PALAEONTOLOGY, STRATIGRAPHY AND SEDIMENTOLOGY OF THE KINDERSCOUTIAN AND LOWER MARSDENIAN (NAMURIAN) OF NORTH STAFFORDSHIRE AND ADJACENT AREAS

by

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STRATIGRAPHY AND SEDIMENTOLOGY

INTRODUCTION TO CHAPTERS III AND IV

Holdsworth (1963a,b) claimed that a study of the coarser-grained sediments of the North Staffordshire Basin allowed its history to be divided into three distinct "phases". In the earliest phase, suggested as being coextensive with the Pendleian (E1), the only coarser sediments to accumulate were graded beds of "calcareous siltstone". Calcareous siltstone deposition continued during the early part of the second phase (E2-R1c), but the sediments peculiar to this second, major phase in the Basin's history are the "protoquartzites", beds of mineralogically highly mature, though usually poorly rounded, sandstone. The third phase, suggested as starting within R1c and continuing throughout the remainder of the Namurian, is marked by the abrupt disappearance of the protoquartzite lithology and the first appearance of mineralogically less mature sands with appreciable quantities of K-feldspar.

In describing the sediments of the basin, Holdsworth used a classification divided into "lithofacies" -- distinctive types of lithological assemblages occurring as units at more than one point in the succession. The calcareous siltstones and their interbedded shales were considered to represent a single lithofacies (1) in which more and less laminated sublithofacies (1a and 1b) could be recognised. Two lithofacies of shales with protoquartzite sandstones were distinguished: the essentially parallel-bedded lithofacies 2 (with sublithofacies 2a and 2b), and lithofacies 3, with more thickly-bedded, coarser sandstones, apparently forming lensate bodies. Holdsworth's lithofacies 4, shales with parallel-sided subarkose beds having high original K-feldspar content, was also divided on the basis of bed thickness and sandstone:shale ratio into sublithofacies 4a, 4b and 4c.

Holdsworth's study was largely confined to the north-eastern portion of the basin. In this area he recognised that the majority of coarser-grained lithofacies and sublithofacies types defined recorded turbidite sedimentation (ie. 1, 2a, 2b, 4a, 4b, 4c). But it was also pointed out (Holdsworth, 1963b) that amongst the spectrum of phase 2 protoquartzites seen throughout the whole basin, non-turbidite environments were probably also recorded. These non-turbidite protoquartzites were referred to as the "traditional Crowstone type".

Subsequent work largely confirmed Holdsworth's outline of the major steps of the evolution of the basin. Trewin (1969) made a basin-wide study of E1-E2b_1. He found that the protoquartzite unit which in the north-east had been taken to indicate the onset of the second phase lay below the _Cravenoceras_ _malhamense_ marine band and was thus E1c. He showed that, except at the extreme north-east basin margin, this unit is everywhere developed, and everywhere constitutes the first appearance of the typical phase 2 lithology. Other protoquartzite units in E2a are equally synchronous and widespread, and the lateral variations of the sheets were shown to be readily explicable in terms of deposition from turbidity currents flowing from a southern proximal locus and fanning out distally to the north and north-east. Trewin also agreed that the calcareous siltstone lithofacies is probably of turbidite origin, and first drew attention to the crude rhythms involving siltstone units, protoquartzite units and marine bands in the E1-E2a succession.

The upper limit of the second phase has proved more diachronous than originally thought. In the north-east, Holdsworth showed that the incoming of the subarkose lithofacies (with the Longnor Sandstone) is at different levels within upper R1c, but Evans *et al*. (1968) state that the protoquartzite lithofacies persists as high as R2 in the Stoke-on-Trent District. However, it remains true that in any one area the ranges of protoquartzitic and K-feldspathic sediments do not overlap, and Holdsworth's contention that the two lithologies are associated with different supply directions -- protoquartzites from the south and west : subarkoses from the north -- has been largely confirmed.

The present study was designed to give more information on the change of environments and sediment distribution associated with the end of the second and the onset of the third phases. It is concerned with the protoquartzite and K-feldspathic sandstone lithofacies between the *H. magistrorum* and *R. bilingue* s.s. marine bands. A detailed study of the faunal succession and the kaolinised ash bands revealed that the stratigraphy of the area is more complex than has previously been recognised. The major part of the area covered consists of the typical Namurian basin succession -- marine shales alternating with non-marine shales and sandstone units. Turbidites of the protoquartzite lithofacies, however, are atypical compared with turbidite successions elsewhere, possibly because of the scale of the basin and the peculiar palaeogeography. Two sublithofacies have been recognised -- (pA) and (pB). Both sublithofacies are confined to tongues, as far as can be seen from field and borehole data. (pA) occurs in two distinct units, but (pB) is confined to one unit in R1c. Deltaic sediments occur in the southern part of the area, and range from R1a to R2b. In the typical section these protoquartzites have been divided into sublithofacies (pC) - (pF).

The K-feldspathic lithofacies is exclusively of turbidity current origin, and has been divided into seven sublithofacies. The development of this northerly derived lithofacies is more constant than that of the protoquartzites, but there is some evidence to suggest that the lithofacies developed in the form of two main lobes, which show different characteristics.

Indications of rhythmic sedimentation have been noted, particularly in the best exposed sequence of the K-feldspathic turbidites, but also in the protoquartzites of the deltaic area.

CHAPTER III

STRATIGRAPHY OF THE K-FELDSPATHIC AND PROTOQUARTZITE SANDSTONES

STRATIGRAPHY OF THE K-FELDSPATHIC AND PROTOQUARTZITE SANDSTONES

THE PROTOQUARTZITE LITHOFACIES

The R. circumplicatile zone, R1a

The most important of the lower faunal bands, with reference to the stratigraphy of the sandstones, is that of the R. paucicrenulatum marine band (R. todmordenense subzone, $R1a_2$) as no Kinderscoutian sandstones are known in North Staffordshire beneath this level. This marine band is well developed in the section in the Combes, but the succession beneath the marine band is not seen. Morris (1967) includes one of the thick protoquartzites of the Combes within R1a, but there is no field evidence to support this conclusion. It is considered that the protoquartzite sandstones at Sharpcliff Hall (Ipstones Edge) are in H since Nuculoceras beds underlie these sandstones (Bolton, personal communication).

In the north of the area, black shale sedimentation continued almost uninterrupted until pre-$R1b_{iii}$ but in the south arenaceous sediments appear in $R1a_2$. The first Kinderscoutian sandstone unit is exposed at Endon Golf Course (Badderly Edge) where it overlies the $R1a_2$ marine band and is itself overlain directly by a marine band containing a lamellibranch fauna only. A pebbly sandstone bed occurs within these marine shales. The next higher marine band is thought to be that of $R1b_{ii}$ because of the abundant Homoceras fauna and the Reticuloceras specimens collected. Thus the first protoquartzite unit lies between $R1a_2$ and $R1b_i$ and is conventionally included in R1a.

Elsewhere there is little trace of this $R1a_2$ sandstone. In the Heath Hay Ravines section, a few thin, sandy, rippled and parallel-laminated layers have been noted between a possible $R1a_2$ marine band (the fauna is poorly preserved) and an unidentifiable higher marine band. In every other section known from Rla_2 to $R2b_i$, all traces of sandstones and siderites (often the distal representatives of sandstone units) are absent. The Rla_2 sandstone is thus of a decidedly local nature, a characteristic shared by the protoquartzite sandstones at higher stratigraphic horizons (see Appendix Figure III).

$\underline{Rlb_i - Rlb_{ii}}$

Exposure of marine bands above Rla_2 is poor in the southern part of the area. The Combes succession shows a shale sequence between Rla_2 and Rlb_i, but higher parts of the succession are obscured by faulting. It is possible that immediately above Rlb_i protoquartzites are present. Their development may be delayed until post Rlb_{ii} as Rlb_i-Rlb_{ii} sandstones are absent at the Endon Golf Course section, but siderites do suggest that protoquartzite lateral equivalents occur at no great distance from the area.

$\underline{Rlb_{ii} - Rlb_{iii}}$

In the Golf Course section, protoquartzite sandstones are found above Rlb_{ii}, possibly between Rlb_{ii} and Rlb_{iii}. Protoquartzites are also present higher in the faulted section but could be anywhere between Rlb_{ii} and R2. Elsewhere in the Endon and Stanley anticline, no other Kinderscoutian fossiliferous exposures are known, except at Rownall Farm (p.272). Here, a fossiliferous band between two sandstones has yielded only one doubtful Reticuloceras specimen. The type of marine facies at Rownall, together with the Golf Course section, suggest that thick deltaic protoquartzites are present in most of the Kinderscoutian above Rla_2 in the area. In the Heath Hay Ravines section, siderites between Rlb_{iii} and (?)Rlb_i would correspond with protoquatzites elsewhere.

<u>$R1b_{iii}$ - $R1b_{iv}$</u>

Development of the protoquartzites continues to be sporadic higher in R1b and is still confined to the southern part of the area. The succession in the Combes is faulted and it can only be assumed that protoquartzites occur between $R1b_i$ and R2a. The sandstone succession, apparently with no major developments of shale, is a minimum of 100 m thick in R1b-R1c. It contains only one known marine band, which consists of black shale with Dunbarella. No definite $R1b_{iii}$-$R1b_{iv}$ protoquartzites are known elsewhere.

<u>$R1b_{iv}$ - $R1b_v$ - R1c</u>

In the upper part of R1b, protoquartzite sandstones extend further north than at any other period during the Kinderscoutian. Developments of these sandstones are seen in $R1b_{iv}$- $R1b_v$ (possibly post $R1b_{iii}$) in the Blake Brook and Oakenclough sections, and in $R1b_v$-R1c in the Blake Brook and Manifold Valley. The sandstone units are distinctly lenticular in shape and only developed locally. This led to some confusion over the exact position of these sandstones until additional data regarding sedimentology, palaeontology and "bentonites" were obtained from the Brund Boreholes. The stratigraphy in this area is somewhat complex and discussed in detail below.

In the field, the position of the protoquartzites can be most accurately assessed from the succession of the Blake Brook where the sandstones are overlain by a marine band now known to be $R1b_v$, though previously identified as R1c (Holdsworth, 1963a). The sandstones are underlain by a shale succession which has yielded the two lowermost R1b bands, and an ankerite horizon with thinner-shelled goniatites alone. The marine band with ankerite nodules immediately underlies the protoquartzites, and the fauna may represent that of $R1b_{iii}$ of

$R1b_{iv}$, the goniatite population having been modified by the local conditions. If the marine band is that of $R1b_{iii}$, it is not impossible that $R1b_{iv}$ has been obliterated by the local development of protoquartzites, a feature noted by Evans et al. (1968, p.22) as they comment that

> Slump beds are developed in H {as in R1b in the Blake Brook} at Gawsworth Common, where sole markings are also numerous. In this area, sediment flooded in at a great rate as evidenced by quartz grains in the mudstones, which fail to yield a fauna despite promising appearance.

Holdsworth (1963a) noted a Dunbarella horizon (a concretion) within the R1b protoquartzite sequence. This could represent $R1b_{iv}$, although a comparison with the Oakenclough sections suggests that $R1b_{iv}$ might be lower.

At Ballbank (Manifold Valley), the position of the sandstones can only be assumed to be in R1b, from the field relationship of the sandstones to an $R1a_2$ fauna. In the headwaters of the Manifold, protoquartzites occur 12-18 m above $R1b_i$.

The Oakenclough section is well exposed, but palaeontological evidence for the exact position of the protoquartzites was thought to be absent. A fossiliferous horizon, in a rotten limestone, was identified as R1 (Holdsworth, 1963a), but no other marine bands were known beneath the protoquartzites, despite good exposure of the shales. Holdsworth's marine band is now known to be $R1a_2$ from the occurrence of *R. pulchellum* at this horizon. The limestone from which the specimens were recovered and the one kaolinised ash band are also typical of the *R. pulchellum* horizon.

A fauna was thought to be absent from the shales between $R1a_2$ and the base of the protoquartzites, but an examination of the lithology suggests that representatives of the marine bands are, in fact, present. The majority of the succession consists of light grey, fissile and brittle shales, but there are three horizons (11, 180 and 90 cm thick) which may represent marine bands (Fig. 3.A). The thinnest of these is underlain at 21 cm by a 4 cm ankerite horizon which suggests quasi-marine conditions. All three horizons are in black marine shale lithology, and the occurrence of poorly preserved Dunbarella specimens in two of these horizons confirms their marine band identity. No goniatites have been found in any of the three black shale horizons, but then goniatites have not been found in the black shales in the $R1a_2$ marine band, only in the decalcified limestone layer. Conditions of preservation are so poor in the shales, which weather to a flaky texture, that only fossils with a stronger ornament, such as Dunbarella, are preserved.

The section in the Oakenclough thus allows for three marine bands between $R1a_2$ and the base of the protoquartzites. Approximately 4 m of the section is unexposed, and it is possible that a marine band occurs within this thickness (Fig. 3.A). The protoquartzites seem likely to occur above $R1b_{iv}$. $R1b_v$ is unknown in the section, but measurements suggest that the marine band should overlie the protoquartzite unit (the shales immediately above the sandstone are unexposed). A marine band with sparse lamellibranchs, which occurs approximately 21 m above the $R1b_{iv}$-$R1b_v$ protoquartzites, and which itself contains two 1 cm layers of protoquartzitic sandstone, is thought to be R1c.

Evidence from the Brund boreholes suggests that the situation is more complex than that deduced from field evidence. The boreholes (1,

STRATIGRAPHIC POSITION OF PROTOQUARTZITES NEAR LONGNOR

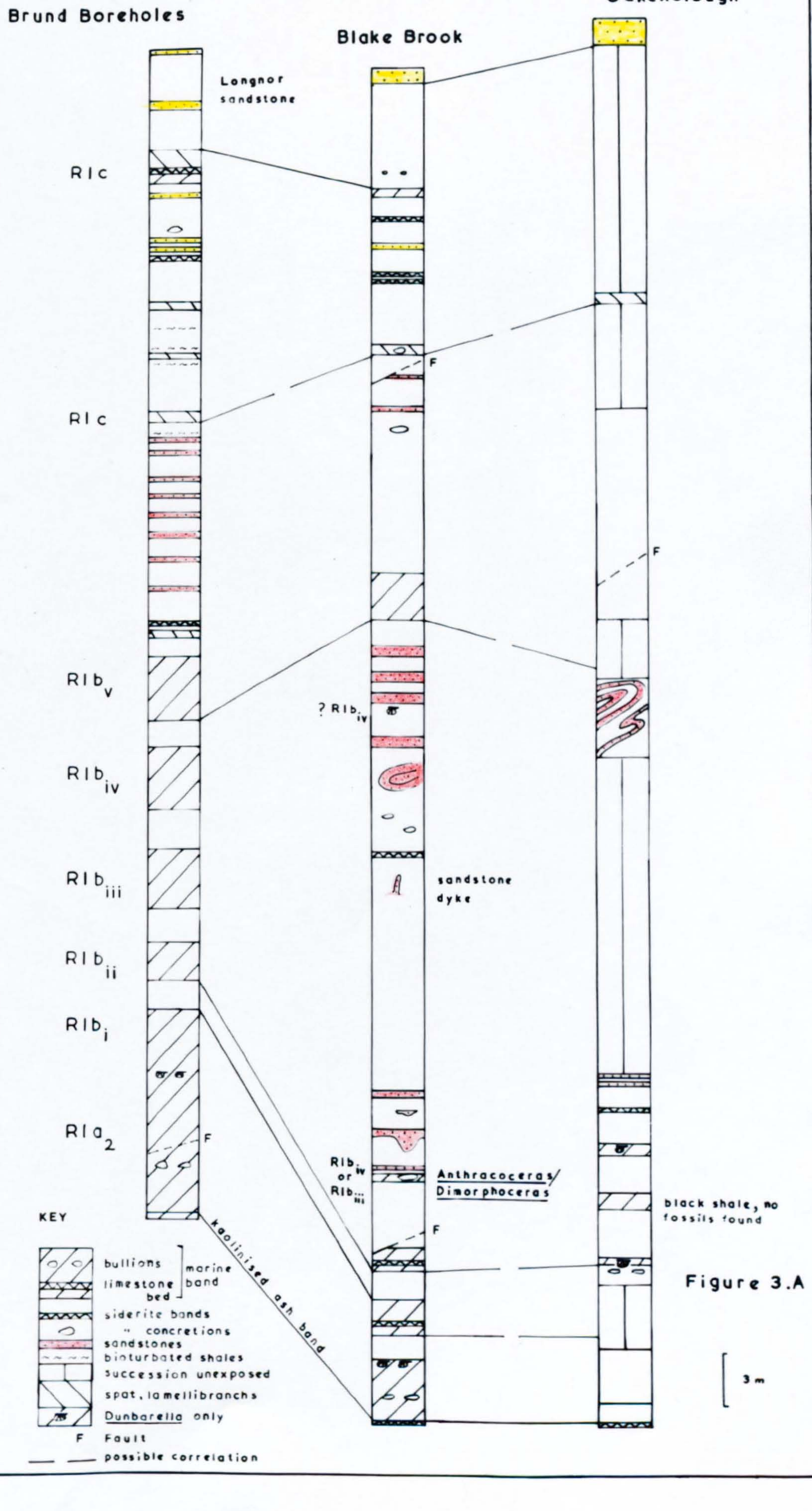


Figure 3.A

2, 3 and 11) consistently show an $R1b_v$ fauna below the base of a protoquartzite unit. Brund 1 provided a fairly complete section from $R1a_2$ to $R1b_v$, consisting almost entirely of fossiliferous black shales. When compared with measured sections in the Blake and Oakenclough (Fig. 3.A), there is clearly no room for the borehole thickness of $R1a_2$-$R1b_v$ shales to fit between $R1a_2$ and the base of the protoquartzites. Thus on these grounds (palaeontological, and simple comparison of thicknesses), it seems that there are two distinct levels of protoquartzite development. Despite the limited distance between the Blake section and the Brund borehole sites (approximately 1.25 miles {2 km} E.N.E. of the Blake section), the evidence does seem to indicate that the protoquartzites were only locally deposited, the major unit being deposited pre-$R1b_v$ in the Blake area, and post-$R1b_v$ to the east. Only thin representatives of the post-$R1b_v$ units are seen in the Blake, and no representatives of the pre-$R1b_v$ protoquartzites in the Brund boreholes.

In the Upper Manifold Valley, measured sections suggest that the base of the protoquartzites is pre-$R1b_v$. The lithology of the lower protoquartzites is comparable to that of the Blake, and the lithology of the protoquartzites at Ballbank, further downstream in the Manifold, is identical. Near the top of the sandstone succession in the Upper Manifold, however, siderite-cemented protoquartzites are common. These are similar to the lithology of the post-$R1b_v$ protoquartzites seen in the Blake Brook. Faulting obscures the relationship of the protoquartzite exposures to each other, and to R1c, but both pre- and post-$R1b_v$ protoquartzite units are probably present in the Upper Manifold.

That post-$R1b_v$ protoquartzites are present is suggested by the occurrence of a lenticular body of protoquartzite a maximum of 10 m thick, in the Upper Churnet Valley directly to the south. The position of the sandstone body in relationship to the marine bands is not known with accuracy, but mapping suggests that the protoquartzite occurs immediately above $R1b_v$. This would pass northwards into the post-$R1b_v$ deposits of the Manifold Valley. The lack of pre-$R1b_v$ protoquartzites in the Upper Churnet again indicates the local nature and sporadic development of these sandstones. This feature of laterally impersistent sandstones is not unique in Staffordshire and in fact seems to be the rule rather than the exception above E2a. Evans et al. (1968, p.19, fig. 5) indicate lenticular sandstone beds in E2, and the protoquartzites of Drystones (Upper Churnet, ?H) also appear to be a lens.

The upper R1b protoquartzites of the Longnor area are the northern-most extension of the protoquartzite lithofacies. The protoquartzites never reached the basin to the north of the limestone massif, and are also absent immediately adjacent to the limestone in the R1b succession of the Upper Dove. Post-R1b, the area of deposition of the lithofacies was restricted to the southern part of the North Staffordshire basin and its margins. This southerly retreat of the lithofacies was accompanied by an advance of the K-feldspathic lithofacies from the north, which has been noted as early as R1b in Swint Clough to the north of the massif.

Protoquartzite sandstones still occur as late as R2a-b in the south of the area, these R2 and R1c protoquartzites both posing some interesting stratigraphical problems.

R1c

The protoquartzites exposed in the Thorncliff area (sublithofacies pB), are proximal turbidites and probably pass laterally into deltaic deposits in the Ipstones and Combes area. The exact stratigraphic horizon of the protoquartzites seen at Thorncliff is difficult to determine due to the absence or rarity of thicker-shelled goniatites in shales above and below the unit. A marine band immediately underneath the sandstone is seen at two localities. At loc. 195 the marine band is 90 cm thick and occurs 2 m beneath the first pebbly sandstone bed. The goniatites are poorly preserved but collection has yielded specimens tentatively identified as R. cf. coreticulatum or R. sp. nova, R1c. A more crenulate form is also present, possibly representing one of the variants of R. reticulatum. It is thought unlikely that this marine band is that of $R1b_v$ as the $R1b_v$ marine band, in an adjacent section, lies some 10-13 m beneath an R1c (sublithofacies pB) sandstone.

At loc. 198 a marine band is exposed at a minimum of 3 m beneath the base of the sandstone. This may be the same as that exposed at loc. 195 as a fragment of a barely crenulate goniatite has been recovered from among the dominantly thinner-shelled fauna.

R. retiforme occurs at an isolated exposure and cannot be used to determine the exact position of the sandstone. Only loose bullions with R. gracile are known in the Thorncliff section above the sandstone and are equally unreliable in estimating its position. At other exposures where the top of the sandstone is seen, it is overlain by shales containing trace fossils (tubes of pyritised material) and fragments of lamellibranchs. A siderite band with a better preserved lamellibranch fauna overlies the protoquartzite at 1 m at loc. 094. The absence of R. gracile group immediately above the sandstone and the possibility of a middle R1c marine band underlying the unit indicate that the sandstone is of pre-Butterly age.

Evidence from the Churnet Valley also suggests that the Thorncliff protoquartzites are of pre-Longnor Sandstone age. Beneath the probable base of the Longnor Sandstone (section partially obscured) thin sandstones occur at 7 m below its base. These thin beds are fine grained and have failed, on etching and staining, to reveal any indications of K-feldspars. Fine-grained sandstone beds derived from the north are generally low in feldspar, and may lack it entirely, but the consistent absence of the mineral from these beds and their relatively clean nature does suggest that they were derived from the Mercian land mass. This is also indicated by the red colour of the sole of the beds, an unusual feature in the Longnor Sandstone. Sole casts on the base of the beds are inconclusive as evidence for the direction of supply of the sediments. Prod casts and ripples suggest derivation of the sandstone from the west, a direction which has been recorded both in the protoquartzites of Thorncliff and the Longnor Sandstone of the Churnet. It is possible that these thin sandstones are the distal representatives of the Thorncliff sandstone, and are separated from the Longnor Sandstone by the *R.* sp. nova band (Butterly). A horizon of rotten nodules in the Churnet some 7 m below the thin sandstone beds could represent a lower R1c marine band, typically poorly fossiliferous as in the Brund Boreholes and the Longnor area.

The lower Marsdenian -- R2a-b

The Thorncliff protoquartzites are the last representative of the protoquartzite lithofacies in this area, the succession at Thorncliff continuing exclusively in a shale sequence until the introduction of high R2b K-feldspathic sandstones. South of this area, however, where the protoquartzite succession is thickest and most persistent, there is evidence to indicate that the protoquartzite lithofacies continued until at least R2b. Evans *et al.* (1968, p.91) indicate that quartzitic sandstones and siltstones continue in the Stoke-on-Trent district up to the middle of R2. The highest protoquartzite beds recognised by the author are thin sandstones below the *R. bilingue* (?early form) marine band (loc. 136) in the Parkhouse Wood section. The section at Oakamoor records no sandstones between the *R. gracile* shell bed and the base of the Roaches Grit. Thin silts and burrowed beds (Plate 5.3c) below $R2b_{ii}$ may represent the bottom-set beds of the southern delta.

It is possible, in the Endon and Stanley anticline area (Stoke-on-Trent district), that protoquartzites higher in R2b are present but there appears to be no direct palaeontological evidence for this. In the section at Badderly Edge (Endon Golf Course) protoquartzites are faulted against an $?R2b_{ii}$ marine band, suggesting only that this lithofacies could be R2. Higher in R2, the Roaches grit appears to have been deposited over the whole of the area and protoquartzite deposition effectively halted.

R2a protoquartzites are known in two sections (Oakamoor, and Felthouse and Parkhouse Woods) in the south of the area. Both are in shallow water, deltaic sublithofacies. Evidence for the R2a age of the sandstones in Felthouse/Parkhouse Wood comes from a red, calcareous, goniatite-bearing bed. This contains *R. gracile* (I.G.S. specimens) and is thought to have come from a position immediately above the protoquartzite. The first appearance of *R. retiforme* is below the sandstone unit, indicating that the sandstone lies between *R. retiforme* and *R. gracile*. The sandstone is therefore R2 in age and effectively splits the *R. gracile* marine band (Appendix Figure VI). This is an unusual feature in the Namurian of North Staffordshire, but the situation is not unknown elsewhere (eg. the *R. gracile* band in the

River Dane section) although the development of sandstone is never as great as the 33-39 m of the Felthouse/Parkhouse section.

As local, thick bodies of sandstone are found in the basin, eg. in the R1b sandstones, it is not surprising that at the margins of the basin a composite marine band, normally split by unfossiliferous shales, can sometimes be separated by thick wedges of locally deposited deltaic sandstones. No evidence of this phenomenon is known from the Kinderscout Grits of the north, but it is possible that detailed work might reveal similar complications.

THE K-FELDSPATHIC LITHOFACIES

With the southerly advance of the northern deltaic complex, K-feldspathic sandstones were contributed to the North Staffordshire Basin. This event was accompanied by the retreat of the proto-quartzite lithofacies. At no stage in the history of the basin is there any sign of interdigitation of individual sandstone beds of the two lithofacies. Nor is there alternation of units of the two lithofacies in the manner of the alternating calcareous siltstone and protoquartzite sandstones of E2, recognised by Holdsworth (1963a).

The earliest indications of the K-feldspathic lithofacies are seen in the Alport area where, in Swint Clough, thin turbidites occur above $R1b_{iii}$. These sandstones constitute the local diachronous base of the Mam Tor Sandstones, the major development of which is post-$R1b_v$ (see below). The palaeontology of the R1c fauna in North Staffordshire and its relationship to the $R1b_v$ fauna is not well known, as thicker-shelled goniatites in the R1c marine bands are rare. The R1c marine fauna appears to be restricted to two marine bands, the higher one of which (Butterly) contains goniatites in the Longnor area. The

Butterly marine band is not known with certainty in the southern part of the area, the R1c exposures known probably being lower than R. sp. nova, R1c.

