sea level changes it is improbable that this caused the small-scale reversals described here; such changes are more likely to be related to oxygen content caused by current density and/or density of carbonaceous material. Whichever processes are responsible for the onset of black shale deposition in the Lower Palaeozoic it is clear that there are several different explanations, exemplified by the assortment of structures seen at Dob's Linn, northern England and the Oslo Region. It is therefore hoped that this brief discussion will stimulate further critical study of similar argillaceous sequences elsewhere.

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