The section in Swint Clough was recorded by Bisat and Hudson (1943), who indicated the base of the Mam Tor Sandstones at 3.96 m (13') above R. reticulatum. This was found at the top of a "sparsely fossiliferous" 3.66 m (12') shale sequence, at the base of which occurs the typical $R1b_v$ fauna in 30 cm (1') of shale. The thickness of this total marine sequence (about 4 m) in Swint Clough is comparable with the thickness for $R1b_v$ alone (3.66 m) in the Brund Boreholes. It is unlikely that the $R1b_v$ marine band of the boreholes has been expanded by a greater rate of sedimentation than in Derbyshire. In fact the converse might be expected as the kaolinised ash bands of the Swint Clough locality are separated by 45 cm of shale compared with 5-8 cm in North Staffordshire. Although a spat band recorded above the $R1b_v$ band of one of the boreholes might represent a low R1c marine band, it is evident that the first indications of an R1c fauna occur in close association with $R1b_v$, and not in a discrete R1c marine band, as is often implied.

Stevenson and Gaunt (1972) point out that the lithology of R1c is variable; in Edale only 4.5 m (15') of R1c is in a shale lithology, which is followed by the Mam Tor Sandstones. This compares with 24 m (80') of R1c shales in Whitemoor Sitch. The nature of the base of the Mam Tor Sandstones is probably as complex as the distribution of the K-feldspathic sandstones and protoquartzites in North Staffordshire, but the main development comes after the $R1b_v$ fauna with "R. reticulatum", recorded by several authors.

Despite the thickness of the Mam Tor Sandstones north of the massif, they are not represented in North Staffordshire. The only K-feldspathic sandstones known with certainty to occur beneath Butterly in Staffordshire are extremely thin (sublithofacies fA) sandstones in the Longnor area. These could be at the same level as the Lower Kinderscout Grit of Derbyshire. In the Manifold Valley, R. sp. nova occurs below the Longnor Sandstone, as in the Blake Brook. In the Upper Dove Valley and at Brand Side (near Thirkelow), however, no R1c fauna can be found and it is possible that nearer the present exposed western edge of the limestones, thicker sandstones were introduced into the North Staffordshire basin prior to R. sp. nova. That the limestone topography was still in existence at this stage can be seen from mapping of the base of the Longnor Sandstone which rests, at progressively higher levels, close to the relief of the limestone (Holdsworth, 1963a). A thin layer of pelagic clay with goniatites is thought to have accumulated over the limestone prior to the deposition of the Longnor sandstone as R1c goniatites have recently been recovered from collapse structures in the limestone (Aitkenhead, 1971). Holdsworth (personal communication) also collected R1b and R1a goniatites from the collapsed deposits at Buxton Quarry. Sandstones were probably first introduced at the western edge of the massif and may have been directed eastwards along its edge. This is suggested by the absence of R. sp. nova in the west around Thirkelow, and the presence of tool marks showing that the sandstones were derived from the west (Holdsworth, 1963a). Tool marks from the west have, however, been recorded in the Longnor Sandstone of the Churnet Valley, further south.

The Longnor Sandstone occurs between R. sp. nova (R1c) and R. gracile (R2a) and is therefore equivalent to the Upper Leaf of the

Kinderscout Grit of Derbyshire. It is best developed in the Longnor and Upper Churnet areas. The _R_. _gracile_ band can be seen to overlie the sandstone in the Churnet. _R_. sp. nova has not been found in this area, but in the Blake Brook section it occurs 6 m below the Longnor Sandstone. A marine band overlying the sandstone in the same section has yielded only poor material, suggesting _R_. _gracile_.

The Longnor Sandstone thins from 60 m in Cistern's Clough to 45 m in the Blake Brook. It is probably thicker in the Hollins Hill area. Further south, 33 m of sandstone in the headwaters of the Churnet decreases to some 12 m a mile (1.6 km) further south. The only more southerly representative of the Longnor Sandstone known in the eastern part of the field area is at Meerbrook. Here one might have expected distal turbidites, but the lithofacies is abruptly terminated in a 3 m section of poorly sorted, badly weathered and apparently structureless sandstones. This radical change in a distance of only 1.6 km from the Upper Churnet exposures indicates that the Longnor sandstone is unlikely to be present further south, where R1c protoquartzites are known. It also suggests that the K-feldspathic turbidites were impeded in their flow by the rise of the southern portion of the basin, and possibly by a rising structure, now seen as the Gun Hill anticline (see p.218).

The Longnor sandstone is also well developed in the western part of the field area where investigations of the sequence have centred on the River Dane area near Wincle. Evans _et al_. (1968) indicate the existence of two leaves of K-feldspathic sandstones between _R_. _reticulatum_ and _R_. _gracile_. Sections through R1c in the Minns area are, however, inadequate to determine the full R1c succession, and either one or two R1c sandstone units could exist. Evans _et al_. (1968, p.51-52) suggest that two sandstones exposed in a stream section near

Pot Lords are both in R1c. They indicate that these sandstones die out southwards, and that the Upper Shell Brook section is "almost wholly a shale sequence". The Longnor sandstone is in fact well exposed in this section, and in the River Dane. A comparison of the sublithofacies of the Longnor sandstone and the R2a sandstone of the River Dane with the two sandstones at Pot Lords and Archgreave suggest that the sandstones thought by Evans et al. to be both in R1c could well be in R1c and R2a. No R2 sandstones are indicated in the generalised sections of Evans et al. (1968, p.17 and 58) although $R2b_i$ sandstones are mentioned in the text.

R. sp. nova is unknown in the western part of the area, and the position of the R1c sandstones can only be defined by R. gracile and a marine band with R. reticulatum (Evans et al. 1968, p.52). It seems likely that R. sp. nova underlies the R1c sandstone exposed in the Dane section, however, as the sandstone is of comparable thickness to that of the Longnor sandstone in the eastern area, and is overlain by R. gracile. The Swythamley section to the east of the Dane is the only area where a sub-Longnor sandstone unit definitely occurs (Appendix Figure III). The 15 m of shales which separate the 5 m unit from the Longnor sandstones contain, near their top, silty calcareous nodules, similar to those found in the R. gracile marine band in the Dane. Elsewhere, such nodules have also been associated with quasi-marine shales, eg. the Blake Brook. The Swythamley nodular horizon may, therefore, be at the position of Butterly.

At the western margin of the basin, the sandstones are absent where the R1 succession thins at Congleton Edge. Further to the south-west at Bowsey Wood (near Betley) a borehole proved only Yeadonian (Gastrioceras cf. cancellatum) at a contact, thought to be unfaulted, with the Dinantian Limestones (Earp, 1961), thus establishing the positive nature of this limestone area which had an effect on the distribution and nature of deposition of the Namurian sediments.

As noted by Evans _et al_. (1968), the R1c K-feldspathic sandstones are absent in the area of Congleton and Lask Edge, and there is no indication of the lithofacies until the deposition of the Roaches Grit. A similar situation is apparent on the flanks of Lask Edge in the section of Dingle Brook. High R2b sandstones beneath the Roaches Grit, and separated from the $R2b_i$ sandstones by a thick shale leaf, are, however, present in the River Dane section, this area locally accumulating a thick sequence of K-feldspathic sandstones, while the Lask Edge and Gun Hill areas received only pelitic sediments.

Exposure around Gun Hill is poor in R1 and R2a, but a section at Fairboroughs Wood, to the east of the Dane, indicates that in a distance of only 1.9 miles (2.8 km) the R1c-$R2b_i$ sandstones have lensed out. The K-feldspathic sandstones immediately underlie the _R. bilingue_ marine band in the River Dane, but are absent in the Fairboroughs Wood section where 10 m of siderite and shales are exposed. The section between $R2b_{ii}$ and R1b is faulted, but it seems unlikely that 117 m of sandstones and shales, present in the Dane between _R. bilingue_ and the base of the Longnor Sandstone, could have been faulted out to leave only shales exposed. A loose bullion has also been found in the stream section, and was found to contain a microfauna (radiolaria and sponges) and large goniatites typical of the _R. bilingue_ early form marine band bullions where sandstones are absent in the local area (eg. DingleBrook). This supports the conclusion that K-feldspathic sandstones are absent in the Fairboroughs section. No sandstones are seen until some distance above _R. bilingue_ where the first sandstone probably represents the Roaches Grit.

Although the Longnor Sandstone is well developed in the Churnet Valley, the R2a-R2b_i succession appears to be thin compared with that of the River Dane. Around Longnor, sections through R2 are poor, but sandstone units in R2, eg. around Sheen Hill, are probably thicker than in the Churnet Valley. These R2 sandstones may be only local in their extent as the R2 sandstones in the Brund Boreholes, just to the west of Sheen Hill, are only a few metres thick. Below _R. bilingue_ sandstones and shales are only 6 m thick, and below _R. bilingue_ early form only 5.4 m. Thin sandstones outcrop in the headwaters of the Churnet, but are soon replaced by only siderite nodules.

CONCLUSIONS

During the Upper Kinderscoutian and lower Marsdenian, the North Staffordshire area could be basically divided into two -- an eastern area around Longnor and the Upper Churnet Valley and a western area centred on the River Dane. The major development of sandstones was restricted to R1c in the east, R2a-R2b_i sandstones consisting of only thin units, compared with the thick sequence of R1c-R2b_i turbidites in the west. The southerly extent of the sandstones was limited in both cases perhaps by the rise of the southern portion of the basin (p.215) and, in the case of the eastern area, by the continued deposition of the protoquartzites until R2b. No protoquartzites are known in R1 in the area of the Dane and the Minns. K-feldspathic sandstones seem not to occur around the Gun Hill anticline (eg. Meerbrook and Fairboroughs), suggesting that this structure may have already been exerting some degree of influence on the distribution of sediments at this stage. The distribution of the sediments may, of course, be fortuitous but there is also some evidence to suggest that the Biddulph syncline (and the corresponding anticlinals of Lask Edge and Congleton Edge) later, to some degree, controlled the deposition of the Rough Rock (C.W. Heath, personal communication). A degree of uniformity appears to have been imposed by the development of the Roaches Grit (R2b) which formed a continuous, if variable, sheet of K-feldspathic sandstones over the whole of North Staffordshire.

CHAPTER IV

SEDIMENTOLOGY OF THE PROTOQUARTZITE AND K-FELDSPATHIC LITHOFACIES

THE K-FELDSPATHIC LITHOFACIES

PREVIOUS WORK ON NORTH STAFFORDSHIRE

The North Staffordshire and Derbyshire succession was described in the nineteenth century by Farey (1811) and Hull and Green (1864). Because of the complex diachronous sequence of sandstones in the Namurian basin, and absence of knowledge of the goniatite faunal succession at that time, the usefulness of accounts published in the nineteenth century is extremely limited.

Hull and Green (1864) noted that, "Farey, in his account of the Yoredale Rocks, mentions what he calls three 'anomalies' as occurring in them: a bed of fine sandstone, the Shale Grit; beds of hard cank-like sandstone; and thin beds of dark blue or black limestone". Hull and Green used these three "anomalies" to distinguish their three divisions as set out from their text below:

A. Shales with a thick bed of sandstone (the "Shale Grit" of Farey), and perhaps a few thin limestones.

B. Sandstones, for the most part thin-bedded and close grained with black shales. This group we shall speak of as the "Yoredale Quartzites".

C. Black shales, with thin, black, earthy limestones towards the bottom.

Their upper division contained a thick bed of sandstone having more affinity with the "Millstone Grit" than the siliceous rocks of the second division. This particular sandstone unit was called the Yoredale Grit and equated with the Shale Grit of Farey, although Farey did not precisely define his term "Shale Grit", and correlated beds of different ages, possibly in simply describing a lithology rather than a particular unit (Morris, 1966b).

The sandstone unit now known as the Longnor Sandstone was first recognised by Hull and Green (1866) in the Sheen Hill area and referred to as the "Longnor Grit". These authors suggested that this sandstone was their "Yoredale Grit", and presumably thought that this sandstone underlay the Kinderscout Grit, at the base of the "Millstone Grit" succession (Hull and Green, 1866, p.247).

The term "Farey's Grit" was introduced by later authors to name sandstones as low as E in the Thorncliff succession (see Morris, 1966b for discussion). Challinor (1921) also suggested that the term "Farey's Grit" for Hull and Green's "Shale Grit" was not valid, partly because he was, ". . . unable to find a continuous band of 'grit' in the position of Farey's Grit". Challinor was in fact familiar with an area where the Longnor Sandstone does not form a feature, and rapidly dies out to the south of the Churnet. Lenticular proto-quartzites in the Upper Churnet area (at Drystones) might well have been taken as a discontinuous "grit". Challinor (1924) also stressed that in Farey's original description (1811) "grits" occurred within the shales with black limestones ("Shale-Limestone") beneath the Millstone Grit, immediately beneath the Coal Measures. Farey's Grits were therefore never intended to be a dividing line, although used in this sense by Hull and Green.

The "Longnor Grit" was again referred to by Hudson (1930), and assigned to the Kinderscout Grit group. He also pointed out that the pre-Namurian topography (Viséan) of the Massif limestones was still in existence prior to the deposition of the "Longnor Grit" (ibid. p.62).

The "Longnor Grit" was assigned to the Upper Kinderscoutian (R1c) by Bisat and Hudson (1943, p.433), who correlated the Grit with the

Mam Tor Sandstone and Parsonage Sandstone, although (ibid. p.391), its stratigraphic position could not be located with any accuracy as a marine band immediately above the sandstones was unknown. The record by Challinor (1929) of a fossiliferous locality (Challinor's loc. S 16) in the Upper Churnet was in fact in a position now assigned to R2b and overlying the Longnor Sandstone, but the sandstone was not remarked upon in this area. Hester (1932) also identified the R2b fauna and noted a "Fourth" and "Fifth Grit" between R. bilingue and R. reticulatum, above quartzitic sandstones.

The more appropriate name Longnor "Sandstone" appears to have been intoduced by Hudson (1945a, p.320 -- for Farey's Grit or the Fifth Grit) for the lowest constant sandstone underlying Hull and Green's first Millstone Grit members. The sandstone was used to indicate the top of the Churnet Shale succession which extended as high as R1c (see below).

Holdsworth (1963a) recognised the true position of the Longnor Sandstone in the succession. It occurs above R. sp. nova, this form occurring in a position ". . . 5' 8" above the Main Leaf of the Kinderscout Grit -- that is between the Lower and Upper Kinderscout Grits . . ." of Derbyshire. A marine band above the R1c sandstone unit in the Blake Brook was identified by Holdsworth (1963a, p.154) as that of R. bilingue early form, but is now known to be that of R. gracile, confirming Holdsworth's conclusion that the Longnor Sandstone is equivalent only to the Upper leaf of the Kinderscout Grit. Evans et al. (1968) have also discussed the K-feldspathic lithofacies in the western area around the River Dane (p. 215).

The term "Churnet Shales" has frequently been used in the description of the North Staffordshire succession including, within the type area, the succession between the "Morridge Grits" (Challinor, 1929) and the Roaches Grits. The term was originally introduced by Hester (1932) for the succession between the above lithological units, and was designed to replace the term "Pendleside Series" of Hind (1901). Hester redefined the Pendleside Series to refer only to the limestones and grit at the top of the Lower Carboniferous of Lancashire.

The term "Churnet Shales" was subsequently modified by Hudson (1945a), who placed the top of the unit at the base of the Longnor Sandstone (R1c), as this sandstone is more persistent than had previously been recognised. Morris (1969) failed to recognise that the Longnor Sandstone is present in the Upper Churnet. He therefore concluded (ibid. p.157) that Hudson (1945a) was not justified in lowering the top of the Churnet Shales to the base of the Longnor Sandstone, rather than defining the shale unit by the base of the Roaches Grit as ". . . there is no evidence for the presence of either Farey's grit or the Fifth Grit". Fieldwork by the author (Holdsworth *et al.* 1970) and Francis (1967) shows, however, the existence of an R1c sandstone in the Upper Churnet, overlain by *R. gracile*.

Evans *et al.* (1968) had already redefined the top of the shale unit by the *R. gracile* marine band as this fauna is easily recognised, and the Longnor Sandstone soon dies out to the south of the Upper Churnet Valley. As pointed out by Holdsworth *et al.* (1970), "a 'Churnet Shales' unit is a reality in only one stream section", which still does not expose the complete faunal sequence. The author prefers to use the term "Churnet-Manifold Group" (Holdswcth 1966a, Holdsworth and Trewin 1968, Holdsworth *et al.* 1970) and abandon the terms "Thorncliff Sandstones" and "Churnet Shales". The Churnet-Manifold Group extends from a persistent sub-*Cravenoceras malhamense* protoquartzite unit (unit A, Trewin, 1969) up to the onset of Holdsworth's phase 3 (ie. the K-feldspathic sandstones), and is therefore a lithological unit incorporating the whole of the local phase 2 protoquartzites.

DESCRIPTION OF THE K-FELDSPATHIC LITHOFACIES

The succession described extends from extremely thin sandstones, possibly equivalent to the Main Leaf of the Kinderscout Grit, up to the sandstone unit immediately preceding the R. bilingue marine band. The succession is so well exposed from $R1c$–$R2b_1$ in the Western area that it has been possible to recognise minor rhythms within a turbidite unit between two marine bands. Such sandstone units have been referred to as "megarhythms" and these have been numbered as set out in Figure 4.A.

In the division of the K-feldspathic lithofacies into sublithofacies it was found that certain of the sublithofacies were clearly related to one or other of the two main areas of deposition of the sandstones, although some of the sublithofacies occur in both areas. These areas have been referred to as "Eastern" and "Western". This distinction is made partly because of the nature of the exposure -- the main outcrops of sandstones occurring in an Eastern region around Longnor and the Churnet Valley and in a Western area around the River Dane -- and partly because of the original area of deposition of the K-feldspathic lithofacies. It is likely that the turbidites of this lithofacies were deposited in the form of two main lobes, the extent of which were limited by the slopes of the southern portion of the basin, and possibly by a structural high within the basin, related to the present structure of the Gun Hill anticline (p.218). These two main areas of deposition also tend to be characterised by different sublithofacies.

All sandstones of the K-feldspathic lithofacies in the area covered are turbidites. A comprehensive picture of the extent and development of the lithofacies cannot be made as exposure is limited particularly in the Western area, and there is little indication of the distance of the area of deposition of the beds from source. The epithets "proximal" and "distal" when applied to the Western area, are therefore used in inverted commas to refer to features which, in better documented areas, have often been found to occur in more and less proximal environments.

It became apparent, especially in long field sections, that a simple two-fold division into proximal and distal sublithofacies would be inadequate to describe the whole sequence. Seven sublithofacies were therefore distinguished. These were first determined on a visual basis, by recognition of distinctive groups of beds from logs of the turbidite succession (Appendix Figure IV). Sandstone:shale ratios were found to correlate with average bed thickness for sublithofacies (fA)-(fE). Sole casts and internal structures often associated with more and less proximal environments also correspond with higher and lower sandstone:shale ratios.

In the description of the sublithofacies, the letter "f" has been used to denote the K-feldspathic nature of the sediments ("p" is used for the protoquartzite lithofacies). The letter "f" is suffixed by the letters A to G to indicate the distal or more proximal characteristics of the sediments.

The succession in the Western area is characterised by sublitho-facies (fA) to (fD), and the Eastern area by (fE) to (fG). (fA) and (fC) occur in both areas but are quantatively unimportant in the Eastern succession, and have been described in the part on the Western area where the typical sections have been taken.

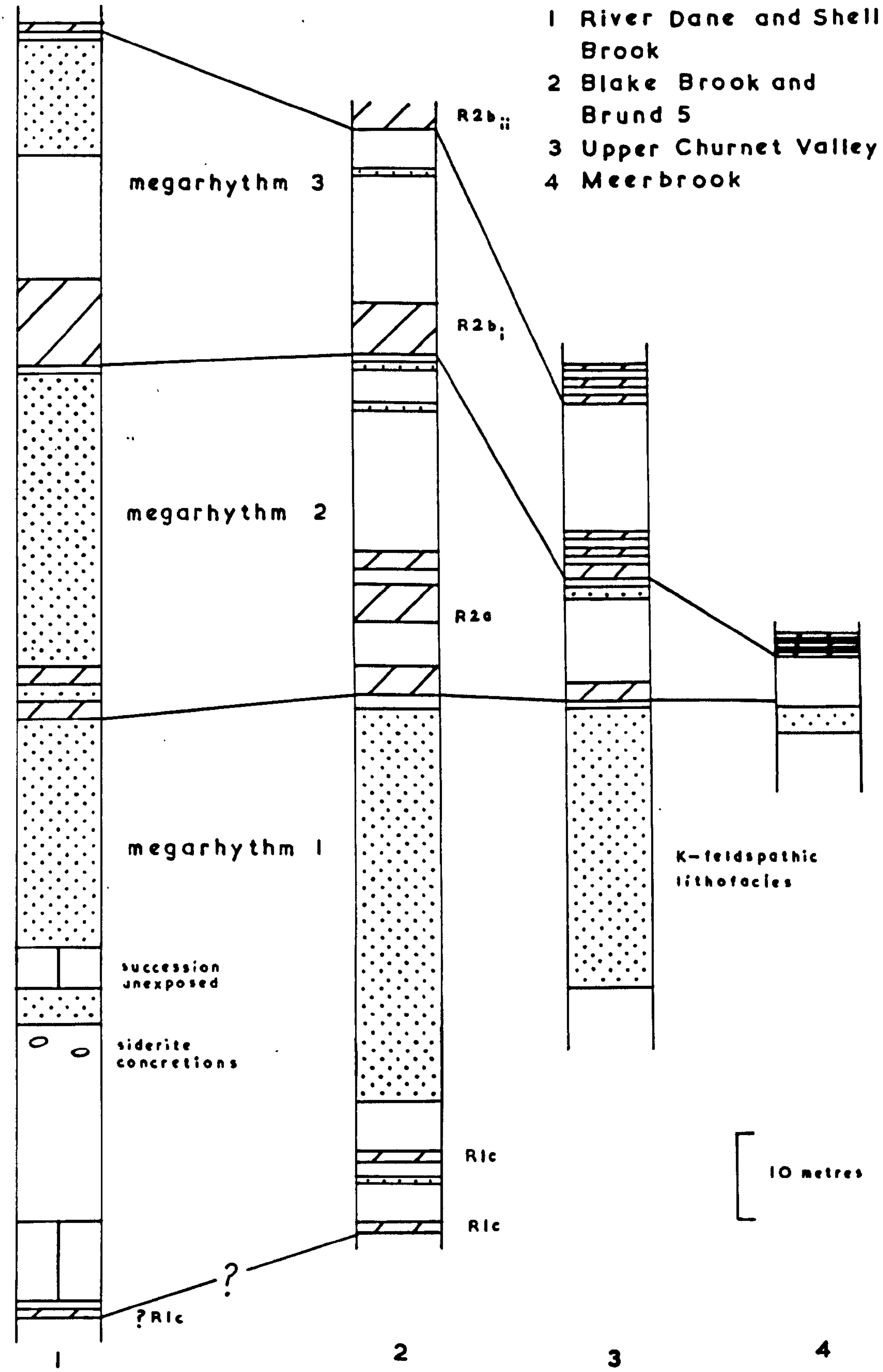
LIMITATIONS OF EXPOSURE AND MATERIAL

In the Western area around the River Dane, description of the sublithofacies has largely been drawn from a single section which extends from R1c to R2b. Although the section shows the relationships of successive sublithofacies, and illustrates the rhythmic development of the sediments, little is known of the variations across the full areal extent of the sandstones. In contrast to the Western area, sections in the East tend to be short but are scattered over a larger area of the sandstones so that it has been possible to note some of the lateral changes in the sandstones.

Preservation of the sandstone beds where a calcite or siderite cement is poor or absent is extremely bad. "Silty shales" overlying calcite-cemented sandstone beds might contain d- and e-division beds and, in badly weathered sections, even b- and c-divisions (Bouma, 1962). Few clean, water-washed surfaces are available to study the structures of the more pelitic beds between the sandy beds, and observations and measurements have been confined to the well-cemented portions of the sandstones. In the few cases where the structures of the intervening shales could be observed several layers of thin, parallel, light-coloured laminae were seen, and also wispy laminae (possibly convolute or ripple lamination). The minor structures and grain size of the "shale" beds would be expected to change from the more distal to the proximal sublithofacies, and it is unfortunate that such changes could not be related to the distinguishing criteria of the sublithofacies.

Figure 4.A

CORRELATION OF THE K-FELDSPATHIC SANDSTONE UNITS



K-FELDSPATHIC LITHOFACIES -- THE WESTERN AREA

SUBLITHOFACIES (fA)

Brief diagnosis. Thin (4 cm) siderite-cemented beds with d- and e-divisions. The sandstone:shale ratio is low.

Typical section. River Dane, base of megarhythm 1 (Longnor Sandstone, Figure 4.A).

Description of the typical section and interpretation of sedimentary structures

In the field, the turbidites appear as parallel-sided, continuous beds of siderite interspersed, higher in the section, with disrupted contorted beds. Siderite concretions are found between parallel-sided beds near the base of the section, but are most common in the shales underlying the rocks interpreted as turbidites. These lowermost concretions probably correspond with lateral equivalents of the K-feldspathic sandstones in areas to the north (North Derbyshire) where the Longnor Sandstone equivalents are thicker.

Faint lamination in the siderite concretions is probably the normal background shale lamination preserved because of the cement. In contrast, the continuous siderite beds appear to be structureless. A few show (in thin section) basal, paler, quartz-rich laminae which can be slightly contorted. These laminae are thought to represent the d-division of Bouma and the overlying structureless part that of e -- pelagic clay. Unlike the faintly laminated siderite concretions, the e-division also contains dispersed angular grains of quartz which become smaller and less abundant upwards. These grains and the clay of the e-division were probably derived from the turbidite flow rather than the continuous clay sedimentation which produced faint laminae with no visible quartz.

Additional evidence for origin of these beds from turbidity currents is the occurrence of hieroglyphs, or trace fossils, on their soles (Plate 4.1a). These small, pre-depositional, unroofed burrows are reminiscent of the regular pattern of Palaeodictyon (Seilacher, 1962). The arrangement here may be fortuitous.

The contorted beds occur as isolated blocks of siderite at specific horizons. They probably formed from the plastic flow of sediment and disruption of an originally continuous bed. These blocks or pseudo-nodules consist of d- and e-divisions and probably background shales which have been isoclinally folded (Plate 4.1b). Faulting within the folded beds is absent, but movement during the formation of the structures may have been accommodated by some slip on the hinges of the isoclines where the sedimentary laminae are streaked out at right angles to the original bedding. The absence of small faults points to the early formation of the structures when the material was still plastic and easily deformed. Siderite may have started to precipitate at this stage and aided in the cohesion of the beds, although the abundance of pelitic material may have been sufficient.

Deformation of the sediments is confined to these single-bed, pseudo-nodule horizons in contrast to series of contorted beds in proximal environments thought to have had high gradients (Ksiazkiewicz, 1958). These (fA) deformed beds are probably similar to slumped beds in distal turbidites described by Lovell (1969) where the slumping was attributed to the types of disturbances which would not necessarily affect coarser grained sediments. Archangualsky (1930, in Dzulynski and Slaczka 1958, p.222) also found that gliding of sediments can take place on slopes of 1^{o}, but this figure is more comparable with the slopes of the Mississippi delta (Shepard, 1956) than sea floors associated with distal turbidites.

Because of the thin nature of the beds and the occurrence of d- and e-divisions, (fA) siderites are thought to represent distal turbidites which were occasionally strong enough to unroof small burrows. It is unlikely that any of these features would have been found if the beds had not been siderite-cemented; the exposure would otherwise have been noted as silty shales.

Proportion of siderite-cemented beds to shale

In the typical section of 7.4 m of shales with siderites, a total of 20 cm of siderites in continuous beds and five nodule and pseudo-nodule horizons occur. These five horizons are approximately equivalent to a further 20 cm of siderite. The proportion of distal turbidites to shale is very low, approximating to 1:18.5.

Comparison of sublithofacies with other sections

A related sublithofacies has also been assigned to (fA) as, although the internal structures of the beds do not compare exactly, the siderite cement of the beds and their position (at the base of the K-feldspathic sandstone sequence), link the two. In a section adjacent to the River Dane (Swythamley), the sub-Longnor Sandstone unit shows beds up to 8 cm thick. These are cemented by siderite which replaces plagioclase feldspar and quartz and grows over abundant carbonaceous material. A crude parallel lamination is retained despite the extensive sideritisation of the beds. Sole marks are absent. As in sublithofacies (fA) in the typical section, siderite nodules occur between turbidites and this feature, as well as the position of the sublithofacies, establish the basic similarity of the two units. Continuous siderite beds are also seen at the base of the Longnor Sandstone in Shell Brook.

Siderite beds and nodules can occur interbedded with sublithofacies (fC) and (fD) sandstones and also occur in the Eastern area interbedded with sublithofacies (fE) turbidites. Developments of typical distal turbidites are rare in the Eastern area, but a sublithofacies similar to (fA) occurs in a dominantly shale sequence lower in R1c. In the Blake Brook, the sublithofacies is represented by continuous siderite beds, nodules and thin sandstones in a pre-Longnor Sandstone unit. No pseudonodules have been found, but the thin siderite and mixed carbonate-cemented convolute sandstones in the Blake, and in Brund Borehole number 11, illustrate the succession's similarity with (fA).

SUBLITHOFACIES (fB)

Brief diagnosis. Siderite-cemented sandstones, 8-15 cm thick, with b-, c- and d-divisions. Rarer calcite-cemented beds, up to 42 cm thick, occur interbedded in the sequence. These are badly weathered; they may contain a-, b- and possibly c-divisions. The sandstone: shale ratio is 1:3.6 in the typical section of 5.2 m. Average bed thickness is 12 cm.

Typical section. Archgreave. The section cannot be accurately located stratigraphically but the lower part of the section exposed is thought, from lithological comparisons with the River Dane and Shell Brook, to be the Longnor Sandstone, R1c.

Description and interpretation

The siderite-cemented beds are thicker than those developed in sublithofacies (fA). No pseudonodules occur. Some beds show irregular lenticular expansion up to 14 cm thick from a minimum bed thickness of 8 cm -- possibly the original thickness of the bed. The undulating base of the bed is unlikely to have originated from scour

Plate 4.1a

Unroofed burrows on the sole of a siderite-cemented d/e-division turbidite.

Sublithofacies fA, megarhythm 1, River Dane, loc. 168

Plate 4.1b

Pseudonodule of folded thin turbidite and shales, cemented by siderite.

Sublithofacies fA, megarhythm 1, River Dane, 168

Plate 4.2a

b/c-division sandstone with convolute layers, cemented by siderite. Section cut obliquely to direction of current flow. Distorted ripples can be seen in the synclines of the convolutions, and anticlines are truncated.

Sublithofacies fB, Archgreave, 170

Plate 4.2b

b-division in the sandstone is followed by convolute laminae. The faint laminae and structureless upper part of the bed are probably d- and e-divisions.

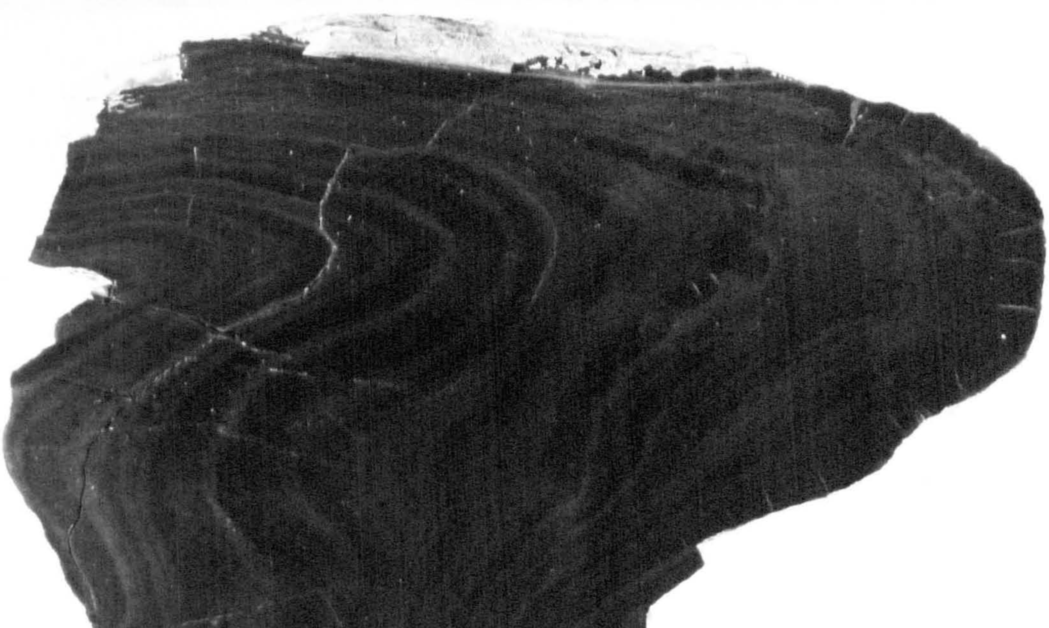
Sublithofacies fB bed, Archgreave, 170

Plate 4.2c

Base of fB bed, Pl. 4.2a. Scattered unroofed burrows and burrows originating from a node. Striations on the sole indicate the orientation of current flow.

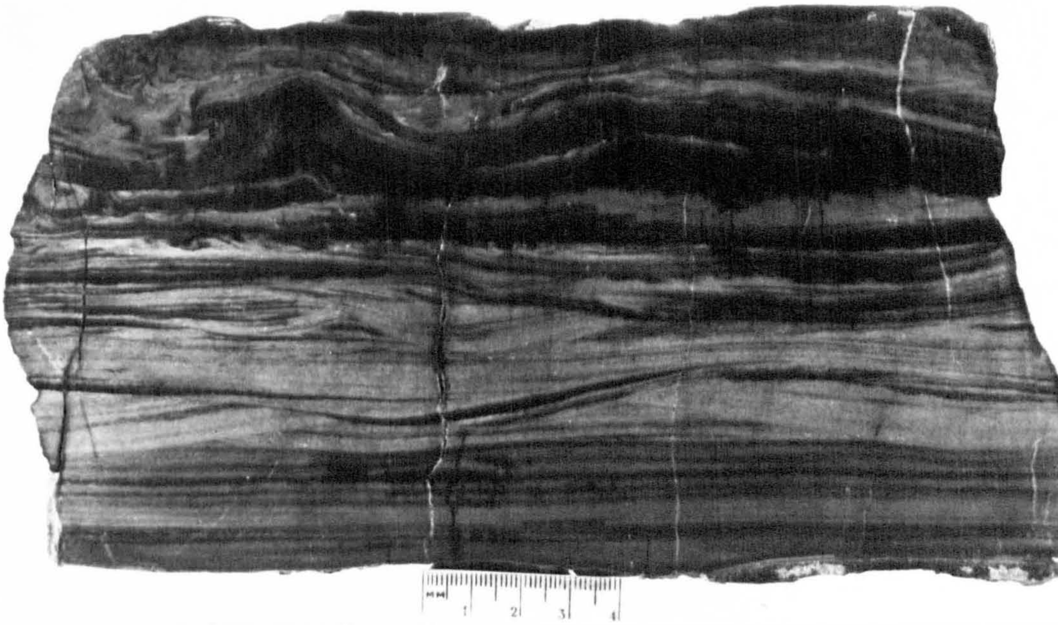
Pl. 4.1

a

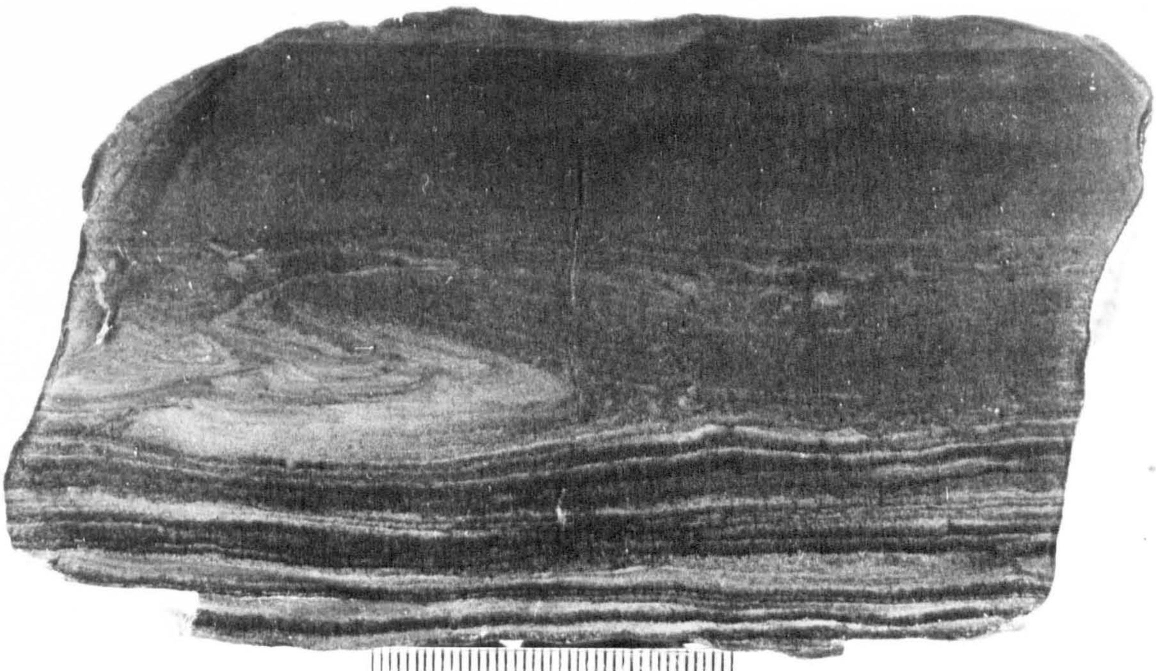


b

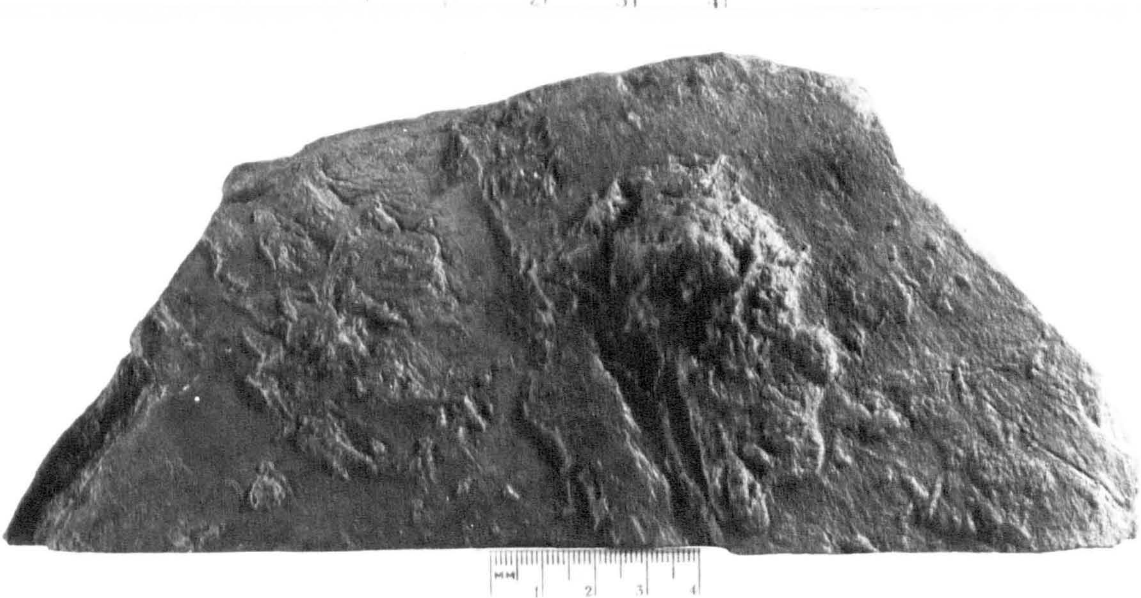
Pl. 4. 2



a



b



c

action because the downward curves of the base are matched by expansion of the top. These lenses could have been caused by irregular precipitation of the cement.

Although d- and e-divisions can be found in the siderite-cemented beds, these are less common than b- and c-divisions and convolute layers. In one example (Plate 4.2a), b-laminae are cut by migrating ripples (seen in section, approximately transverse to the direction of current flow). The two most distinctive convolute layers show the formation of anticlines, in pelitic material, up to 1.5 cm in height with load-casting of the quartz-rich synclines. Anticlines are sharp crested and can be truncated. Laminae in the cores are more disturbed than the outer layers but synclines are broad and shallow and the pelitic material here undisturbed. Ripple-laminae also occur in the quartz-rich synclines. Load casting associated with the less cohesive layers (with distorted ripples) and adjacent anticlines in pelitic material indicate that the convolutions formed in the manner described by Sanders (1960), which allows for the formation of several syn-depositional convolute layers within a bed.

In another example, convolute lamination may have formed by lateral movement (Plate 4.2b). Convolutions between the b- and e-divisions do not appear to be associated with ripples and differential liquefaction and lateral injection of the layers may have taken place as suggested by Williams (1960). Dzulynski and Walton (1965, Fig. 119) suggest that such structures might form simply by the shearing action of the current.

Sole structures of the base of b/e-division beds consist of small striations (prods and bounce casts) and trace fossils (Plate 4.2c). These unroofed tubular burrows, 1-2 mm in diameter, appear to radiate from a central point. The higher relief of the burrows in (fB) beds than in (fA) is probably associated with the greater capacity of the (fB) turbidites to erode the sea bed.

Calcite-cemented beds in the same section are thicker, but internal structures could not be determined. A few thinner (5 cm) calcite-cemented beds consist of b-laminae with round, unroofed burrows on the base of one bed.

Sublithofacies (fB) is intermediate between (fA) and (fC) in that both siderite- and calcite-cemented beds occur. In contrast to (fA), b- and c-divisions are common in siderite-cemented beds, and sandstone:shale ratios are higher than in (fA).

Comparison with other sections

(fB) has not been noted in the Dane Valley but may be present in the unexposed part between (fA) and (fC) in the Longnor Sandstone. Similar siderite-cemented beds occur only rarely in the R1c sandstones in Upper Shell Brook (eg. Plate 4.3a) with (fC) beds. Other examples are unknown.

SUBLITHOFACIES (fC)

Brief diagnosis. The calcite-cemented sandstones have a-, b- and c-divisions. Siderite cement is absent. Thin b-laminated beds occur in the shales between the thicker sandstones. Average bed thickness is 14.5 cm in the typical section and the sandstone:shale ratio is 1:2.

Typical section. River Dane, megarhythm 2, R2a (Figure 4.A).

Description and interpretation

Megarhythms 1 and 2 are separated by calcareous horizons thought to represent the *R. gracile* composite marine band (p.304). Although a marine phase intervenes, sandstones on either side of, and between the two calcareous horizons, are more like sublithofacies (fC) than (fB). An additional feature in this part of the succession is the occurrence of small (4 cm) silty nodules which appear to contain kaolinite vermicules replaced by calcite (Plate 4.3b). Such nodules have also been noted in the Swythamley and Upper Shell Brook sections (though not necessarily at the same horizon) and seem to be associated with the deposition of coarse clastic sediments under marine conditions.

Unlike sublithofacies (fA) and (fB), siderite cement is completely absent in the turbidites. Siderite bands and nodules only occur in the thicker 2.2 m and 2.3 m shale leaves where (fC) sandstones are absent.

Sandstone beds are extremely variable in thickness in (fC). 1-7 cm b-laminated beds are common. Thin laminated beds have been referred to the b-division rather than d since the tool marks (prods and bounce casts) are on a larger scale than those found on the base of d-divisions beds elsewhere. A single example of a 2.5 cm bed showed a rippled top, confirming the identity of the lamination.

Thicker beds, from 10 to 54 cm (few beds exceed 40 cm), can show convolute lamination and other forms of disturbed bedding. In one example, convolute lamination appears to have formed in silty material above a b/c portion of the bed (Plate 4.4a). The rippled division is possibly marked by the lenticular wavy laminae above the b-division, but is not well developed. Its formation could have been suppressed by the pelitic nature of the bed above the b-laminae. The abundance of pelitic material probably aided in the formation of the convolutions. In a vertical section cut parallel to current flow

Plate 4.3a

Siderite-cemented bed with b- or d-division passing up into e-division. The paler, irregular laminae at the top of the bed were probably formed from a later pulse carrying coarser material. Small prod and bounce casts occur on the base of the bed.

Sublithofacies fB bed, near base of Longnor Sandstone, Upper Shell Brook. 171.

Plate 4.3b

Thin section of calcareous nodular bed from thin sandstones between the lower and upper main R. gracile leaves, Upper Shell Brook. The vermicular and tabular crystals may have been kaolinite, often found in the K-feldspathic sandstones (Holdsworth, 1963a), later replaced by calcite.

x55

Plate 4.4a

Calcite-cemented bed showing b-division, poor development of the c-division due to the abundance of pelitic material, and convolutions elongated in the direction of current flow.

Sublithofacies fC, megarhythm 2, River Dane, bed 5. Loc. 168

Plate 4.4b

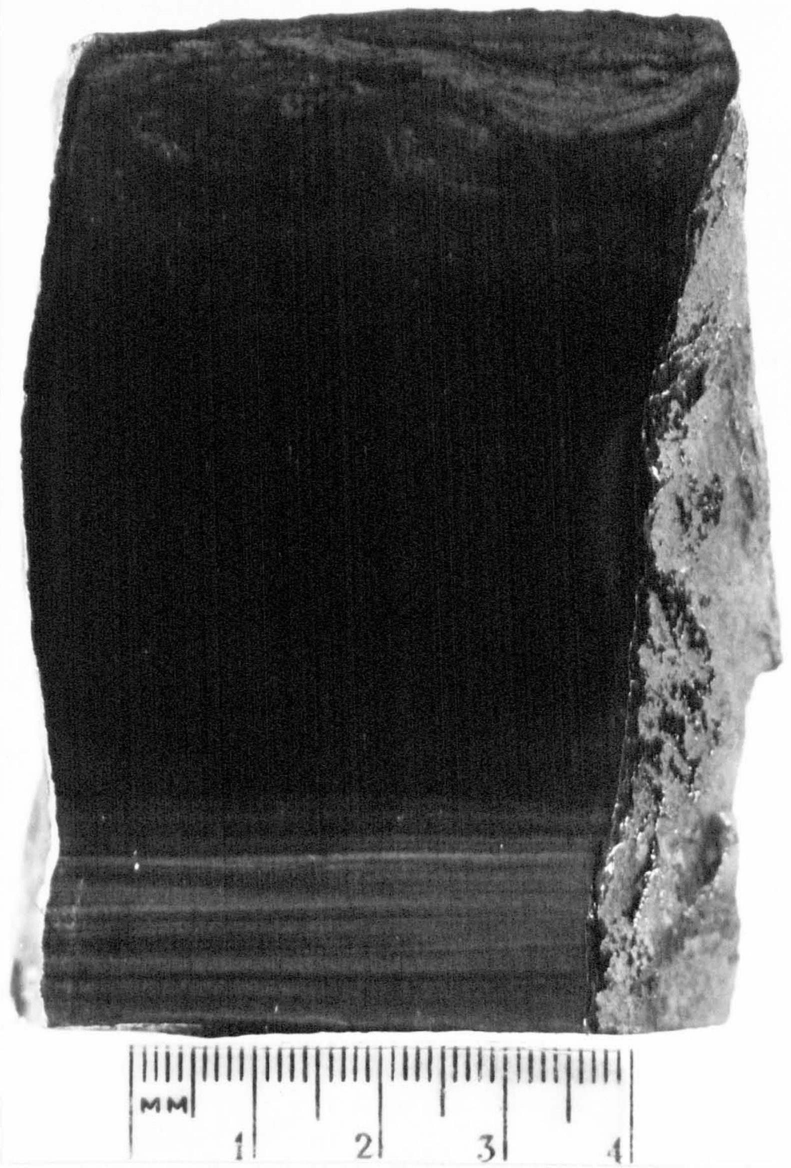
Convolutions of same bed in plan view showing lobes streaked out in direction of current flow (left to right).

Plate 4.4c

Inclined lamination infilling small scour, followed by b-lamination. The sole of the bed shows a polygonal pattern passing into small longitudinal ridges around the scour. Loc. 168

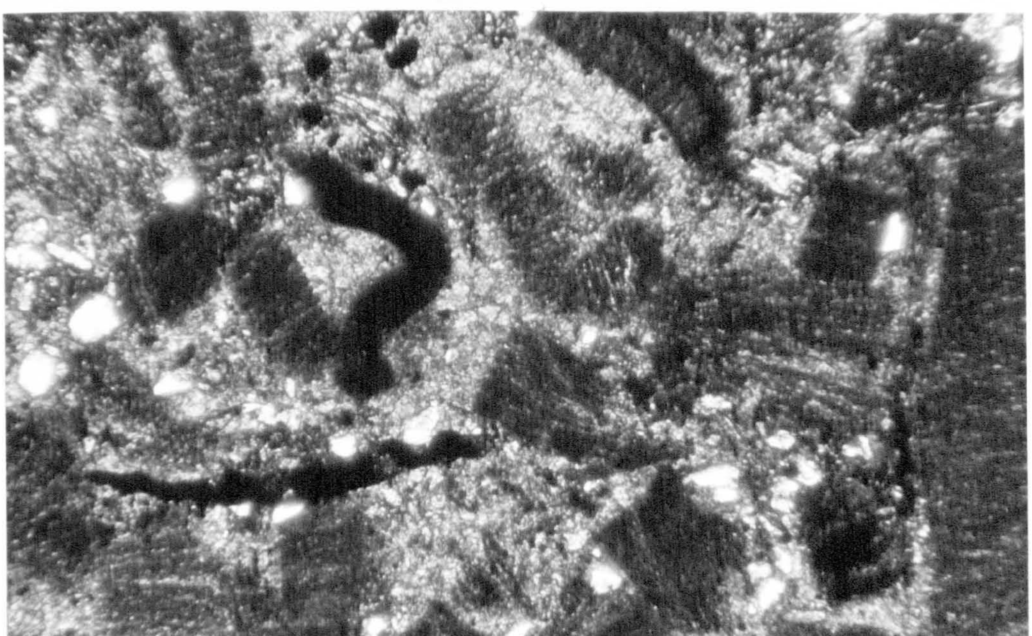
Sublithofacies fC, megarhythm 2, River Dane, bed 12.

Pl. 4.3

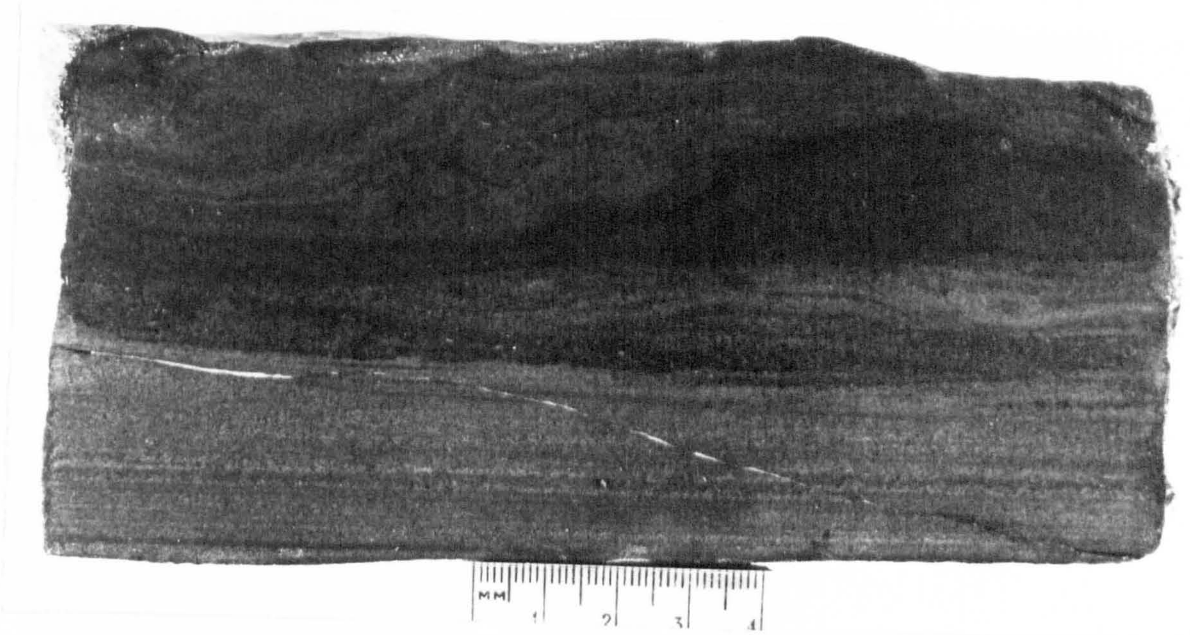


a

b



Pl. 4.4



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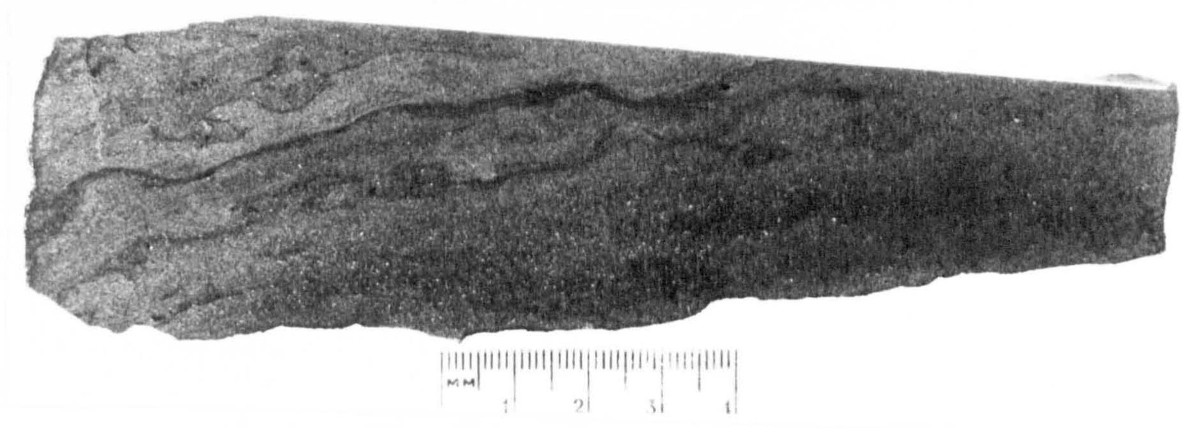

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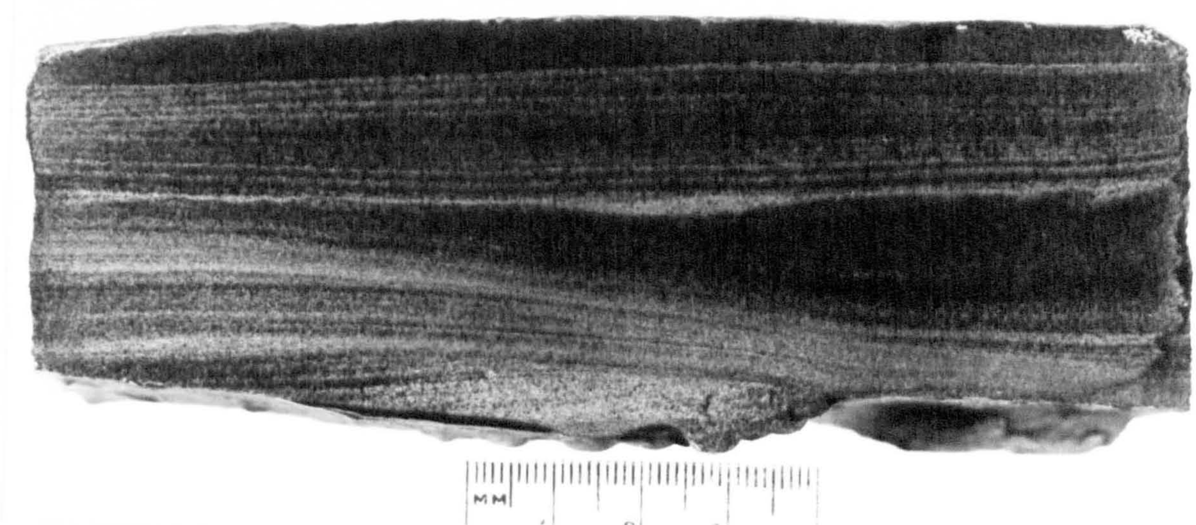


c

Plate 4.5a

a-division bed formed from two flows. The lower part of the bed appears to have been followed by a more pelitic division, subsequently partly eroded by a second flow. Imperfect annealing has taken place. The sole of the bed has eroded thin ?c-division laminae.

Sublithofacies fC, top of megarhythm 1, River Dane, 168.

Plate 4.5b

Sole of fC turbidite showing prod and bounce casts. The small tool which formed the bounce cast on the right was rotated, leaving a thickened part on the bounce cast, before returning to the current. Current flow from right to left.

Upper part of the Longnor Sandstone, Upper Shell Brook. Below R. gracile, loc. 109.

Plate 4.6a

Sublithofacies fD turbidite showing load casts on base of a-division bed. The load casts may be elongated in the direction of current flow. Coarser grains are concentrated on the base of the bed.

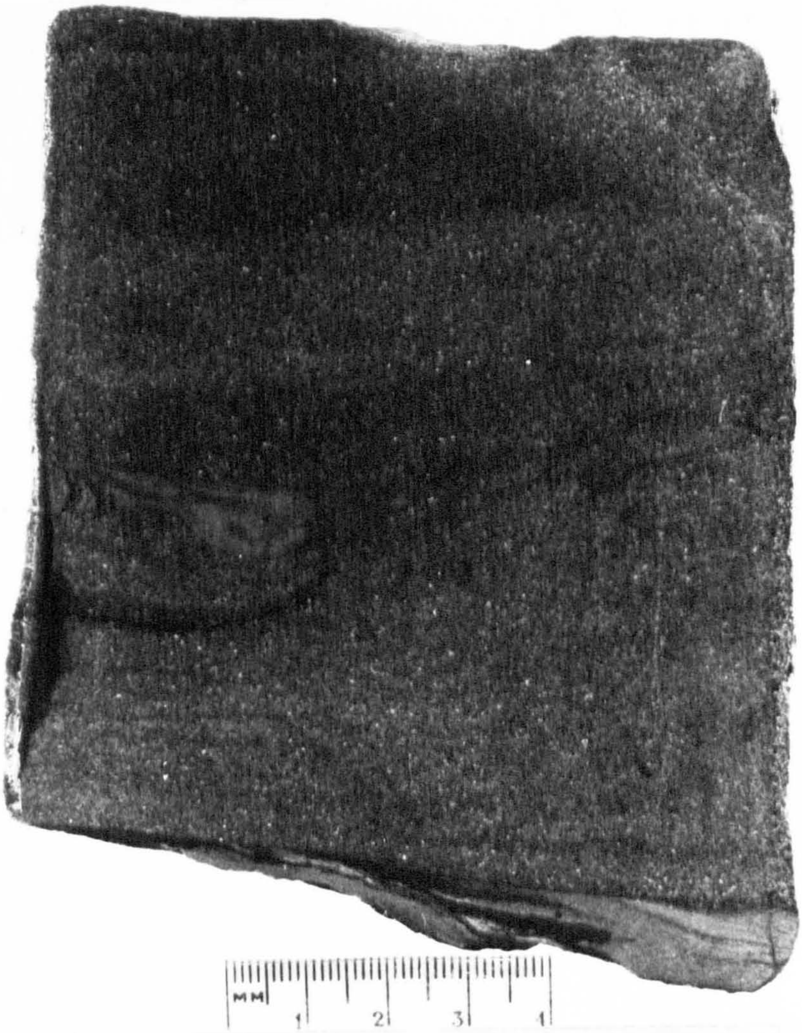
Sublithofacies fD, megarhythm 2, River Dane, bed 36. Loc. 168.

Plate 4.6b

The lower graded a-division passes upwards into poorly laminated beds then convolute lamination. Some of the convolute, quartz-rich laminae appear to have been thickened by ripple load casting.

Megarhythm 3, River Dane, 168.

Pl. 4.5

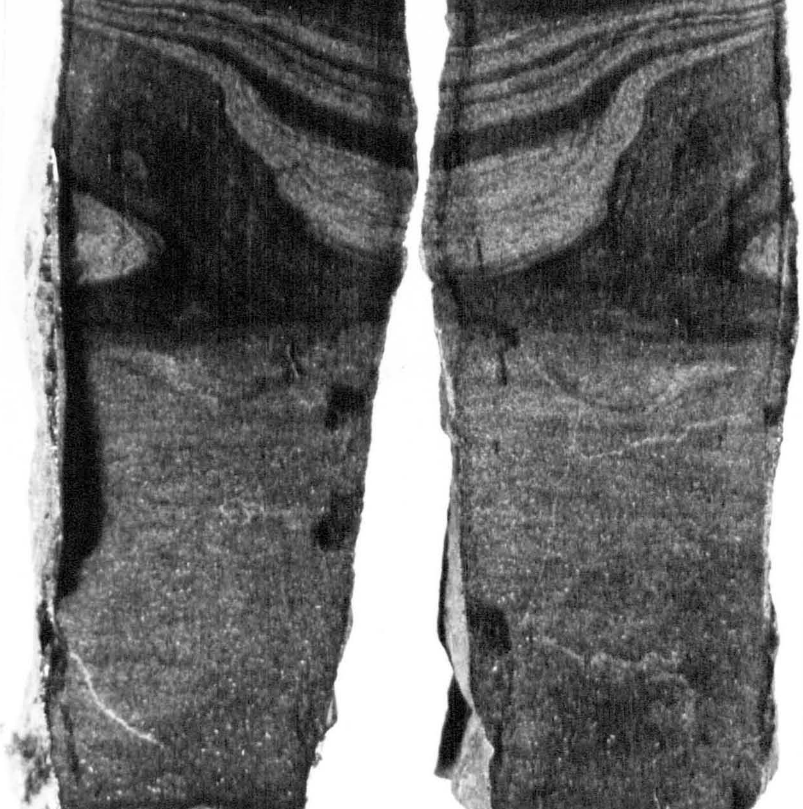


a

b

a

Pl. 4 6



b

(Plate 4.4a), the disturbed laminae form an elongated depression. A section in plan view (Plate 4.4b) also shows an elongated form with secondary lobes stretched out in the direction of current flow. The form of the convolute layers suggests that their origin is related to organisation of current flow capable, in cohesionless material, of forming longitudinal ridges (Dzulynski and Smith, 1963). That current flow capable of forming L-ridges within a sandstone bed could have existed is shown by the L-ridges found on a parting surface within an a-division of another sandstone. It therefore seems possible that "longitudinal threads of turbulence" (ibid.) could cause convolutions in cohesive sediments in a manner similar to that described by Sanders (op. cit.). Some of the thicker (fC) sandstone beds may have been formed from several flows -- either independent currents, or pulses of the same current, carrying different material. One bed (Plate 4.5a) shows an a-division turbidite eroding a thin bed. One part of the a-division appears to have formed from a single flow, the other (left-hand side of the plate) shows that perfect annealing has taken place. The a-division appears to pass upwards into more pelitic material which has been contorted by the passage of the second flow. The pelitic material is unlikely to be a soft, distorted shale pellet.

As can be seen from the preceding comments, a-divisions occur but e-divisions are no longer seen in the cemented portions of the beds. a- and b-divisions are the most common Bouma "intervals"; the paucity of c- and d-divisions may be because of the poor cementation of the sandstones. c-divisions have only been found in a few cut specimens (Plate 4.4c), where inclined laminae have formed around an irregularity.

Bounce and prod casts are characteristic sole marks (Plate 4.5b). A strong grain orientation is present on the base of some beds in areas where tool marks are absent. Tool marks tend to be larger than those observed in (fB) beds and large groove casts also occur, particularly towards the top of the (fC) section.

Comparison with other sections

Sublithofacies (fC) sandstones have been noted in several other short sections. They occur in the upper part of the succession at Archgreave above sublithofacies (fB) beds, in sections through the Longnor Sandstone in Upper Shell Brook and in a sandstone unit thought to be the Longnor Sandstone in a much faulted tributary section to the Dane at Bearda Mill.

In the Eastern area, no typical development of (fC) has been noted. Rare sandstone beds, similar to those of (fC), occur with (fE) sandstones and shales in the Upper Churnet. Bed thickness in these sandstones does not exceed 8 cm. Grading is well developed in the a-division and the b-division also occurs in the cemented part of the bed. Soles usually show bounce and prod casts. These beds with more "distal" characteristics are, however, quantitatively unimportant in the Eastern area.

SUBLITHOFACIES (fD)

Brief diagnosis. Calcite-cemented sandstones with only a- and b-divisions and scour marks rather than tool marks. No siderites occur except in one thick shale leaf. Sandstone:shale ratios increase to 1:1 and average bed thickness is 27 cm.

Typical section. River Dane, upper part of megarhythm 2.

Description and interpretation

Sublithofacies (fC) passes upwards into a sequence of shales and thicker sandstones showing more "proximal" characteristics than those of the lower part of the succession. Bed thickness increases to an average of 27 cm compared with 14.5 cm in (fC). Thin b-division beds occur more rarely. b-divisions are relatively rare in the thicker sandstone beds and c-, d- and e-divisions are unknown. Grading within the a-division is usually well developed and is shown by a decrease in the size of the larger quartz and rare feldspar grains and an increase in the clay content upwards. Plant debris and micas increase at the expense of detrital quartz.

The climax of the megarhythm is in (fD) beds and is marked by the thickest sandstones, in some cases obviously annealed. Mud-flake partings have been noted in some (fD) sandstones only 9 cm thick and also in the upper 22 cm of a 52 cm bed where a crude lamination occurs due to abundant rafted plant material and mud-flakes.

Tool marks are uncommon as sole casts. The most common type of sole casts are broad, shallow, parallel L-ridges (60 cm x 5 x 1) which cover the whole lower surface of some sandstones. Such structures were originally described as load casts (Kuenen and Prentice, 1957), "elongate flute casts" (Kuenen, 1957) and "Load cast striations" (ten Haaf, 1959). Experimental evidence (Dzulynski and Simpson, 1966, and Dzulynski, 1966) has shown that L-ridges form in a convecting medium (where a fluid of lower density is overlain by a fluid of higher density) subjected to forward movement. Two helicoid spirals of movement result producing a scouring effect in essentially laminar flow, thus explaining the absence of tool marks on the base of these beds.

Evidence of scour caused by more turbulent motion is rare. Flute casts occur only as isolated examples and only one rill mark has been found. These features could have been caused by scour about chance irregularities (eg. Crowell, 1955). Apart from these examples, other sole casts are infrequent. A single example of a load-casted bed has been found (Plate 4.6a). Flame structures do not extend far into the a-division.

Comparison of the sublithofacies with other sections

Megarhythm 3 contains sandstone beds with characteristics of (fC) and (fD), the top of the megarhythm is thinner bedded than the middle and contains a- and b-division beds, one with convolute lamination (Plate 4.6b). A thin bed near the base of the sandstone unit consists of two flows, the lower flow have resulted in the formation of transverse wrinkles (Plate 4.7). Wrinkles are formed by the shearing action of the current on the bottom mud surface (Dzulynski and Sanders, 1962) which behaves as a viscous fluid. Such structures have been formed experimentally in slow flowing, dense suspensions by the pushing action of the current on the mud in distal currents (Dzulynski and Walton, 1965). A slow flow over a mobile substrate produces the same effect, but a more rapid flow results in the formation of L-ridges. The transverse wrinkles appear to have formed in this case because of the slow-flowing turbidity current -- this latter feature having been assumed from the abundant pelitic material and the virtual lack of the b-division.

This and other thinner (6-11 cm) sandstones showing predominantly a-divisions (characteristic of fD) are interbedded with 25-40 cm sandstones. Average bed thickness is 21 cm, but the 1:3 sandstone: shale ratio is low for (fD). Other characteristics, such as the straw-yellow weathering cement of the thicker beds and alignment of plant

Plate 4.7a

Turbidite bed formed from two flows. The lower part of the bed is darker in colour and more pelitic than the upper. It consists of poorly developed lamination and an e-division. The upper part shows the a-division passing up into b-lamination.

Megarhythm 3, River Dane,168.

Plate 4.7b

Sole of the same bed showing transverse wrinkles. These were formed by the pushing action of the dense, slower flowing current carrying pelitic material on the mud bottom. Direction of current flow was from left to right.

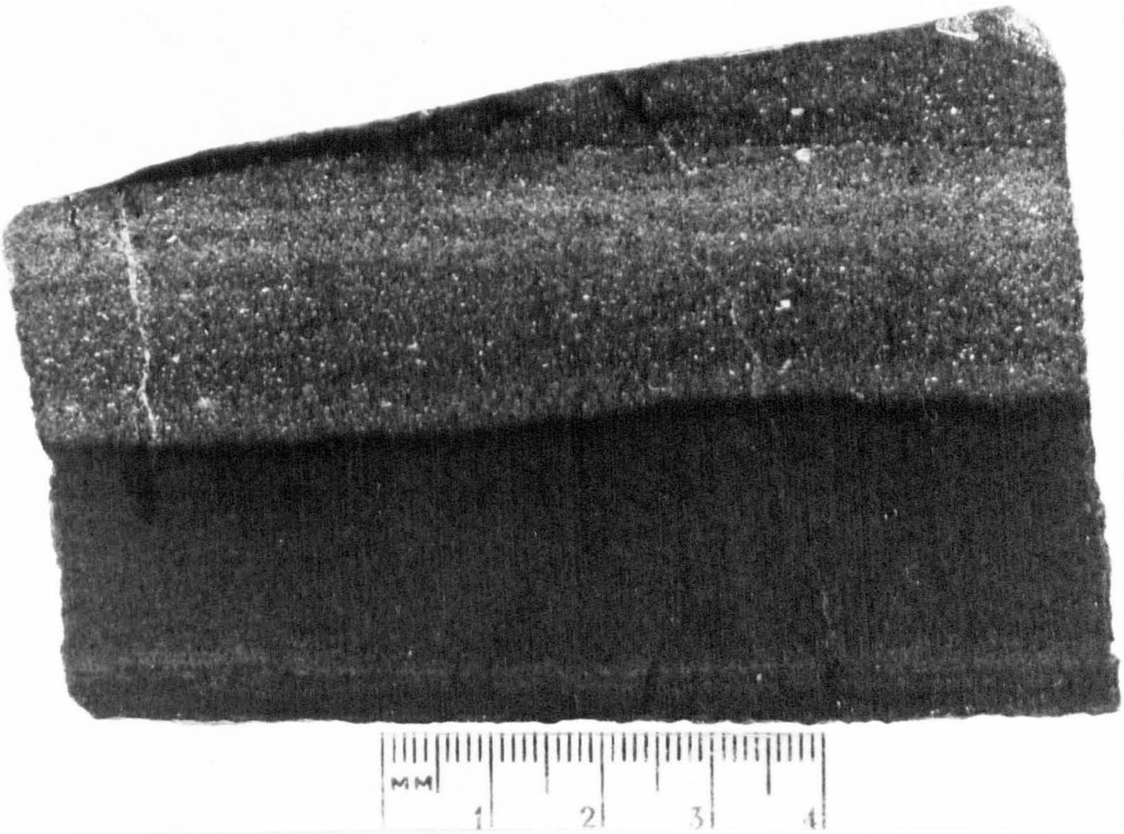
Plate 4.8a

Elongated flute casts developing into L-ridges. Base of sublithofacies fE sandstone, Upper Churnet. Direction of current flow was from left to right. Loc. 173

Plate 4.8b

Turbidite wedging out, at Brand Side, near Thirkelow, loc. 178. The sandstone consists entirely of the a-division, shows upcurrent grain imbrication, and is devoid of sole structures. Shale and a thin siderite bed are cut out by the sandstone, the total amount eroded reaching 4-5 cm (after compaction).

Pl. 4.7



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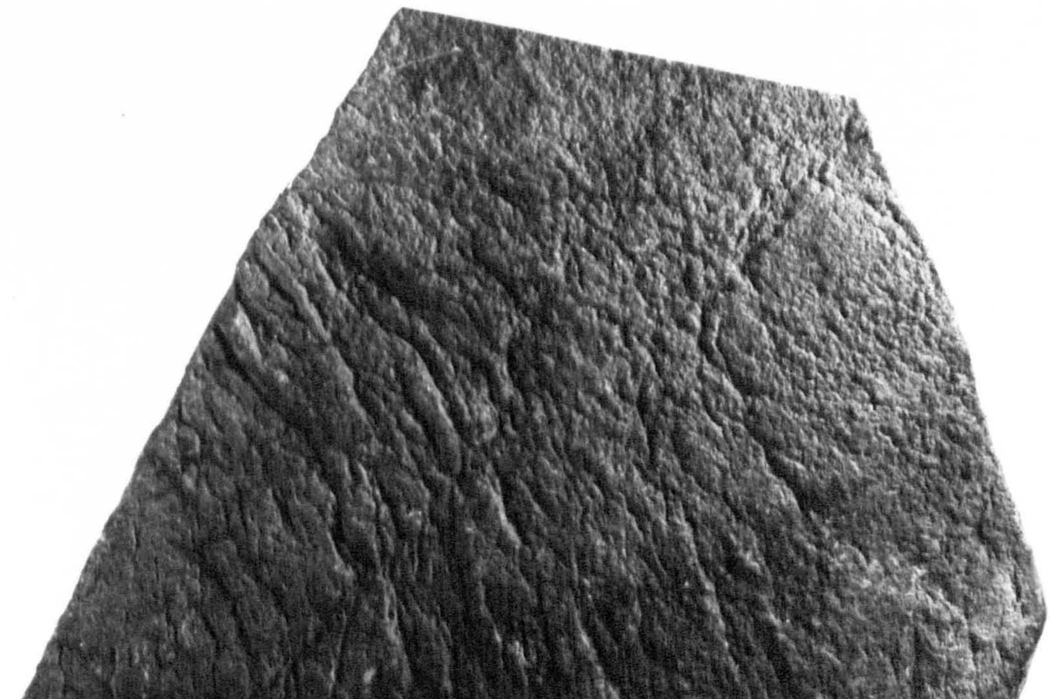
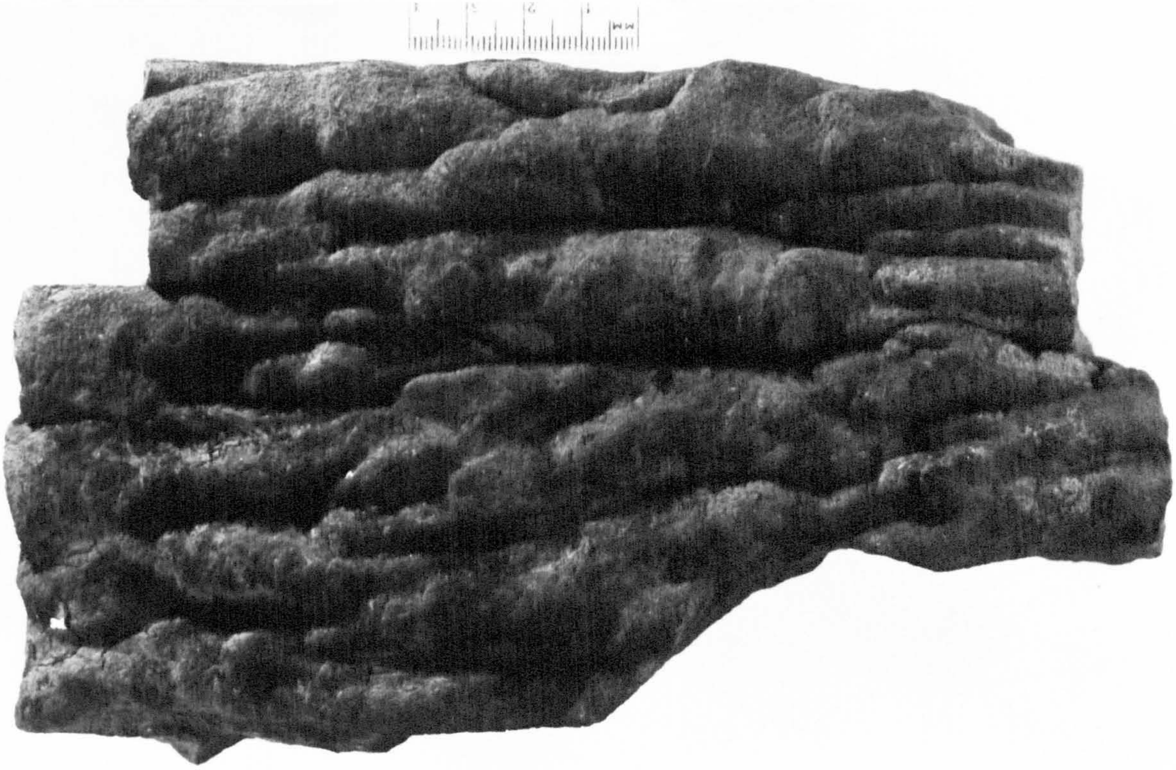


b

Pl. 4.8



a

b

and mud-flake debris to form crude laminae in a-division beds show their affinity with (fD).

K-FELDSPATHIC LITHOFACIES -- THE EASTERN AREA

SUBLITHOFACIES (fE)

Brief diagnosis. Sedimentary structures are similar to (fD) and a calcite cement is frequently present. a- and b-divisions predominate in the sandstones and sole structures consist, where present, largely of L-ridges. In the three sections recorded in the Upper Churnet Valley, average bed thickness is 12, 15 and 27 cm. Sandstone:shale ratios are higher than those of (fD), but average bed thickness is less (see table, p.245).

Typical section. Sublithofacies (fE) is virtually restricted to the Longnor Sandstone in the Upper Churnet area. Three sections have been used in its description and slight differences between them noted, (p.246).

Description

Sole structures

Many of the sublithofacies (fE) sandstone beds appear to be devoid of sole structures and even lack any grain orientation on the base of the bed. Where sole structures are present they consist largely of grooves and scours, though a few prod casts have been observed. Grooves associated with sublithofacies (fE) sandstones tend to be of greater relief than those of sublithofacies (fC), the former attaining 1.5 cm in width and 0.5 cm in height. Flute casts sometimes occur on the base of beds which show a-divisions. L-ridges in the form of broad, shallow, parallel troughs are the most common sole structure, as in the (fD) sandstones. L-ridges or elongated flutes of smaller dimensions also occur on the sole of thinner beds (Plate 4.8a).

Thinner, graded, a-division beds, 10 cm thick, have smaller sole structures in the form of bounce and prod casts. They also have some grain orientation in patches on the base of the bed. Thin beds (5-6 cm) at the base of the Longnor Sandstone show a-divisions or only a crude b-lamination. Hieroglyphs occur on the soles of these beds, but nowhere else in the Longnor Sandstone, as far as can be determined.

Internal structures

Only poorly graded a-divisions are seen, except in a few sandstones near the base of the unit. These have been noted under sublithofacies (fC). b-laminae may be present in some of the typical (fE) beds above the well cemented a-division. The b-laminae appear only as silty shale, except in rare, stream-washed sections where thin, parallel-laminated layers also appear in the shales between the thicker sandstone beds. Rippled divisions are uncommon, possibly because of weathering, possibly because the high clay content of the beds inhibited the formation of ripples.

SUBLITHOFACIES (fF)

Typical section. The section chosen is near the base of the Longnor Sandstone, a few metres above R. sp. nova at Ballbank.

Description

Although the sandstone:shale ratio of 1:1 is similar to some sections in (fE), sandstone bed thickness (average 32 cm) is higher than in (fE) or (fD). Sole casts are even less varied than in (fE), L-ridges or flutes occurring only occasionally. The sandstone beds consist almost exclusively of an a-division, but the upper parts of some particularly badly weathered beds may have b- and c-divisions. The shales are more silty than those associated with the sublithofacies previously described and often contain pieces of plant debris. These are particularly abundant in beds which could be weathered b-divisions.

Comparison with other sections

Several short sections in the area near to the base of the Longnor Sandstone compare with the typical (fF) section. Similar beds are exposed upstream where the first sandstone bed (67 cm) occurs at 2 m above R. sp. nova. In the Blake Brook, the first sandstone (87 cm) lies 6 m above the same horizon (Appendix Figure IV). Apart from the first sandstone bed, the turbidites of the Blake are on average thinner than in the typical section. A few thin, b-laminated beds occur, but the predominance of the a-division, rarity of sole casts except for L-ridges, and characteristic grey colour of the sandstones establish the section's similarity to (fF).

Grey-coloured a-division sandstones are also common beneath (fG) sandstones in the Upper Dove and at Brand Side (near Thirkelow). The Upper Dove exposure on the south-west side of Hollins Hill shows an 8 m section of shales and siderites (concretions and beds) before the first sandstone. Only three, grey, badly weathered sandstones, 70-90 cm thick, occur before an abrupt change in lithology (Appendix Figure IV). Bed thickness of these sandstones is greater than in typical (fF). These sandstones were noted as sublithofacies 4a by Holdsworth (1963a), in contrast to sublithofacies 4b of the Blake section.

At Brand Side, approximately 14 m of shales and grey a-division sandstones, up to 30 cm thick, occur at the base of the sandstone unit. No sole casts have been noted, but one bed (Plate 4.8b) lenses out within one metre. Apart from this, the sequence is similar to (fF).

SUBLITHOFACIES (fG)

Typical section. Right bank of the River Dove at southern end of Hollins Hill.

Description

The sandstones at this locality have previously been described by Holdsworth (1963a, sublithofacies 4c). They are probably down-faulted, appearing to be at the same level as the grey sandstones (fF) on the S.W. side of Hollins Hill. About 17 m of sandstones, separated by thin shale partings, are exposed. The two basal sandstones are 40 and 75 cm thick, but beds higher in the succession can be more than one metre thick. The sandstones weather to a straw yellow colour, similar to the calcareous beds in (fD). Internally, they are light grey, well cemented by calcite and frequently have "doggers" developed. The bases of the sandstone beds, as far as can be seen, are usually smooth. One shows non-orientated dimpled structures similar to those produced experimentally in proximal turbidites by Dzulynski and Walton (1965). Holdsworth (op. cit.) noted that the beds were frequently annealed. Shale partings with mudflakes disappear laterally to produce perfect annealing. Thin, convoluted shale laminae left from imperfect annealing occur in the middle of some beds. The sandstones are generally massive, but a few show, towards their top, a crude lamination produced by the alignment of mud flakes.

Comparison with other sections

This massive-bedded proximal sublithofacies is frequently exposed in the Longnor Sandstone, well above its base, between Dove Head and Hollins Hill. The relationship of (fG) to the underlying sublithofacies (fF) is best seen, however, at Brand Side where (fF) beds are abruptly followed by (fG) beds 0.4 and 1.3 m thick, separated by shale partings. The beds appear in the field to be internally structureless. Massive sandstone beds, which may be an even more proximal development than typical (fG), occur on the higher part of Hollins Hill and in Cistern's Clough where the Longnor Sandstone is 60 m thick.

An additional feature in the Cistern's Clough section is the development of thin sandstones above (fG). These probably merit a separate division but have only been seen in this one section. They consist of 2-4 cm almost exclusively rippled beds, each separated by 3-7 cm of shales. The abundance of thin, rippled sandstones with occasional b-lamination is totally unlike any other sublithofacies.

CEMENT OF THE SANDSTONES

Siderite-cemented sandstones are virtually confined to sublithofacies (fA) and (fB), the latter also containing some calcite-cemented beds. (fB) is transitional between (fA), which has only siderite, and (fC) with only calcite.

Siderites occur only rarely in the thicker shale leaves of (fC), (fD) and (fE), and sporadically in (fF) shale leaves. The siderites are generally featureless or show only a crude lamination, produced by the alignment of small plant particles. Such siderites may represent dilute turbidite flows formed during minor regressive phases, or periods of reduction in the supply of clastic sediments due to other causes.

(fC) beds are usually grey in colour, have some calcite cement, and can be cut by calcite veins. Thinner beds tend to be grey in (fD), but many of the thicker sandstones weather to a straw-yellow colour and contain abundant calcite cement throughout the rock or in concretionary forms known as "doggers". Bed thickness and calcite cement are only related in a general way, as some 25 cm beds appear to virtually lack a cement whereas some 17 cm beds can have doggers. Thinner beds are not, however, invariably less coarse grained than the thicker ones in (fD). The tendency for siderite to occur in thinner bedded, finer grained sandstones of (fA) and (fB), and calcite to occur in thicker bedded, coarser grained sandstones of (fC) and (fD) does suggest that the abundance of siderite might be related to the porosity and content of the sandstones. This is supported by the evidence of Einsele (1963) who found that the grain size and chemical composition in convolute beds were related. MgO and FeO increased as the silt proportion increased, at the expense of the sand fraction and CaO.

RELATIONSHIPS OF THE SUBLITHOFACIES

Sublithofacies (fA) occurs at the base of the Longnor Sandstone in the River Dane section and, together with the underlying siderite nodules, represents the most "distal" aspect of the Western turbidites. (fA) is followed by (fB) -- often siderite cemented -- which shows an increase in the incidence of b- and c-divisions and convolute beds in comparison with the d- and e-divisions of (fA). (fC) introduces the first beds with an a-division but b-divisions are the most common. In contrast to the (fA) beds, both (fC) and (fB) sandstones show tool marks which are slightly larger in (fC). Finally, (fC) is followed higher in the succession by (fD), which commonly has a-division sandstones, some annealed beds and sole casts in the form of scours. The progression from sublithofacies (fA) to (fD) is also accompanied by an increase in the sandstone:shale ratios and average bed thickness of the sandstones (see table, p.245).

In themselves, structures of turbidites, bed thickness of the sandstones and sandstone:shale ratios do not prove a proximal or distal origin for groups of turbidites. This was recognised by Walker (1967) who found, however, that certain associations of features indicated more and less distal environments. Lovell (1969), first defining the palaeogeography of the area of deposition of the Eocene Tyree Formation turbidites, found a distal decrease in the sandstone: shale ratios, and an increase in the proportion of sharp-based sandstones and light minerals, e.g. biotite. Internal and sole structures, bed thickness and other features were less reliable. Sandstone:shale ratios have been found by other authors (cited in Lovell) to correlate with distance from source, and it is thought likely that the steady increase in the sandstone ratios from sublithofacies (fA) to (fD) does indicate a transition from distal to more proximal turbidites.

Although the field data on internal structures is inadequate to use Walker's ABC index (1967), the predominance of Bouma d- and e-divisions in (fA) in comparison with a-divisions in (fD) and intermediate stages in (fB) and (fC), also indicates the same trend as the sandstone:shale ratios.

Changes in sandstone:shale ratios and internal divisions are also accompanied by variations in the size and type of sole structures. Indications of very little erosion in (fA) are replaced by tool marks in (fB) and (fC), then scours in (fD). Lovell (op.cit.) found no significant change in the proportion of groove and flute casts distally. In the R1c-R2a succession, however, scour marks are commonly associated with higher sandstone:shale ratios, a-divisions and thicker sandstone beds -- all of these features suggesting a more proximal environment for these sandstones in comparison with the thinner-bedded sandstones which have an abundance of tool marks.

AVERAGE BED THICKNESSES AND SANDSTONE:SHALE RATIOS OF THE K-FELDSPATHIC SANDSTONES

Section	Sublitho-facies	Average bed thickness in cm	Sandstone:shale ratio
Western Area			
River Dane, Megarhythm 1	(fA)	2.3	1:18.5
Archgreave	(fB)	12.3	1:3.6
River Dane, Megarhythm 2. Typical (fC) beds 8-17	(fC)	14.5	1:2
River Dane, Megarhythm 2. Average for total (fD), beds 18-64	(fD)	27.0	1:1
Upper part of (fD), beds 53-64	(fD)	22.0	1:1.5
River Dane, lower part of megarhythm 3	(fD)	21.0	1:3
Eastern Area			
River Churnet, loc. 104 (north)	(fE)	15.0	1:0.7
River Churnet (middle)	(fE)	12.0	1:0.8
River Churnet, loc. 102 (south)	(fE)	27.0	1:1.3
Ballbank	(fF)	32.0	1:1

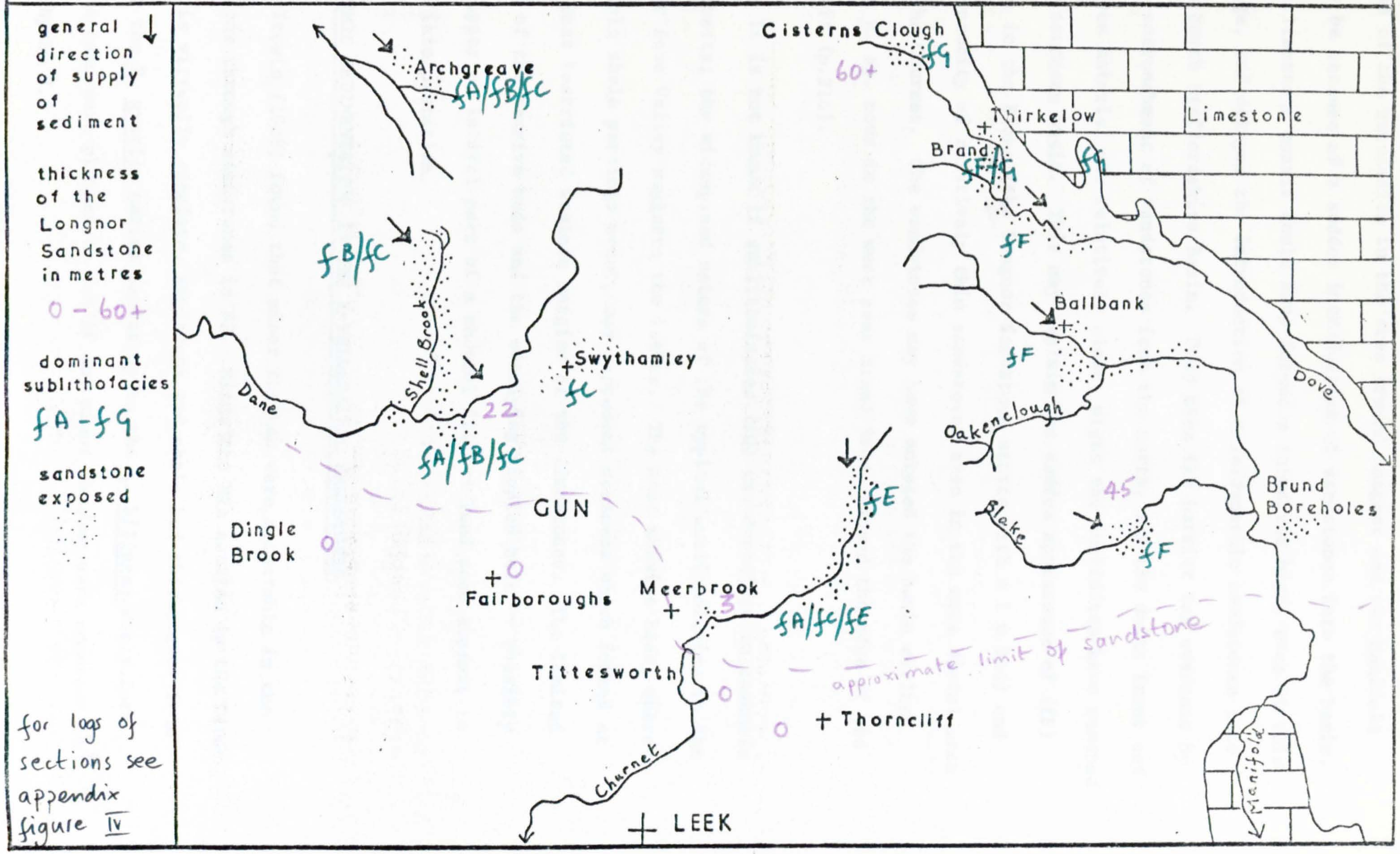
Turbidites also tend to be coarser-grained in more proximal than distal deposits (Walker, 1967) and also contain less pelitic and plant material. Since the grain size of the turbidites is linked with the mineral content and porosity of the beds, and hence with the beds' cement (p.243), it is thought that the occurrence of siderite-cemented beds in (fA) and (fB), and calcite-cemented beds in (fC) and (fD), also lends support to the interpretation of the Western R1c-R2a sandstones as a sequence of increasingly proximal beds.

In the Eastern area, sandstone:shale ratios in sublithofacies (fE) are slightly higher than those of (fD) in the west. (fE) has ratios of 1:0.7, 1:0.8 and 1:1.3 in the Churnet Valley (p.245). The thinner sandstone beds in sublithofacies (fE) are compensated by the frequency of the sandstones, which are more numerous than in (fD), and less widely separated by shales. The (fE) sandstone:shale ratios, given in a north-south order, suggest an increase in the shale ratio distally (ie. towards the south). The Eastern R1c unit as a whole appears to be more uniform than megarhythms 1 and 2 in the Dane, although minor rhythms can be detected in measured sections in both areas. The first sandstone:shale ratio (north) was measured in the top part of the sandstone unit, immediately below the *R. gracile* marine band (loc. 104). This probably gives a slightly lower figure for the ratio and average sandstone thickness than for the whole unit because sandstone bed thickness tends to decrease sharply at the top of a sandstone unit, eg. in megarhythm 2, River Dane. Despite this, the shale ratio increases towards the south, but is accompanied by an increase in average sandstone bed thickness to 27 cm from 15 cm in the north and 12 cm in the middle exposure. This suggests that thicker sandstone beds in the Churnet area are laterally persistent but that thinner beds of the northern exposures rapidly die out. The southern exposure (loc. 102) also shows, in addition to the typical (fE) beds, some siderite nodules and thin, siderite-cemented sandstones in the thicker shale leaves. The introduction of first (fC) beds, then siderite-cemented beds, in the more distal parts of the Longnor Sandstone in the Eastern area supports the conclusion that the siderite-cemented (fA) and (fB) beds were also deposited as distal turbidites, and that (fC) is distal to (fD).

The more proximal (fF) sandstones are thicker and sections show a higher sandstone:shale ratio than (fE). Although several sections have been noted under (fF) beds, it is noticeable that in the Blake section (S.E. of the Manifold and Dove sections) bed thickness tends to be less, and the sandstones are not followed by the most proximal development, (fG). In the Manifold section, (fE) occurs immediately above R. sp. nova, but further north at Hollins Hill and Brand Side, the marine band is unknown. Although there is no direct evidence for this, it may be that the position of the marine band lies somewhere within the sandstone unit.

(fG) commonly occurs above (fF) in the Manifold Valley, but the most massive bedded sublithofacies is found only in the most proximal deposits of Hollins Hill and Cistern's Clough. Even at these exposures, these massive beds do not constitute the whole of the sandstone unit. The preceding beds at Brand Side and Cistern's Clough show (fF) sandstones with one sandstone wedge at the former locality (p.240). There is no transition in bed thickness from (fF) to (fG). Similarly, (fF) beds at Hollins Hill are followed abruptly by a sandstone-rich series. These sharp changes in the nature of the sublithofacies are in contrast to the sequence of the Western area where the turbidites, thought to be more distal, show a transition from one sublithofacies to the next. The lack of thinner beds at the

EXTENT AND THICKNESS OF THE LONGNOR SANDSTONE



base of the succession in the area around Longnor and the Manifold may be because of a sudden introduction of sandstones into the basin. The limestone massif could have formed a submarine high, even at this stage, and delayed the introduction of K-feldspathic sandstones into the North Staffordshire Basin. Only when the barrier was overcome by the encroachment of sandstones from the north, and the delta front and source material was relatively close, might the turbidites have reached the southern basin. This may explain the sudden appearance of (fF) beds in the Blake (the Longnor Sandstone starts with a 1 m bed) and the paucity of relatively thin sandstones even in the more distal area of the Churnet. The sandstones may have entered the basin earlier than R. sp. nova in the west near Brand Side, around the edge of the massif (p.214).

It is not known if sublithofacies (fG) was deposited in channels of sheets; the widespread nature of the typical sublithofacies in the Upper Dove Valley suggests the latter. The most massive beds, where no thin shale partings occur, may represent channels which formed at the less restricted western margins of the limestones. The limited area of the massive beds and the overlying rippled beds -- possibly the upper or lateral part of a channel fill -- lend some support to this interpretation.

RHYTHMIC SEDIMENTATION IN THE K-FELDSPATHIC SANDSTONES

Trewin (1969) found that minor rhythms were detectable in the sections through sandstones in E2. Since the R2a section in the River Dane is virtually complete, sandstone and shale bed thicknesses from below the R. *gracile* marine leaves up to the R. *bilingue* early form marine band were plotted to see if any minor rhythms were apparent in megarhythm 2.

The graph of sandstone and shale thicknesses (Appendix Figure V) indicates that there could be a minimum of five rhythms. These have been identified visually by the occurrence of a thick shale leaf followed by the gradual increase in thickness of overlying sandstones. After the point where, for a given rhythm, the sequence is sandstone-rich and sandstone bed thickness is at or near a maximum, sandstone bed thickness rapidly decreases and a thick shale leaf is again developed. The graph therefore proceeds in a step-wise fashion.

Rhythms 1 and 2 illustrate the typical course of each rhythm. 1 begins with the R. gracile lower main leaf and ends with the formation of the upper main leaf. Rhythm 2 is similarly begun by a shale leaf and terminated by the start of another, but between rhythms 3 and 4, the shale leaf is not well developed. These two rhythms have been distinguished, however, by the decrease in the sandstone:shale ratio between the two, and the change in slope of a curve which can be drawn to follow the graph (Appendix Figure V). Where transgression, or some other factor, resulting in the deposition of thick shale leaves is followed by regression and a gradual increase in sandstone bed thickness, the curve is concave. After maximum bed thickness is attained, the curve becomes convex until the next rhythm is initiated. This same trend in the curve corresponding with the smoothed graph is apparent in rhythms 3 and 4 although no thick shale leaf is present.

In megarhythm 2, the number of sandstone beds (more than 2 cm thick) is at a maximum in rhythm 3. This is shown in the table below, and is a minimum figure for rhythm 3 since unexposed beds in the section are not estimated. The number for rhythm 4 may be slightly low as 1 m of the section is unexposed and may conceal sandstones. The numbers for rhythms 2 and 5 are roughly equal.

Rhythm number	Number of sst. beds	sst:shale ratio	ave. sst. bed thickness
5	12	1:1.8	22.0 cm
4	14 or more	1.2:1	28.9
3	17 or more	1:1	35.3
2	15	1:2.4	23.3
1	6	1:5.5	15.0

The two rhythms with the greatest number of sandstone beds also have the highest sandstone:shale ratios (4 being the higher of the two) and average sandstone bed thickness (3 being the higher). The acme of the megarhythm may therefore be represented by either rhythm 3 or 4.

Rhythms 2 and 5 are superficially similar in that bed thickness and frequency are similar. The sandstone:shale ratio is higher in 5 than 2, and there is no equivalent to rhythm 1 higher in the succession above 5. Comparing such factors as those set out in the table above, there appears to be asymmetry of the megarhythm in that its acme (measured by sandstone-richness) appears in rhythms 3 and 4 rather than 3 alone; 2 compares with 5 rather than 4; and the thinner-bedded rhythm 1 has no equivalent in the higher part of the succession.

Rhythm 1 and the lower part of rhythm 2 (sublithofacies fC) are composed of shales and calcareous sandstones, the latter consisting predominantly of b-lamination and convolute lamination. Sole casts are limited to small prod and bounce casts. Within rhythm 2 there is a change, taken at the point preceding the thickest sandstone bed -- bed 19. Bed 18 is taken as the base of (fD) because at and after this point tool marks (where present) are large, L-ridges are common and isolated flutes occur -- predominantly on the base of a-division sandstones. These features continue in rhythms 3, 4 and 5. Although 5 is similar in some respects to 2 (see previously), the internal and sole structures of the sandstones as well as the sandstone:shale ratio clearly indicate its affinity with (fD) rather than (fC) and emphasise the asymmetrical nature of the rhythm.

If conditions necessary for the formation of deltas and turbidites were at an optimum during periods of marine regression (Trewin, 1969), then it is likely that rhythms 3 and 4 were deposited at maximum regression, and 5 on renewed transgression. The failure to return to sublithofacies (fC), and the asymmetrical nature of the megarhythm, indicate that either the proposed rise in sea level was so rapid that (fD) sandstone were simply followed by black shale, or that an illusion of rapid rise in sea level is gained because at a critical point a relatively constant rate of change in sea level resulted in the inundation of the delta top and lower reaches of rivers. This would have produced alluviation upstream and the cutting off of material for turbidites.

So far, the cause of the development of barren shales and sandstone units between marine bands has been assumed to be the result of at least basin-wide fluctuations in sea level. This accounts for the synchronous deposition of marine sediments, containing a specific fauna, over the whole basin. If fluctuation in sea level were also the cause of the formation of the rhythms superimposed on the megarhythm, then the number of obvious rhythms in the R2a sandstone unit, where it is well devloped, should remain constant. There are no other long sections to completely check the whole of the succession. However, the first and second rhythms are each initiated by the local representative of the lower and upper main R. gracile leaves. These two leaves, separated by either a barren interval or a faunal phase other than goniatites, can be distinguished in Yorkshire, Staffordshire and at Ashover (p.339). This suggests that the first two rhythms at least are related to basin-wide changes in sea level. Such fluctuations were superimposed upon the major changes in sea level which determined the deposition of sandstones and non-marine shales, and marine bands. The minor fluctuations probably continued for the whole duration of each major transgressive-regressive phase and could have been as important in the formation of rhythms, such as those observed in the R2a sandstones, as other more local controls of the supply of sediments.

THE PROTOQUARTZITE LITHOFACIES

PREVIOUS WORK ON STAFFORDSHIRE

Apart from Holdsworth (1963a, b), the protoquartzites of R1 and R2 have only received passing mention by a few authors. Morris (1966) recorded loose bullions with R. gracile in Solomon's Hollow (Thorncliff, grid. ref. 0032,5819). The locality for these bullions is in a position which overlies the protoquartzites which are R1c (Holdsworth et al. 1970) and which were recorded by Morris as ?R2. The lower of the two thick protoquartzite units of the Ipstones/Combes succession, recorded by Morris (1967) as R1, is thought to be lower in the succession (p.202).

Protoquartzite lithologies were described briefly in Gibson, Barrow and Wedd (1905) as "Crowstone" and an ?R1 locality at Rownall Farm mentioned (p.272). Evans et al. (1968) also noted that proto-quartzite sandstones range as high as the middle of R2 in the Stoke-on-Trent district.

Holdsworth (1963a) recorded the R1 protoquartzite lithofacies around Longnor as the Ballbank Sandstone Member (ibid. p.174, lithofacies 2a) after the type section of the sandstone near Ballbank, where it is a maximum of 12 m (40') thick. The same sandstone was also recorded from the Blake Brook where reference was made to "chaotic quartzite beds" and slumped quartzites (Holdsworth and Trewin, 1968). No sandstones occur at the same R1b horizon in the Upper Dove, and their absence was explained by the effect of the rise of the margins of the massif (Dinantian) limestones, which also prevented the protoquartzites from reaching the Derbyshire basin.

Sandstones at the R1b level were thought to be lenticular in extent, being similar in this respect to the ?H1 lenticular deposits at Easing Farm and Dry Stones (Upper Churnet). No channels were recognised in Holdsworth's lithofacies 2a, but the R1b protoquartzites of the Blake Brook and the Oakenclough localities were thought to have been affected by slumping after deposition. The area in which slumping had taken place suggested an unstable zone possibly related to the massif/basin junction.

DIVISION OF THE PROTOQUARTZITES INTO SUBLITHOFACIES

Division of the protoquartzites into sublithofacies has been made in a different manner from that of the K-feldspathic lithofacies, which exhibit a greater degree of uniformity in the mode of deposition of the sandstones than the protoquartzites. Basic division of the protoquartzite succession according to average bed thickness was not feasible, as long sections through the sandstones were often not available. Bed thickness in a given sublithofacies can be extremely variable, and the protoquartzites do not have a common turbidite origin. Subdivision of the lithofacies was thus made on other sedimentary features which indicated the environment of deposition of the sediments. In the case of sublithofacies (pA) which occurs exclusively in the north of the area, it is the complexity of the sediments rather than a common characteristic, which distinguishes the sublithofacies. Sublithofacies (pB) is more uniform in character, although less so than any one of the K-feldspathic sublithofacies. A considerable range of bed thickness occurs throughout the sandstone unit, but certain sedimentary characteristics refer the formation of the sandstone unit as a whole to a distinctly different environment from the other sublithofacies.

In the case of sublithofacies (pC-pF), each sublithofacies may only persist for a small part of the total succession. For example, only 2 m of sublithofacies (pC) has been recognised, in contrast to 33 m of (pA) in the Blake Brook. Each sublithofacies in the deltaic environment (pC-pF) is, however, distinctly different and recognisable, the period of its duration or its quantitative significance in the succession seen making no difference to its status as a sublithofacies.

EXPOSURE AND AVAILABILITY OF MATERIAL

The protoquartzites are rarely well exposed, and description of a sublithofacies has frequently been drawn from a single section. Sublithofacies (pA) occurs in the north of the area and is well represented in the area of the Upper Manifold, the Blake Brook and the Oakenclough Valley where a considerable part of the succession can be seen. Description of sublithofacies (pB), however, has been drawn from sections in a single area around Thorncliff, and sublithofacies (pC-pF) have been described only from the Combes Valley.

Each sublithofacies, or group of related sediments, is exposed in a distinct area. Limited exposure prevents detection of any original lateral gradations, but the distribution of a particular sublithofacies is believed to be related to the original pattern of environments within the basin. The protoquartzite sandstones are thickest in the south of the area, extending from R1b-R2b. Around The Combes, the protoquartzites occur exclusively in a deltaic facies and are virtually uninterrupted by major shale units. Periodic discharge of sediments into the basin appears to have been more limited than in E2, possibly due to the reduction in relief and thus supply of sediments from the Mercian land mass. Lateral equivalents of the deltaic sandstones, in the form of turbidites, occur at two levels in R1b in the north of the area, and at one level in R1c around Thorncliff.

SUBLITHOFACIES (pA)

Brief diagnosis

Sublithofacies (pA) protoquartzites were interpreted by Holdsworth (1963a) as turbidites. The present writer concurs. The variation of sedimentary structures within individual units is greater than that noted in turbidite sequences elsewhere. The beds have also often been distorted by slumping. Internal structures of these generally clean, but poorly graded protoquartzites are poorly known and, as far as may be seen in the field and in cut specimens, only a- and b-divisions are commonly present. Description of the sedimentary features is largely confined to those which can be seen in the field.

Description of the typical section

The Blake Brook succession has been used to describe the typical section because 33 m of protoquartzites and shales are exposed between ?Rib_{iii} and $R1b_{v}$.

Sedimentary features

Channels

These occur in the form of isolated bodies of sandstone, lenticular in shape, at the base of the protoquartzite succession. The channels are usually about 15 cm deep and have a width of 60-70 cm. One larger structure may be a channel or a rotated block of sandstone. Immediately beneath this massive sandstone (Plate 4.9a) two thin, lenticular sandstones appear to be at the level of other disturbed structures. The two thin sandstones are separated from each other by a crude parting or by the inclusion of shale pellets. The massive sandstone may be a slightly later channel which distorted the earlier beds by load casting during the deposition of the bed (see Unrug, 1959, p.220) or during compaction.

Slump structures and contorted beds

Contorted lenses of ankerite were described from sandstone beds deposited by "watery slides" (Dzulynski and Slaczka, 1958) in the Krosno beds. Slump blocks were only common in the upper part of these beds, the lower part resembling a normal turbidite. Thus the beds were deposited by a combination of sliding and turbidity current flow, and are fluxoturbidites. Such deposits do not occur in the Rlb protoquartzites and slumping appears to be restricted to a post-depositional phase rather than contemporary with turbidite flow. Such post-depositional movement is similar to that described by Ksiazkiewicz (1958) where submarine slumping, involving more than one sandstone bed and shale unit, took place.

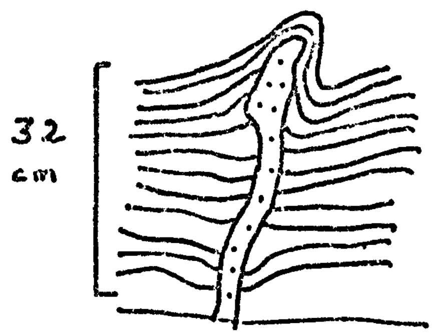
At the level of disturbance of the channels, nodules of sandstone and siderite occur in displaced attitudes, and also blocks of shale aligned with the bedding normal to that of the undisturbed sequence. The exposure is clearly not affected by faulting, and the disturbed shales and nodules can be accounted for only by movement after deposition of the sandstone and at least initial formation of the siderite nodules in the shales. Hook-like overfolds occur in the sandstones, similar to those described by Ksiazkiewicz (1958), and are overturned to the west, north-west and north. The direction of overturning could indicate the local palaeoslope, but as Dzulynski and Walton (1965) point out, "The orientation of fold axes and thrust planes vary from one place to another and the folds may trend both parallel to the main direction of slumping as well as at right angles to it."

Slumping of the sandstone beds occurs on a larger scale higher in the succession (Plate 4.9b) where beds 20-30 cm thick are overturned and folded in a similar manner to those figured by Dzulynski and Walton (1965, fig.129B). In one case, the fold is overturned in a westerly direction, and in another, to the north. The structures are similar to the "concretionary sandstones" figured in Hull and Green (1866, p.63, fig.20) from a quarry near Pygreave, east of Macclesfield (H or E2).

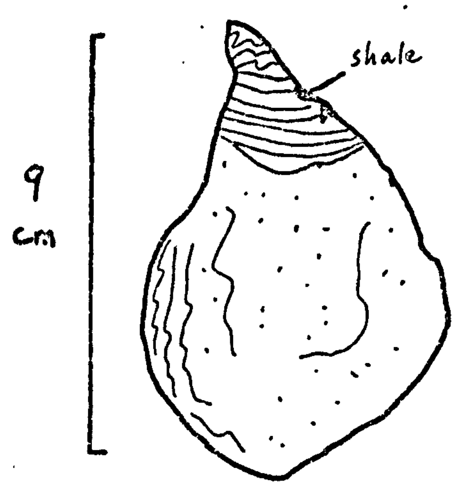
Isolated sandstone nodules which occur in the slumped deposits may have originated as slump balls prior to the movement of the deposit as a whole, when they were rotated out of position. A cross section of an isolated nodule shows the bending of faint laminae around the periphery of the ball, but an apparent lateral truncation of the turbidite b-division (Fig.4.B). Sandstone nodules (structureless) have also been noted in H1 in the Upper Dove near to the Massif limestones. A small sandstone dyke occurs with the pseudonodules in R1b. The dyke consists of a featureless fine grained sandstone, which extends vertically for a distance of 32 cm, and is 6 cm thick (max.). The dyke is seen to truncate the shale laminae for the greater part

Figure. 4. B

STRUCTURES IN SUBLITHOFACIES [pA]



sandstone dyke



Cross-section of pseudo-nodule showing a- and b- divisions of the original sandstone bed

Loc. 182

Figure 4.C

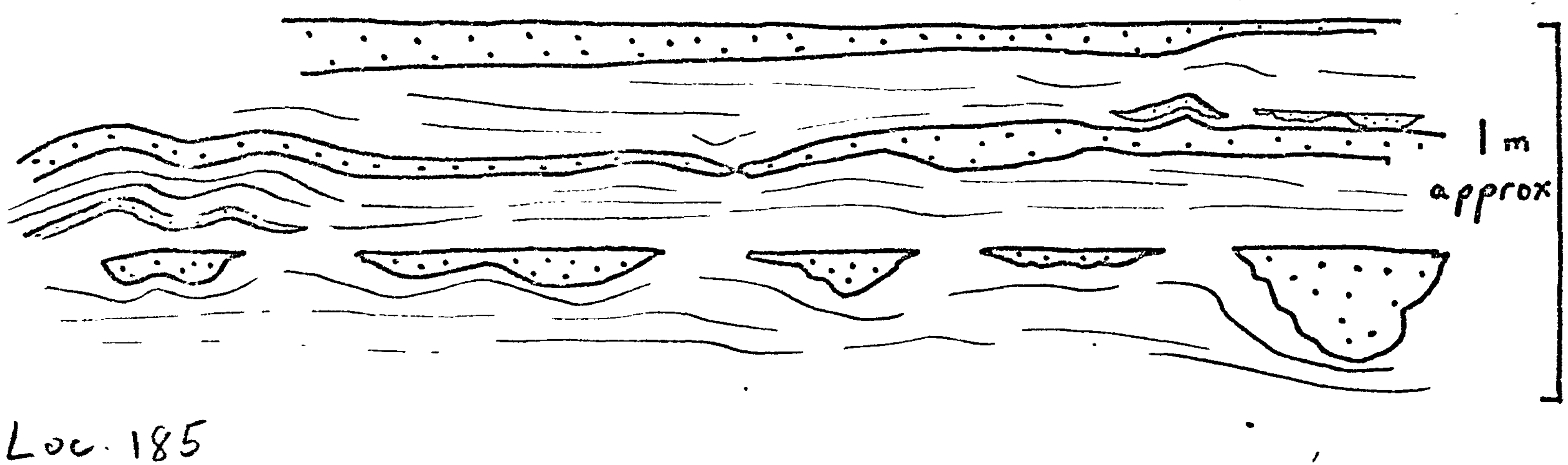


Plate 4.9a

Channel in sublithofacies pA protoquartzites, Blake Brook, loc. 182

Plate 4.9b

Slump folds in pA beds, Blake Brook, loc. 182

Plate 4.10a

Basal mud pellets are overlain by a thin b-division, then climbing ripples in the c-division. These ripples were formed as material continuously fell out of suspension, unlike the rippled beds in sublithofacies pB. Sublithofacies pA sandstone, lower R1b sandstone unit, Upper Manifold, 186.

Plate 4.10b

Lower part of sandstone bed showing a-division and rafted mud pellets which are sufficiently abundant to form a parting. Sublithofacies pB sandstone, Thorncliff stream, 189.

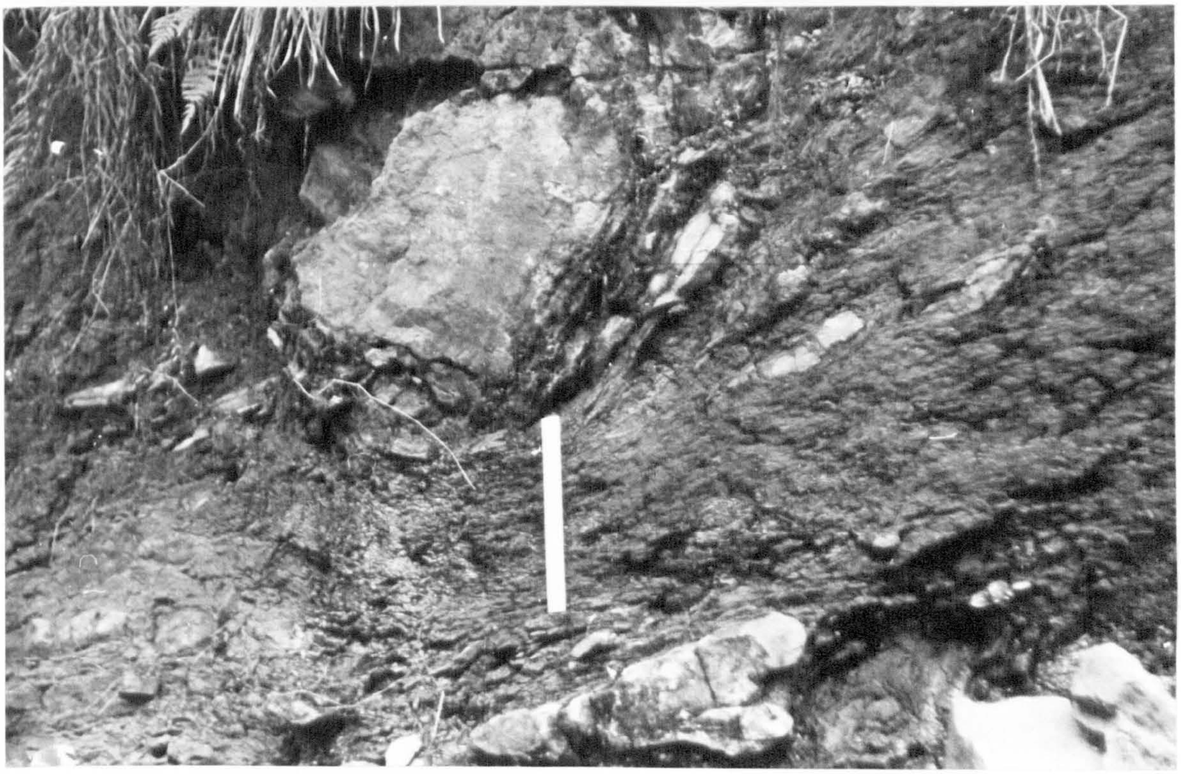
Plate 4.11a

Sublithofacies pB turbidite showing basal mud pellet layer followed by poorly developed b-lamination and the c-division. Pelitic material is scarce, unlike in the K-feldspathic turbidites. Loc. 189

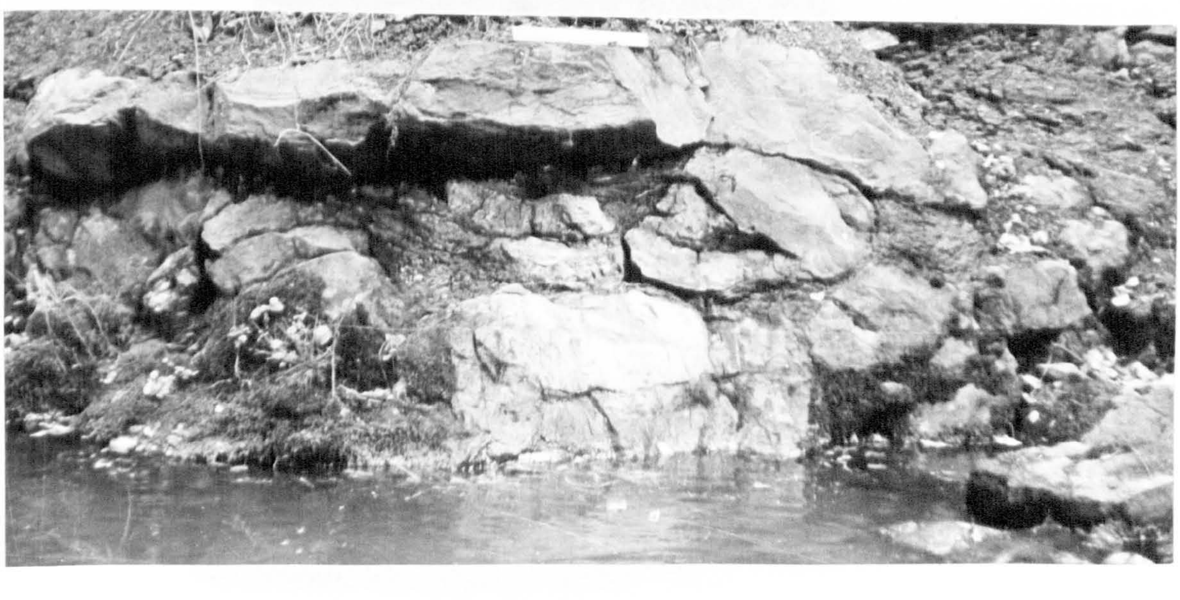
Plate 4.11b

Thin b- or d-division bed with siderite-cemented top, possibly an e-division. This type of bed is unusual in sublithofacies pB. Loc. 189

Pl. 4.9



a



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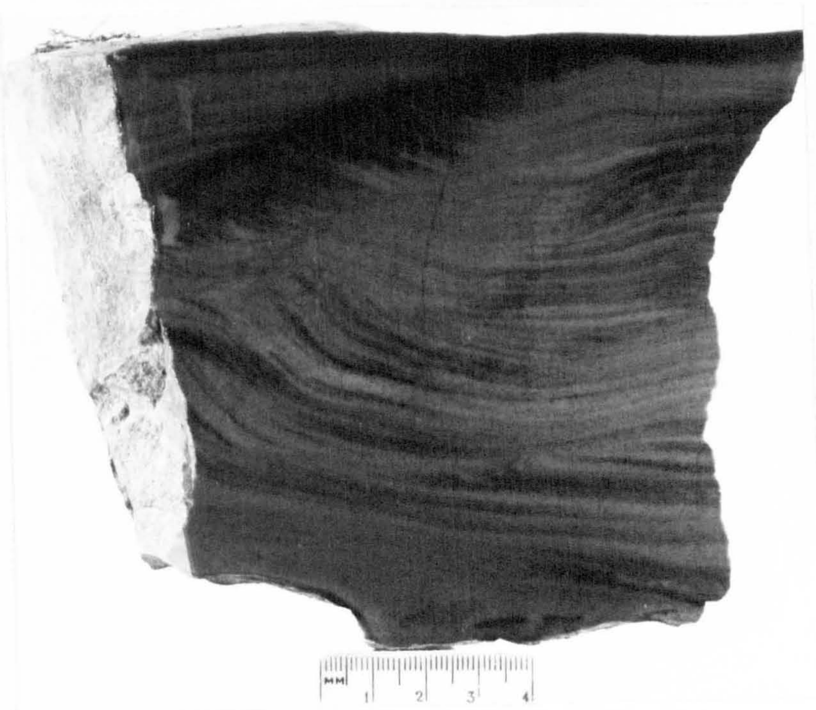
Pl. 4.10



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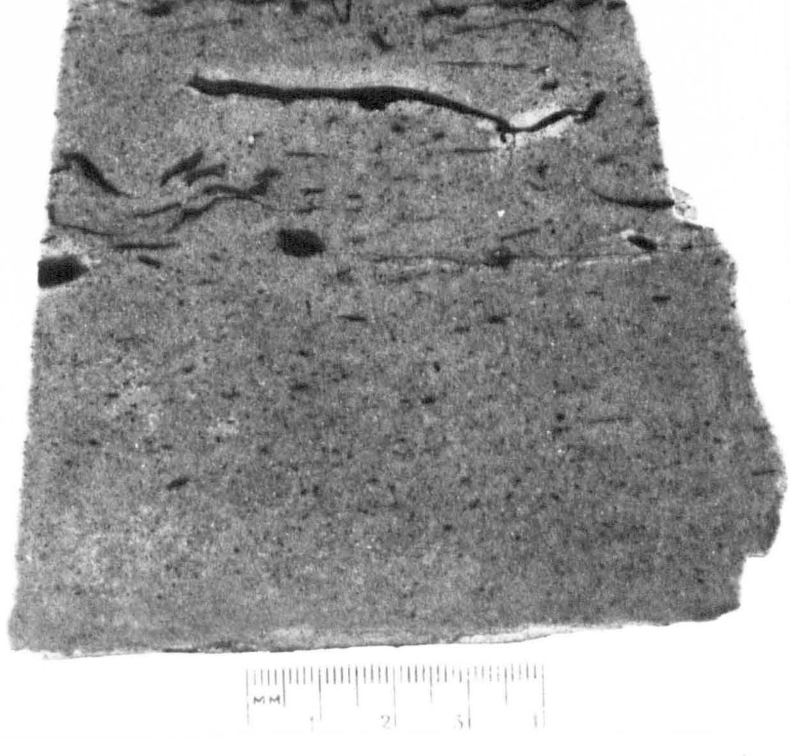
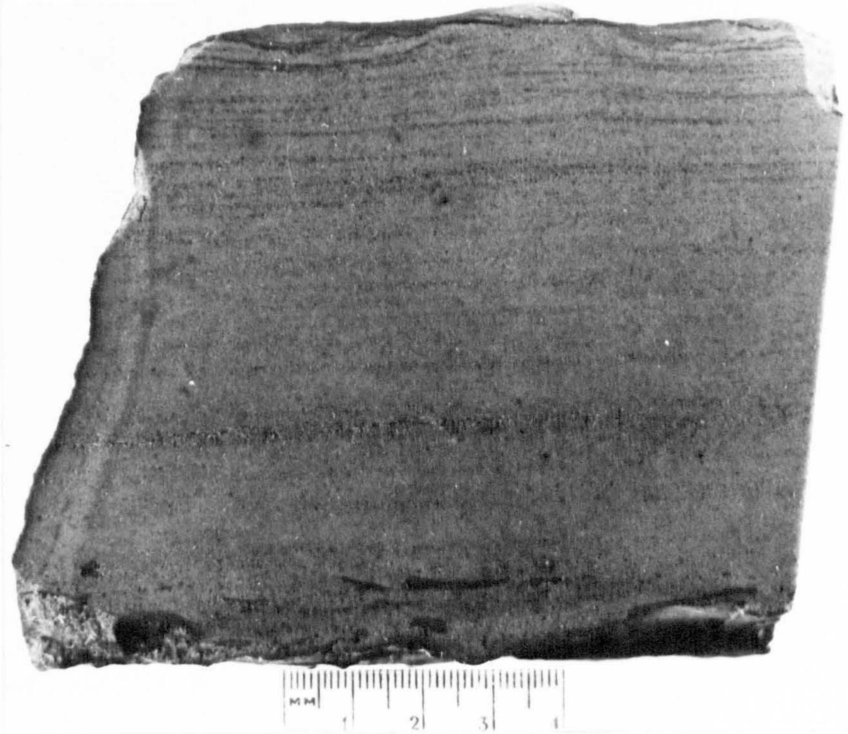


b

Pl. 4.11



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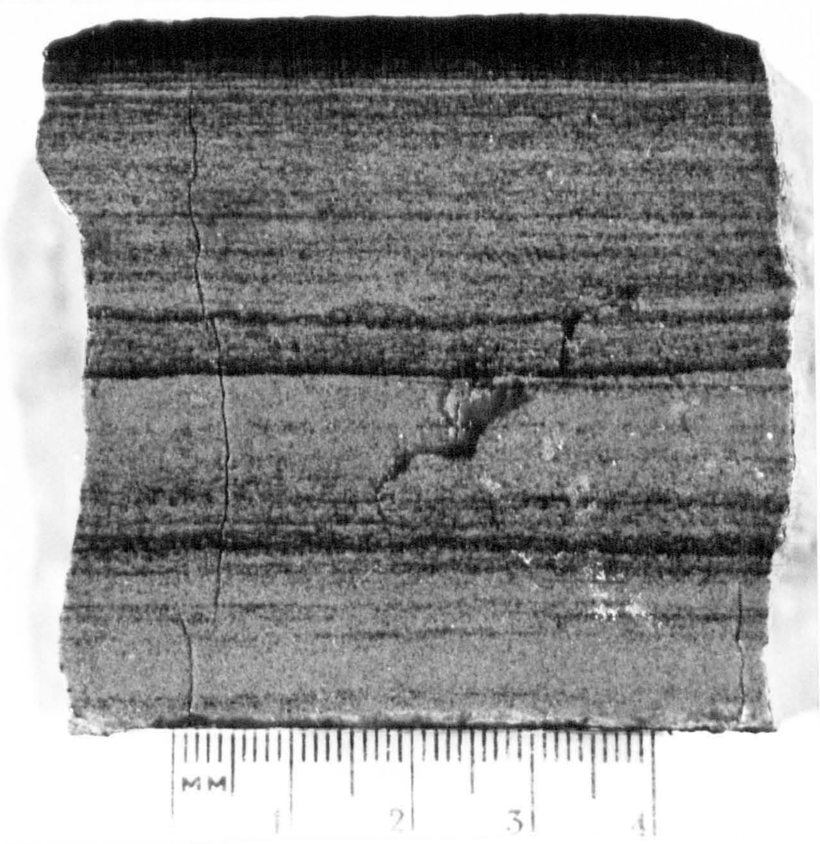


b

of its length, but on termination of the structure, the shales bend over the top before again assuming a horizontal position (Fig.4.B). The lower part of the feature and the source beds are not seen.

Siderite concretions and continuous siderite beds

These are relatively rare in the Blake Brook succession, thin siderite beds and a few nodules being well developed only in a small part of the sequence where 4 m of shales are present.

Comparison of the sublithofacies with other sections

Channel sandstones also occur as isolated bodies of sandstone in the Ballbank section (Fig.4.C). The undersides of the sandstones are frequently load casted and show groove casts, these features being similar to those recorded in sublithofacies (pB). The channel sandstones are interbedded with thinner sandstone beds showing features such as a thin a-division and a well developed b-division. Sole marks are hieroglyphs (Granularia) and prods and grooves. Derivation of the sediments was from N 150-160^{o} east. Siderite beds, up to 4 cm thick, are also well developed in this section in contrast to the section of the Blake.

Protoquartzites in the section in the Upper Manifold occur at 12-18 m above $R1b_i$. Bed thickness of the sandstones is extremely variable. One bed reaches 2 m in thickness and consists of clean, massive protoquartzite with no visible structures. Other beds in the same sequence are only 5 cm thick and consist of a thin a-division, with some shale pellets at the base of the bed, followed by a well developed b-division then continuous ripple-laminae (Plate 4.10a).

Higher in the succession, protoquartzite sandstones occur between $R1b_v$ and R1c (p.207). Bed thickness is again vaiable, ranging from a few centimetres to at least 60 cm but a siderite cement is ubiquitously developed. Thin siderite-cemented beds show a crude lamination and, in one case, flame structures. The thicker beds show the most abundant development of siderite cement where a "floating texture" of the quartz grains has been developed in the a-division. Siderite bands were also recorded in $R1b_v$-R1c of the Brund Boreholes, where the succession consisted of about 10% sandstone. Sandstone beds showed a-, b- and c-divisions, and appear to be similar in lithology (they are described as "ferruginous sandstones") to the thinner siderite-cemented sandstones of the Upper Manifold, and those which occur between $R1b_v$ and R1c in the Blake section.

Siderites in the Oakenclough Brook section, which shows only the base and top of the protoquartzite succession, appear to be confined to the base, where they occur as continuous beds up to 4 cm thick. Thin sandstones up to 2 cm thick occur interbedded with the siderites. These sandy beds are poorly graded and coarse grained for their thickness, quartz grains frequently attaining 1.3 mm in length. The base of such a bed is irregularly load casted. Siderite cement also occurs in these beds, and grows over plant material. In the higher part of the section, protoquartzite beds are contorted, and appear to have been folded from slumping, as in the Blake section. The exposure in this case is near a fault which cuts the shales, but faulting does not appear to be responsible for the slump-folding of the sandstones. In the unexposed part of the section, large, loose blocks of protoquartzite, which appear to be structureless, indicate that the thickest beds of the sequence (1.5 m), similar to the 2 m beds of the Upper Manifold, occur nearer the middle and upper part of the protoquartzite unit.

SUBLITHOFACIES (pB)

Limits of exposure of the sublithofacies

Sublithofacies (pB) is well exposed in Solomon's Hollow, Fig. 1.C (typical section in the Thorncliff stream) in sandstones approximately 15 m thick. In sections less than one mile to the east (grid ref. 0103,5843 and 0104,5815), the sandstone unit is a maximum of 9 m thick. The unit must also thin rapidly in a northerly direction because at Meerbrook, 1¾ miles (2.8 km) to the north, the protoquartzites are absent. The sediments were derived from the south-west (Fig.4.Db).

Brief diagnosis

Sandstone beds commonly show a-, b- and c-divisions. A single example of an e-division is known. In contrast to (pA), siderite cement in the sandstone is rare, but rippled beds showing stoss side erosion are very common. Annealing of sandstones takes place and small scale channels occur.

Sedimentary features of the typical section

In the typical section of Solomon's Hollow, bed thickness ranges from 1.8 m in annealed beds to 1 cm in b-division beds. Channels are found in the more pelitic part of the succession. The thicker sandstone beds occur where the sandstone:shale ratio approaches 100% sandstone as the shales are reduced to thin parting or shale pellet layers. Bed thickness in almost 100% sandstone sequences is commonly as little as 10-35 cm, the sandstones consistently being composed of a- and b-divisions with rarer c-divisions.

Internal structures of the sandstones

a- and b-divisions and associated structures

Top truncated a-division beds which have no b- or c-divisions are usually the thickest in the succession. Bed thickness ranges from

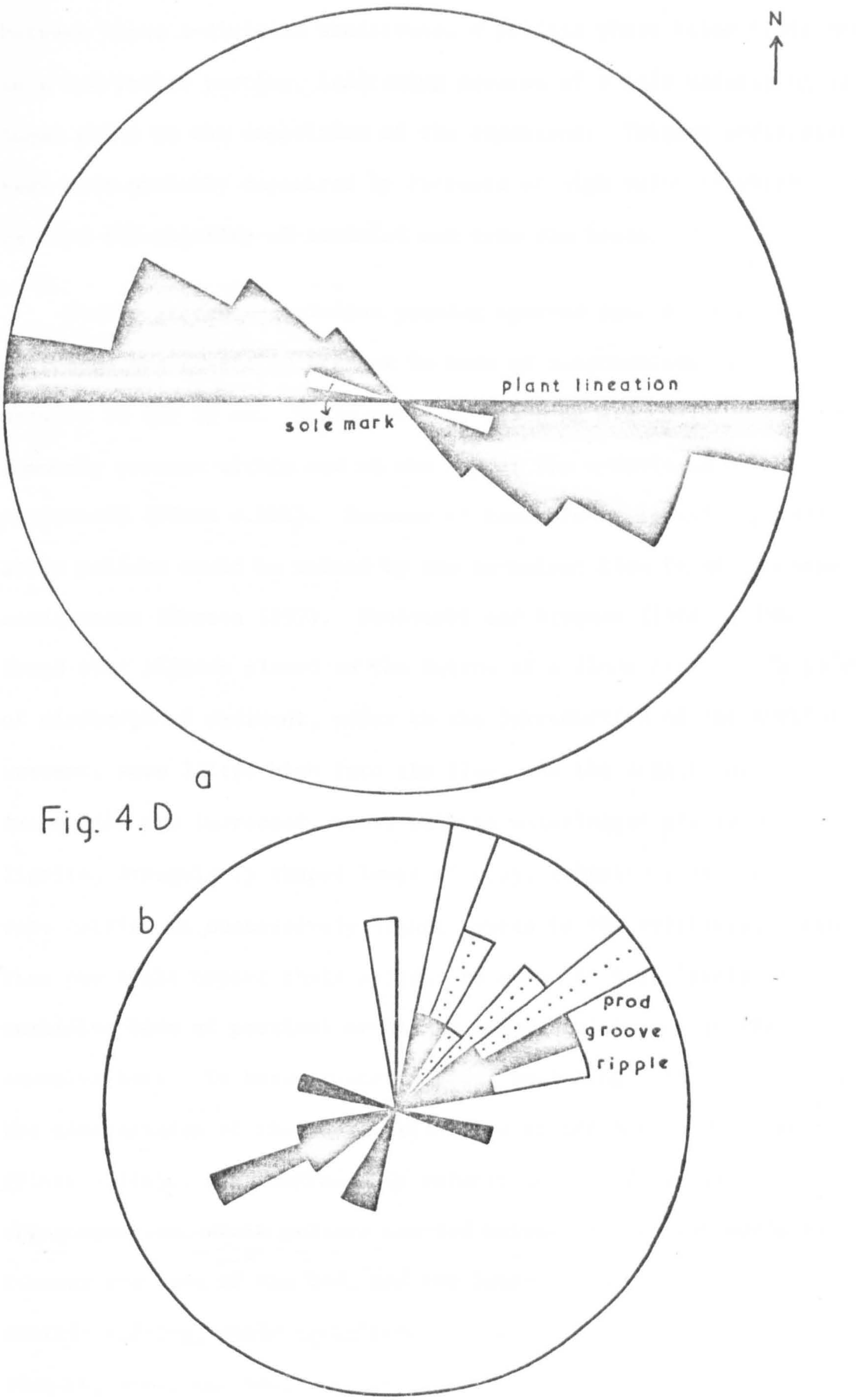


Fig. 4.D

0,5-0.4 m but can be as little as 12 cm. Shales are rarely developed between these a-division sandstones, a pelitic phase being restricted to a mud pellet parting, indicating erosion of a thin underlying shale layer prior to the deposition of the sandstone. Thinner a-division beds were probably deposited by currents of high velocity which carried the majority of material out into the basin.

Poorly graded a-divisions passing upwards into b- and c-divisions are generally present in beds of intermediate thickness between 10 and 33 cm. Shale pellets, reaching 4.5 cm in length, are commonly present within and at the top of the a-division of sandstones (Plate 4.10b). Because of their lower specific gravity, shale pellets would be rafted by the turbulent flow in the proximal environment (Kuenen 1957). Dzulynski and Simpson (1966, p.198) found that objects placed on the bottom of a flume near to the point of discharge of sediment, prior to the introduction of the turbidity current, were lifted high into the flow. As the density of the suspension was increased, tools such as waterlogged pieces of lignite, irregularly shaped lumps of clay, cohesive clay discs, etc., were carried at successively higher levels in the artificial current. Thus one might expect shale pellets to occur at high levels within turbidite beds of proximal origin and high density, as in the examples here. In base-truncated beds, beginning with a b-division, the concentration of the shale pellets is at the base of the bed (Plate 4.11a). With decrease in velocity of the flow and density of the suspension, shale pellets carried within the current would fall towards the base of the bed, and the laminar flow, which would inhibit rafting, would contribute to the formation of groove marks (Hubert, Scott and Walton, 1966), common on the base of b-division beds.

b-lamination is often weakly developed, and indicated by an alternation of the grain size in quartz-rich material, rather than the development of alternating quartz-rich and more pelitic layers. This suggests that the turbidity currents which deposited the beds were poor in clay-grade material, in contrast to the K-feldspathic lithofacies. The individual laminae of the b-division are themselves poorly graded, ranging from 0.75-2.0 cm in thickness. Thinner sandstone beds (6 cm) which have better developed lamination from the incorporation of more pelitic material, consist entirely of b- and c-divisions. These sandstones show well developed parting lineation from the orientation of the long axes of quartz grains (McBride and Yeakel, 1963). Allen (1968) found that primary current lineation, measured from the long axes of quartz grains, was bimodal. The two modes occurred at 15-20^{o} from the statistical mean, suggesting the formation of primary current lineation by tubular corkscrew vortices in the flow. Although parting lineation is well developed in hand specimens, thin sections cut in the plane of flow of the current do not show elongate grains. Cementation and compaction of the protoquartzite sandstones (unlike that of the K-feldspathic sandstones) appears to have obliterated any primary grain texture.

b-laminae in these thinner sandstone beds are finer, ranging from 0.1-0.3 cm in thickness. Plant remains up to 3 cm in length are common on parting planes of the darker laminae, these laminae probably being composed of abundant fine grained carbonaceous debris rather than clay. Larger plant fragments are abundant in some of the beds with thicker b-laminations, and can be abundant enough to form thin coalified layers. Alignment of these fragments produces "charcoal fragment lineation" (Crowell 1955, p.1361, and Hubert, 1967), which is parallel to the direction of current flow, deduced from parting lineation. This can be seen in Figure 4.Da where, in the rose diagram, plant fragments are seen to be aligned parallel or sub-parallel to current flow, deduced from sole casts.

The c- and e-divisions

The ripples of such a division show either stoss-side erosion or continuous laminae, but are linguoid in plan in all cases seen. a-, b- and c-division beds are most common in the thicker part of the sandstone unit, but rippled beds alone occur commonly where the sandstone unit is thinner (p.268). Most sandstone beds appear to be top-truncated after the formation of the c-division. A single example of a laminated sandstone with a siderite-cemented top shows fine 0.5 mm laminae (b- or d-division) passing upwards into a pelitic, cemented division (Plate 4.11b).

Erosional features of the turbidites

Annealing of sandstone beds

In the thicker-bedded part of the typical succession, erosion of thin mudstone partings between the sandstones is common, and can be pronounced enough to lead to the annealing of sandstone beds. Annealing of sandstone beds into a composite unit was described by Walker (1966) from the Shale Grit, and by Holdsworth (1963a, p.297) from the Longnor Sandstone. As grading is poorly developed in sub-lithofacies (pB) due to the relatively uniform grain size of the deposited material, it is impossible to distinguish perfectly annealed multiple grading in the field, but annealed beds have been recognised by the lateral passage of partings with occasional mud pellets into mud pellet conglomerates or shale layers. The total thickness of an annealed unit in one case reaches 1.6 m, consisting of sandstones deposited from at least two flows.

Channels

Channels are common in the typical section in the more pelitic part which precedes the upper part of the section (almost 100% sandstone). Orientation of the channels is in a south-westerly and southerly direction in accordance with sole markings on adjacent parallel-sided beds. The channels vary from 3 to 16 cm in depth, and are up to 33 cm in width.

The material filling the channels is of a similar grain size to that of the a-division parallel-sided sandstones, or finer. "Fine grained conglomerates" and coarse sandstones which formed the channel fill of lenticular bodies described by Unrug (1959), are absent in this sublithofacies. The channel fill is often faintly laminated, the laminae rarely showing signs of distortion. This faint b-lamination passes upwards in some cases into ripple-lamination on the upper surface of the channel. Mud pellets are generally absent from the channel sandstones, but a few examples of channels, 5 cm deep, have mudflakes concentrated near the base of the a-division channel, as in the examples described by Unrug. The lateral passage of the channels into thin, parallel-laminated beds (Fig. 4.E) suggests that similar, numerous beds in the turbidite sequence, not continuous with channel forms, are in fact b-divisions rather than d.

Channels such as those described from sublithofacies (pB) may be the source of intraformational shale pellets (McBride, 1962), but many of the thicker parallel-sided sandstones must also have eroded shale fragments judging from the shale pellet conglomerates at the base of some of the partially annealed beds. The lower surfaces of the a-division channels with shale pellets are irregular, but channels filled with faintly laminated sandstones are smooth except for groove casts on the lower surface (Plate 4.12a).

Erosion can amount to 8 mm of compacted shale and silts for a total channel depth of 3 cm. In Plate 4.12b, exactly 2.2 cm of the channel sandstone corresponds with 8 mm of silts and clays indicating a compaction ratio of 1:2.75 (sandstone:shale). The 8 mm of the channel unaccounted for may be accommodated by load-casting (1-2 mm is suggested by the slight bending of the b-laminae in the channel) or undetected erosion. Other a- and b-division channels may have greater parts of their depths accounted for by load-casting since distortion of a-division fills cannot be detected. The slightly rounded nature of the base of some channels and the bending of the underlying shale laminae demonstrate that this is the case in the largest of the channels (Fig. 4.E).

Sole structures

These are not generally well developed in the protoquartzites, the bases of the majority of the sandstone beds showing only irregularly load-casted surfaces. Numerous shale pellets are often incorporated into these beds. Beds which are less than 6 cm thick show a variety of structures attributable to current marks, tool marks and organic activity, and are most common in sections adjacent to the typical section. Tool marks do, however, occur on the bases of thinner-bedded sandstones beneath the part of the section where channels are common, and in sandstones interbedded with the channel forms and thicker a-division sandstones.

Prod, bounce and groove casts

These occur on the base of b-laminated sandstones. Prods are commonly 1-2 cm in length and bounce casts up to 5 cm long. Striations parallel to the length of the bounce casts suggest that the tools may have been objects such as the Calamites stems, impressions of which are common on intra-bed partings.

DIAGRAMMATIC SECTION –

CHANNELS IN SUBLITHOFACIES [pB]

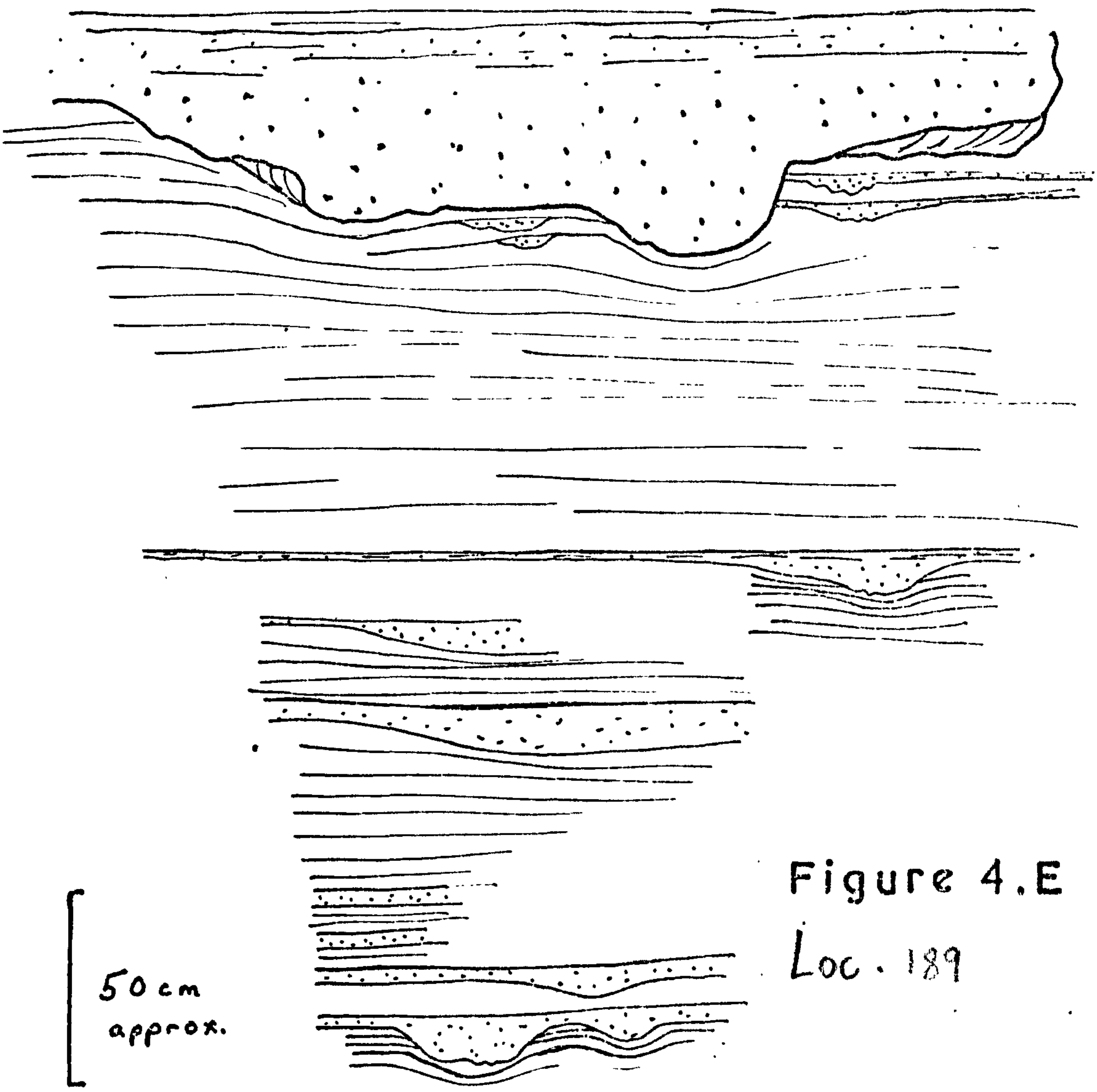


Figure 4.E
Loc. 189

Plate 4.12a

Small sublithofacies pB channel showing a- and b-division channel fill. The lower surface of the channel shows groove casts. Loc. 189.

Plate 4.12b

Small pB channel showing b-division passing upwards into c. The channel erodes mud and silty laminae, seen on the left. Loc. 189.

Plate 4.12c

Thin pB sandstone showing b-division. The dark material is plant debris which forms coaly partings. The base of the beds shows rounded protuberances, which are filled with coarser material, seen in cross section. These irregularities are interpreted as unroofed burrows. Loc. 192.

Plate 4.13a

Cross section of groove cast in b-division bed with well developed parting lineation. The laminae within the groove cast are distorted, unlike the overlying laminae, indicating load casting. The groove has cut out thin silty laminae in the shales, seen to the left. Loc. 189.

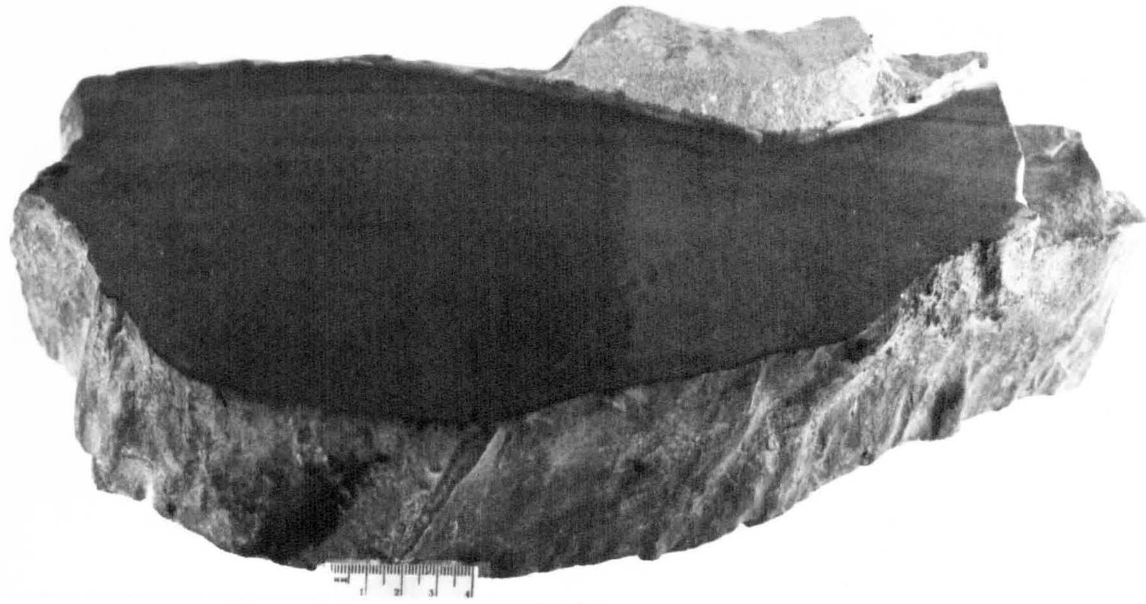
Plate 4.13b

Rippled bed from the thinner part of the sandstone unit adjacent to the typical pB section, loc. 190.

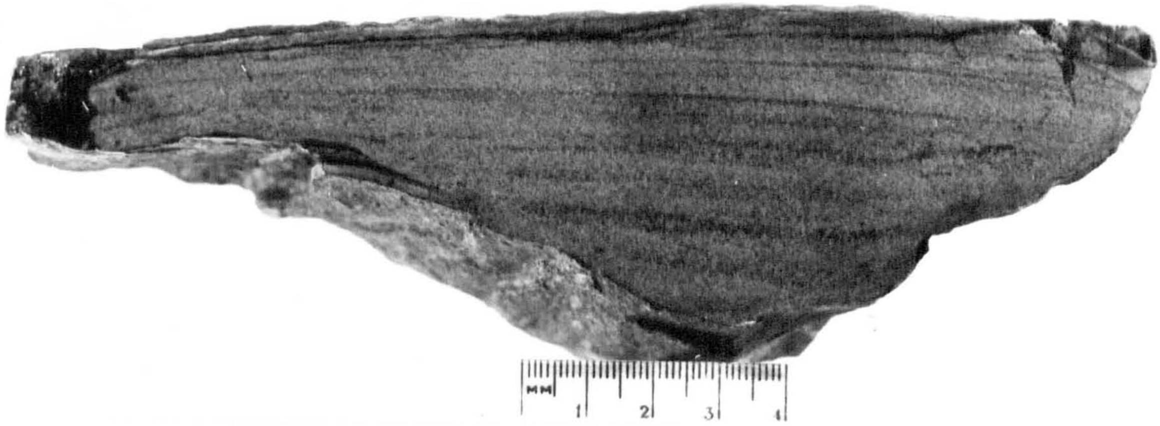
Plate 4.13c

As above, showing clean sandstone in rippled top and irregular partings within the bed. The base of the bed and intra-bed partings show L-ridges. Disturbed bedding indicates syndepositional origin of the L-ridges.

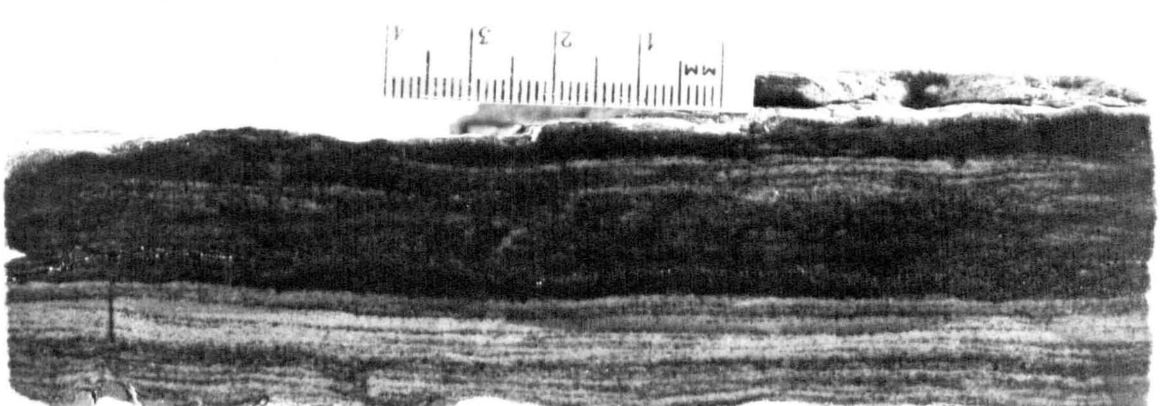
Pl. 4.12



a

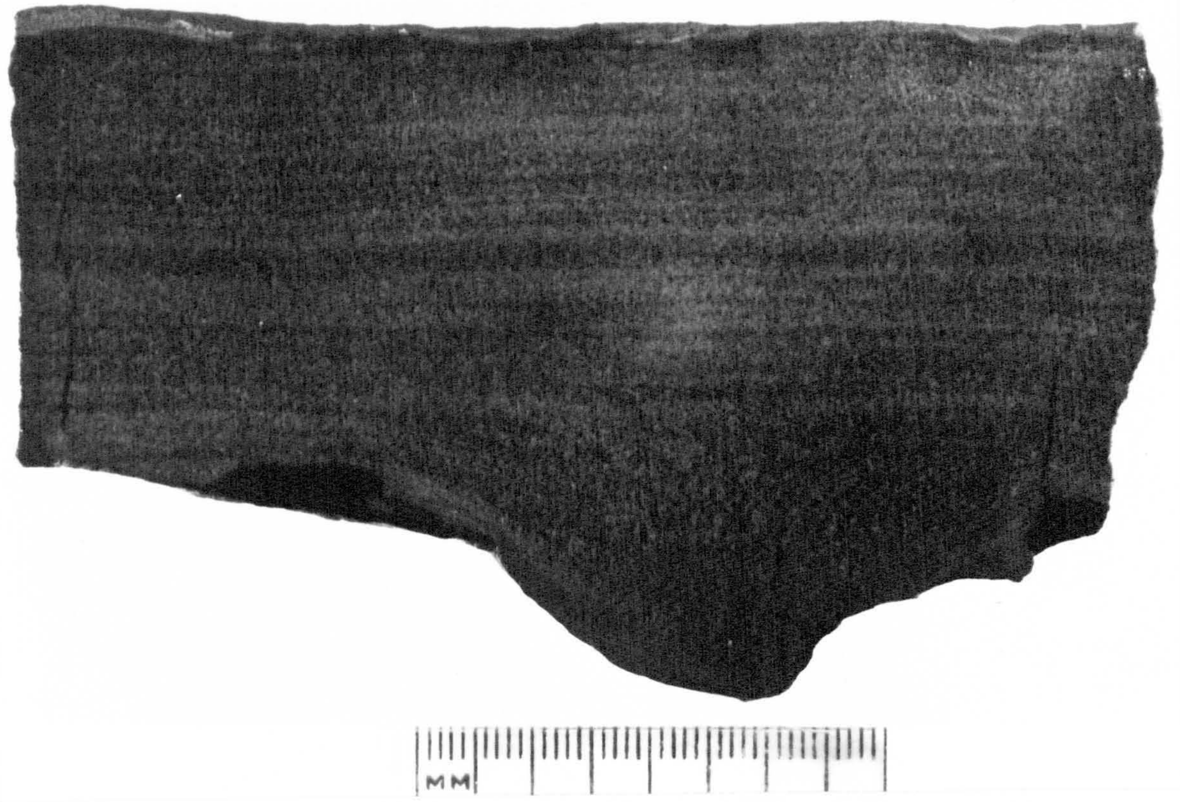


b



c

Pl. 4.13



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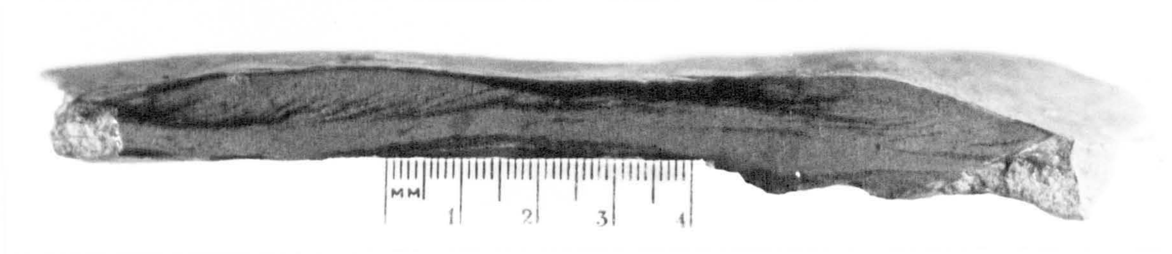

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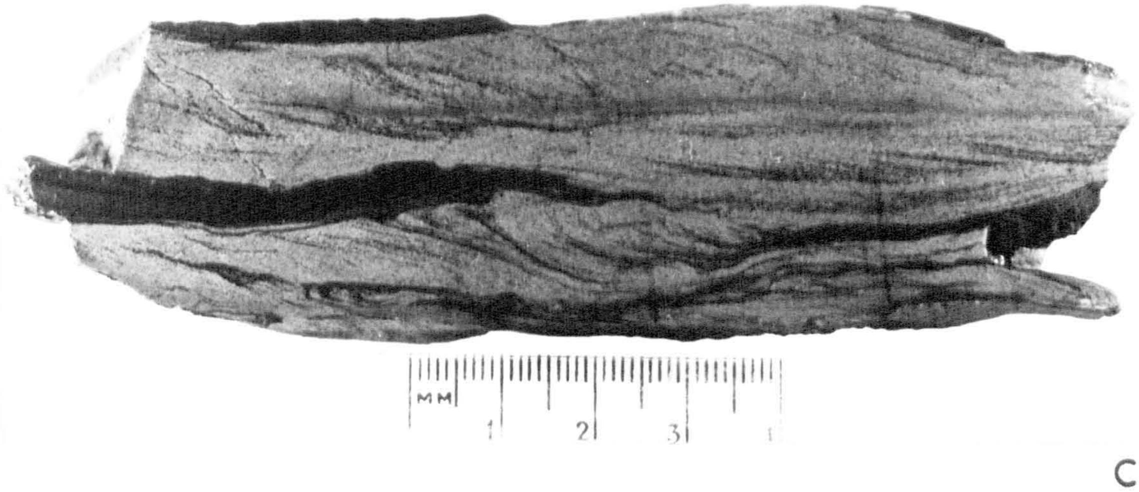


c

Prod and groove casts occur on the base of the same bed in some examples, but groove casts tend to be more common on the base of the thicker (6 cm) b-division sandstones. The grooves are continuous for a minimum distance of 30-35 cm and are either straight or slightly curved along their length. Height and width is generally approximately 1.5 and 3 cm, the features having been made by tools of larger dimensions than the prod casts. Such marks could have been formed by larger plant fragments found in coalified layers in the thicker sandstone beds above the a-division. The high frequency of drag marks in Kulm greywackes with profuse plant remains led Kuenen (1957) also to suggest that waterlogged stumps and sticks might be suitable as tools.

Groove marks on this larger scale are frequently exaggerated by load casting (Plate 4.13a) of the infilling sand. Small flames of mud protrude upwards into the sandstone, and thin quartz-rich laminae within the underlying mud cut out by the formation of the groove, are seen to be distorted. The laminae of sand which fill in the groove are distorted, but subsequent laminae are parallel, indicating that load casting took place early in the deposition of the sand.

Groove casts on the base of sandstone beds can be parallel to each other or diverge at fairly high angles. Kuenen (1957) found that where groove marks on a single bedding plane are parallel, those on different beds in the same area diverge by only a few degrees. Where grooves do diverge, they tend to form two sets of parallel furrows, intersecting at an angle of approximately 30° with only a few marks in intermediate directions. Examples from sublithofacies (pB) show two sets of grooves diverging at an angle of approximately 34°. One set of groove casts appears to be later than the other, and the direction of primary current lineation (N 59°E), seen on splitting the bed, is more closely related to the later set of grooves at N 49°E than the earlier set at N 15°E.

Divergent sets of groove marks have been attributed by Hsu (1959, p.534) to the picking up of sheet sands by a current flowing in a different direction from the first depositing current. Crowell (1958) also attributed different trends of sole markings to different currents, which eroded flute and groove marks, but Kuenen and Ten Haaf (1958) doubted that empty flute marks might be left behind by a non-depositing current. Anderson (1965) explained two sets (or more) of lineations by suggesting that two or more currents may have been operative, the second current completely removing the previous sand bed before it cut its own current marks. This phenomenon may be necessary to explain sets which diverge by as much as 90°, but as Ten Haaf (1959) suggested, divergent sole markings may be cut by the advancing lobes of a turbidity current fanning out in a radiating manner, and would adequately explain the grooves with a low angle of divergence, such as those noted here.

Comparison of the typical section with other sections

All other sections associated with sublithofacies (pB) occur within a radius of 1 mile (1.6 km). In these three sections, the sandstone unit is a maximum of 9 m thick and the thinning of the unit is accompanied by a decrease in the number of massive a-division sandstones, and an increase in the number of b- and c-division beds. No small channels have been noted in the thinner parts of the sandstone unit, except at one exposure where pebbly beds are present. These occur at the base of the turbidite sequence at 2 m above the R1c marine band. The basal bed is a parallel-sided 10 cm sandstone, containing grains of quartz and shale up to 4 mm in length.

Rippled sandstones

Although the c-division is common in the typical section, rippled beds occur to the exclusion of other features where the unit thins. Bed thickness in such cases rarely exceeds 4 cm, and the sandstone base and partings within beds frequently show modified longitudinal ridges (see below). Discontinuous partings occur within beds (Plate 4.13b and c) and ripples usually show stoss-side erosion.

As noted in the typical section, b-division beds rarely contain much pelitic material, which probably explains the abundance of ripple-topped sandstones in the unit as a whole. Beds which consist of shale pellets and the c-division only may have been deposited from high velocity currents which carried the bulk of their material into the basin or central part of a channel. a- or b-division sands would readily be reworked if pelitic material were not available since the surface would remain cohesionless, and ripples form in the waning flow. When grain movement eventually ceased, ripples would remain as the relict bed form. These c-division beds are in contrast to the few examples of ripples recorded from (pA) where they were formed as material fell continuously from suspension (Plate 4.10a).

Sole structures of the rippled beds

Modified longitudinal ridge patterns are common on the base of the composite rippled beds, and on the soles of intra-bed partings.

Ripples seen on the upper surface of the sandstone are invariably linguoid in plan and this pattern is reflected on the lower deformed sandstone surfaces. These have smoother areas with an apex pointing down-current, and load-casted inter-areas with polygonal cell patterns. These patterns form on the down-current side of linguoid ripples, and are drawn out into longitudinal forms around the shape of the linguoid ripple.

Such structures have been described as "modified ripple marks" (Craig and Walton, 1962), and furrow casts superimposed on ripple marks (Winterer, 1964, p.170-171). Structures described by Kuenen (1957, p.235) as "rill marks" on the down-current side of ripples may be a structure of similar origin.

The origin of longitudinal ridge and scaley patterns associated with ripples on the underside of rippled beds may be pre- or syn-depositional. Winterer (1964) suggested that such sandstones were deposited on the already rippled surface of the underlying muds, the ripples having originated from deposition of a thin layer of mud over the underlying bed, or from scour. The furrows (L-ridges) were cut on this rippled surface by a subsequent current which also cut flute marks, obliterating some of the L-ridge pattern (Winterer 1964, fig.16-18) before the deposition of the graded sandstone. The origin of the structures in this case is certainly pre-depositional (as also suggested by Craig and Walton, 1962), but similar structures described by Dzulynski and Kotlarczyk (1962) appeared to be post-depositional in origin and were thought to be related to the "flowage of water and sand along the mud interface".

In the sublithofacies (pB) examples, it is difficult to tell if the structures are syn- or postdepositional. Modified L-ridge patterns on the base of intra-bed partings may have formed before the deposition of any sediments in response to the already rippled sediment surface (as in the examples cited by Winterer). Cross sections of some of the beds, however, show distortion of the basal laminae (Plate 4.13c), this and the close correspondence of the distribution of the pattern on the lower surface with the linguoid pattern of the upper suggesting a syndepositional origin.

Non-directional sole casts

Thinner sandstones frequently show hieroglyphs on their soles. Holdsworth (1963a) and Trewin (1969) found that the majority of Namurian trace fossils were pre-depositional in origin, as are the examples in sublithofacies (pB).

Vertical burrows

These occur as round, isolated protuberances. In cross-section, the burrows do not transect the b-lamination of the sandstone bed, and are infilled with coarser material, indicating the pre-depositional origin of the structures. The fill of the burrows is slightly distorted indicating some exaggeration of the feature by load casting (Plate 4.12c).

Other features interpreted as vertical, unroofed burrows are the same as those figured by Trewin (1969, fig.2.1 Du). These are small projections, 1 mm in height, which form a hackly surface on the sole. Some marks are horizontal, forming trails 1 mm broad and up to 5 mm in length.

Horizontal burrows

Horizontal burrows are rare. Those which have been found have similar dimensions to the "pyrite tubes" (probably *Planolites*, p.333). They are pre-depositional and can show right-angle branches.

Trace fossils are not sufficiently numerous to suggest a series of relative depth zones for the basin. Modern polychaete worms live in the inter-tidal zone or shallow depths of water (see, for instance, Zenkevich, 1957), but traces of burrowing animals are known from sediment cores taken from depths of more than 5,000 m (Hass *et al.* 1962, p.w 183). Conical mounds and holes formed by holothurians and sea worms have also been noted by Emery (1953) at 295' off

California, but in oxygenated bottom conditions life was in evidence at 3,600' (Emery and Rittenburg, 1952). The Namurian Basin is highly unlikely to have been as deep as the Californian basin environments, but these findings do indicate that a fairly abundant benthonic fauna can occur at depth, providing food and oxygen are available. While some of the trace fossils described from the distal turbidites of the K-feldspathic lithofacies may have lived in the deeper parts of the basin, the forms similar to the pyrite tubes are possibly indicative of shallower water conditions (p.338).

SUBLITHOFACIES (pC) - (pF)

Sublithofacies (pC) - (pF) are exclusively shallow water sediments which accumulated in a deltaic environment. From the fragments of the succession seen, it is thought that a sequence in these sediments can be distinguished indicating shallowing-upwards conditions. The sediments range from those possibly deposited off a distributary mouth to those found in channels. Each sublithofacies, although forming only a small part of the succession seen, is quite distinct.

Extent of sublithofacies (pC) - (pF)

This sublithofacies group is found only in the south of the field area. A similar sublithofacies occur in H1-H2, and possibly in the upper *Eumorphoceras* stage in the Endon and Stanley area, where thick protoquartzites are present. The lithologies are briefly described in Gibson, Barrow and Wedd (1905, p.27).

> The beds associated with, and separating the different bands of Crowstones, are more often white and red marls and fireclays then grey and dark shales, though the latter occur at times.

> Their nature may be seen in the quarry between the two Crowstone {ie. protoquartzite} outcrops west of Endon. "Smuts" and thin seams of coal occur occasionally associated with fireclay; and one of these was worked on the south side of Hough Wood, south of Stockton Brook. As far as could be ascertained it was rarely as much as a foot thick, and appears to be of a local nature, for it was only followed for a short distance. In an old clay pit close to Rownall Farm, rather more than a mile to the north of Werrington, some marly shales lying between two beds of Crowstone contain calcareous nodules with well preserved specimens of *Goniatites*.

The quarries mentioned above are now overgrown, but the Rownall Farm quarry has yielded goniatite fragments possibly referable to R1. The Houghwood quarry still exposes at the top a marine band containing *Nuculoceras nuculum* and *Eumorphoceras* mut. *beta* indicating an E2c or a pre-E2c age for some of the sediments described above.

The group of sublithofacies is rarely well exposed. Good sections are available in H1-H2 sandstones (sublithofacies pF) on Endon Edge, and sections of sandstones of uncertain age (probably H) are seen at Woodhouse Green and near Morris House (Endon and Stanley area). Though the "Crowstones" at Rownall Farm are unexposed except for one thin, calcareous sandstone, it is possible that the sublithofacies developed is (pF) as the lithology of the overlying marine band is comparable to that of the *R. gracile* shell bed which itself succeeds (pF) sandstones at Oakamoor.

Typical section

Fragments of the sublithofacies group have been recognised at the above localities, which are confined to the south of the field area, but descriptions of the typical sections have been drawn exclusively from the stream section of The Combes. Exposure in this area is relatively good, though limited in areal extent, so that interpretation of the sublithofacies group is difficult because of the lack of geographical control. Current directions have not been measured as they would be of little use in interpretation of the sediments when concerned with only a small area. The general direction of supply of the sediments, deduced from current structures, was from the south as might be expected from previous studies of local Namurian proto-quartzites.

SUBLITHOFACIES (pC) -- grey and purple mudstones

Dark grey and black, fine grained marine and non-marine shales typical of the basin environment to the north are virtually unknown in the area of deposition of the deltaic sediments. Only a single black shale band containing Dunbarella is present in the succession exposed in The Combes. Other faunal horizons and the influence of the environment on their fauna are discussed in the section on condensed shell beds.

Mudstones without a pronounced fissility, and containing more mica than those interbedded with sublithofacies (pF), are best developed at the base of a rhythm (Plate 4.14a) where 90% of the lower 2 m of the rhythm consists of purple but mostly grey shales and mudstones with thin interbedded silty and sandy beds. The siltstone beds vary from 3-8 cm in thickness and are structureless or faintly laminated, and lack sole casts. The intervening shales are grey or purple, the siltstone beds light grey or yellowish at the base of the bed where a patchy yellow stain indicates a secondary origin for the colour. This sublithofacies passes upwards into mudstones and more numerous sandstones and siltstones interbedded with purple shales, similar to sublithofacies (pD). Sublithofacies (pC) immediately overlies a (pF) sandstone but the relationship between the two sublithofacies is not seen elsewhere.

SUBLITHOFACIES (pD) -- sandy streak beds

The sandy beds, which appear to be laterally continuous in the field, are composed of 2-8 cm rippled sands and silts interbedded with grey mudstones similar to (pC). The sandy streak beds show continuous ripples and cross-lamination similar to the ripple-drift cross lamination type 1 of Walker (1963, p.181, fig.2). The sandy beds can have a sharp base and top, but some show gradation into silty streak sediments. The lower laminae of the sandy beds decrease in thickness from 3-1.5 mm and pass into silty streak beds with discontinuous laminae. These silty beds have only been seen on cut surfaces. Some of the grey mudstones between the sandy beds may also consist of silty sediments.

In the cases where the base of a sandy unit is sharp, it is likely that it is erosive, as the base is often slightly irregular. In cross section (Plate 4.14c and 4.15a), the sandy laminae cut out the lower silty laminae, bending them down at the margins of the erosive feature, possibly due to compaction. These small erosional features may be similar to those (2 cm wide and 0.5 cm deep) noted by Walker (1969, p.131) at the base of cross-laminated siltstones. In the examples noted here, however, dimensions of the erosive features reach up to 8 cm in width and 2 cm in depth. Specimens in plan view commonly show small protuberances on the base of the bed, interpreted as trace fossils (small burrows). Burrows are fairly common in the sandy streak sediments within the beds and on the soles of the beds. Trace fossils on the base of one bed are up to 2 cm in length and slightly meandering, forming an S-shape. The burrows (Plate 4.15b) are round in cross section (3 mm in diameter) and filled with sandy material. The same sandstone bed is also penetrated by vertical burrows, shown by the bending downwards of occasional mud wisps around the original entrance to the structure. Some burrows within the bed are horizontal and the top of the bed, which appears to be structureless, may have been bioturbated, resulting in the partial destruction of the laminae.

The sandy streak lithology described above is interbedded with grey mudstones, but at another locality purple shales also occur interbedded with the (pD) sandy beds, above sublithofacies (pC) mudstones. Here, the sandy beds do not show small scale erosional features, but have climbing ripples and inclined lamination developed (Plate 4.15c). Calcite veins associated with small amounts of pyrite cut these beds. The pyrite indicates that these thin sandstone beds, in this case interbedded with grey, not purple, shales were deposited in conditions less oxidising than normal in this part of the succession, resulting in the reduction of the iron and a grey colour for the sediments.

SUBLITHOFACIES (pE) -- cross-laminated and interbedded lithologies

The lithology between the cross-laminated sandstone is extremely variable, ranging from purple mudstone, to greenish mudstones and grey, silty streak sediments. Burrowed sandstones also occur with the typical cross-laminated sandstones, but since this type of

Plate 4.14a

Sublithofacies pC beds. Mudstones with thin silty bands rest on a pF sandstone. pC beds pass upwards into sandy streak beds. Loc. 193.

Plate 4.14b

Upper surface of the pF sandstone at the same locality showing parallel-orientated logs of wood.

Plate 4.14c

Sublithofacies pD beds (sandy streak). The harder ribs of sandstone frequently have an erosive base, but can grade into sandy beds from silty streak beds (see the lower of the two sandy beds). The sandy streak beds are also interbedded with grey mudstones. Loc. 194.

Plate 4.15a

pD bed showing erosive base, loc. 194.

Plate 4.15b

pD bed showing cross section of burrow on the base of the bed and bioturbated laminae, loc. 194.

Plate 4.15c

Climbing ripples in a bed from the upper part of the section shown in Plate 4.14a. These beds are probably gradational between pC and typical pD.

Plate 4.16a

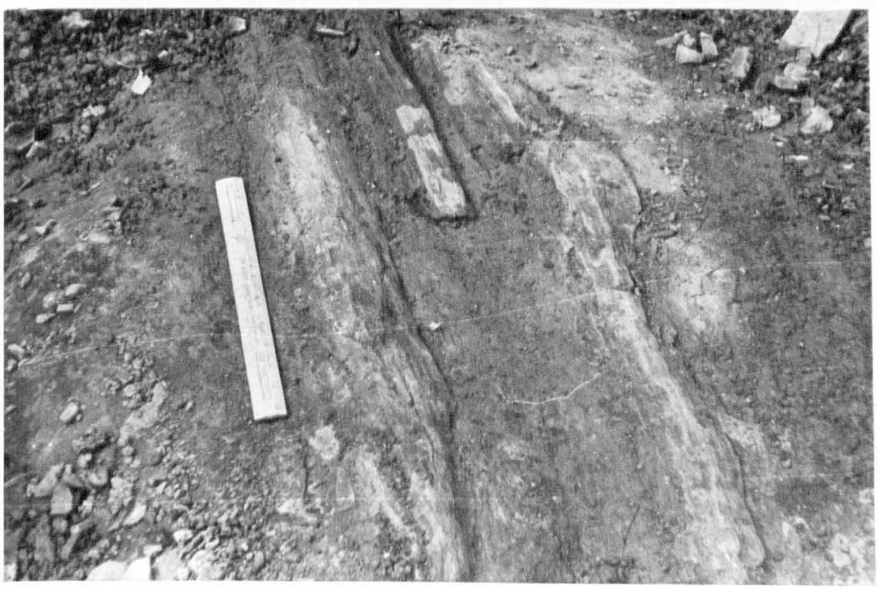
Silty streak beds with rippled sandstones, sublithofacies pE, loc. 195.

Plate 4.16b

Sublithofacies pE sandstone showing gradational base and sharper top. The entire bed is ripple cross-laminated, and shows more iron staining in the central part. Loc. 195.

Pl. 4.14

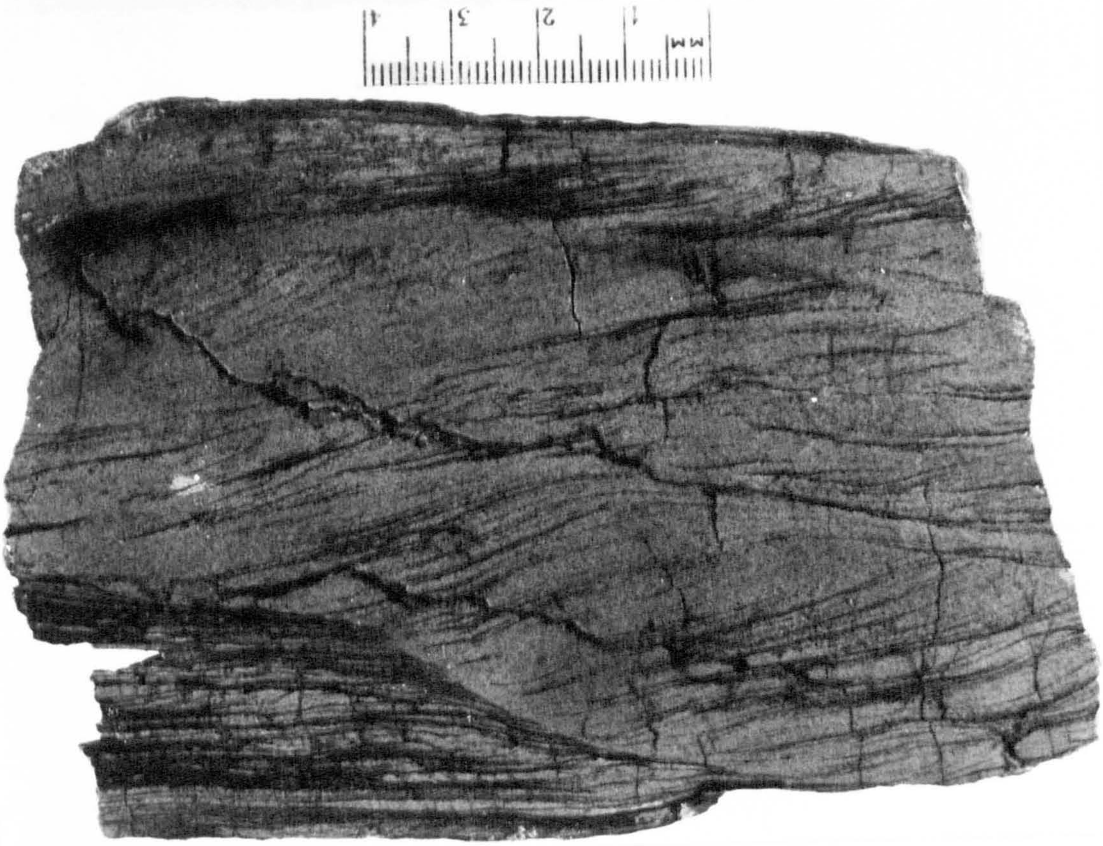
a



b

c

Pl. 4.15



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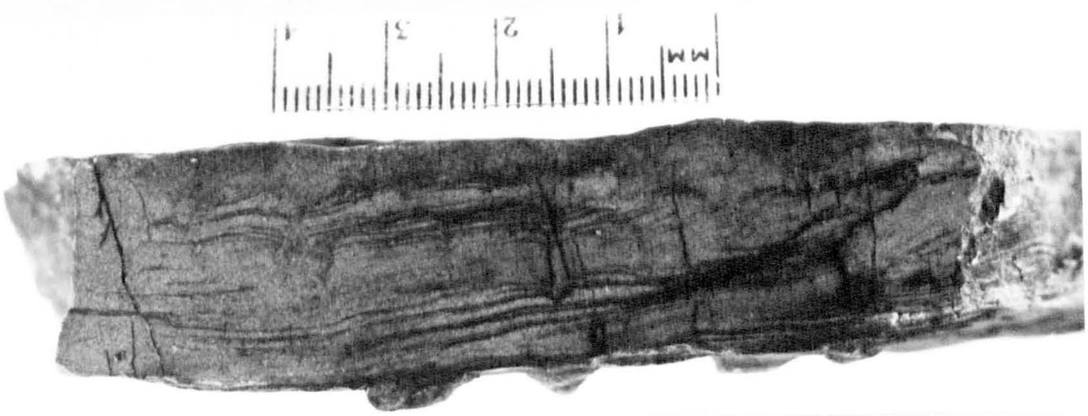

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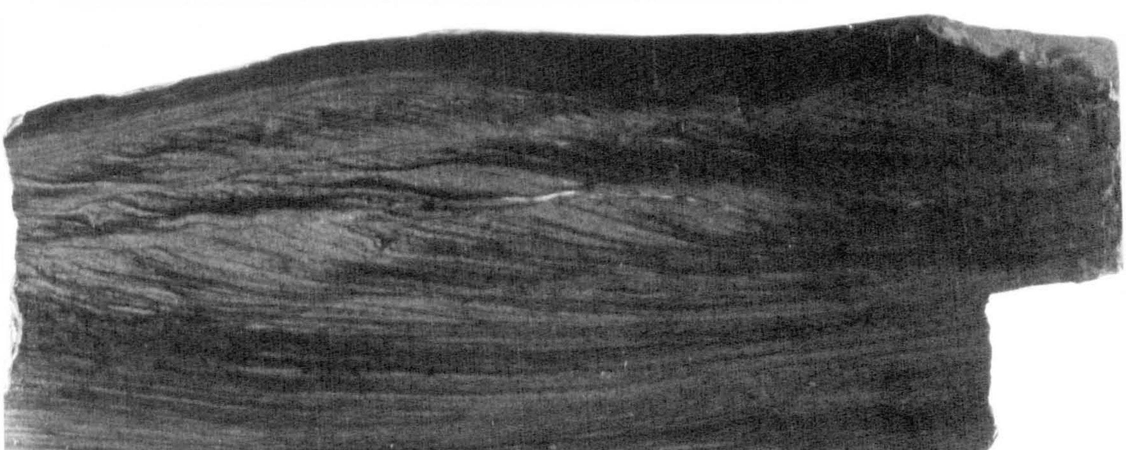
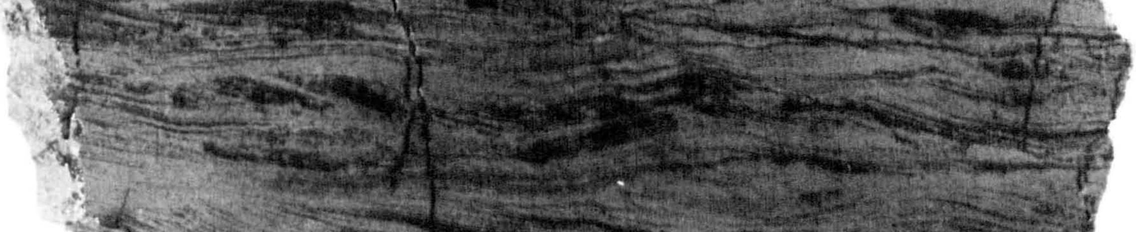


c

Pl. 4 16

a



b

sandstone is rare, and gradational from the cross-laminated sandstones, description has been included in this section. The sublithofacies thus includes a number of types of lithology which, had sufficient exposure been available, might each have merited the status of a separate sublithofacies.

The silty streak sediments between the cross-laminated sandstone beds consist of lighter coloured quartz-rich laminae (1-3 mm thick) alternating with finer grey laminae 2-4 mm thick. Plant debris is not abundant on parting planes, small fragments of plants 1-2 cm in length occurring only in the silty shales above the sandstone beds. The lighter coloured laminae are roughly parallel-sided over short distances, but are laterally discontinuous. The lithology grades into either purple shales, or into a more sandy bed. Silty streak beds can reach up to 58 cm in thickness (Plate 4.16a).

Purple shales between sublithofacies (pE) sandstones are generally reduced to partings 1-2 cm in thickness, but can be expanded to 6 cm. The most intense colour is often developed immediately above the sharp sandstone tops. The purple shale units tend to be most common in the succession where (pE) cross-laminated sandstones are well developed beneath sublithofacies (pF). (pF) can be preceded, however, by interbedded (pE) sandstones and thicker units of mudstones. These range from purple to grey and greenish colours and occur in a unit 2.75 m thick, in contrast to the thin units of purple shales alone.

Cross-laminated and associated sandstone beds

The sandstone beds contain virtually no pelitic material, in contrast to the sandy streak beds. Some thinner sandstones in the sublithofacies unit (approximately 7 m above sublithofacies (pD) beds) are transitional between sublithofacies (pD) and (pE) (Plate 4.16b). The sandstone beds often have a distinctive red-brown stain, especially where interbedded with purple shales higher in the sequence.

Where transitional beds occur at the base of the sequence seen, the base of a particular sandstone bed is gradational, poorly laminated mudstones passing upwards into ripples with thin mud drapes which are reduced to lee-side ripple laminae in the overlying sets (Plate 4.16b). Ripple forms in the thicker sandstone beds are often partially obscured by the heavy red-brown stain, typical of a large proportion of the sandy deltaic sediments in the Combes area, and in similar sediments in H. The stain of the sublithofacies (pE) sandstones is more pronounced on the lee-side of ripples showing stoss-side erosion, and is probably related to the accumulation of plant and pelitic material in the lee of the ripples. In beds overlain by grey silty streak sediments, the concentration of the red-brown stain is in the middle of a sandstone bed where stoss-side erosion is most common. These ripples pass upwards into forms with continuous pelitic laminae, suggesting that the red stain is related to shallower water and more active transport of the sediment where iron was more readily oxidised, or remained in an oxidised state. Staining tends to be more pronounced in the thicker sandstones up to 0.75 m thick which are almost wholly composed of ripple lamination structures, sometimes trough cross-laminated.

The colour of the sandstones is most pronounced in the rare, thinner, bioturbated 5-8 cm sandstone beds which are purple and almost invariably overlain by purple shales. Internal structures of the purple sandstones can show basal ripple sets 0.5-1.5 cm thick. These pass upwards into more deeply stained and finer grained sediments, alternating, on some occasions, with lighter-coloured quartz-rich layers (Plate 4.17a). The lighter-coloured layers of the sandstones contain horizontal and vertical burrows, as well as vertical burrows which penetrate the base of the bed (Plate 4.17b). Quartz-rich layers and the finer-grained layers, in particular, also show wispy lamination in cross section, suggesting that the original sedimentary structures have been disorientated by bioturbation of the sediments (Plate 4.17a). The structures are similar to those shown in vertical sections of the laminated sandy marsh clay and argillaceous sandstone figured by van Straaten (1954, pl. 1, a and b) from Recent tidal flat deposits and sediments of the Condroz (Devonian).

Also associated with sublithofacies (pE) rippled sandstones, in a position higher in the shallowing upwards sequence, are 5-8 cm parallel-laminated sandstones. Rippled sandstones increase in thickness up to 0.75 m and are interbedded with thicker units of blue-grey and purple shales and parallel-laminated sandstones. A transition can be observed between rippled sandstone units and parallel-laminated sandstones, where the frequency of ripple lamination within a bed decreases at the expense of the development of the parallel lamination. Parallel-laminated sandstone units also occur in association with 35 cm rippled sandstone beds in a more sandy part of the succession. Here, purple shale units are reduced to 18 cm and frequently 5 cm in contrast to the succession with the coloured shales up to 2.75 m thick. In both cases the parallel-laminated / rippled sandstone association passes upwards into sublithofacies (pF).

Structures of the ripple cross-laminated sandstone beds

Linear structures were noted on the upper surfaces of several of the rippled sandstones in the field, and were originally thought to be trace fossils. On sectioning of the rocks however, the structures were seen to be penetrative, and not simply surface trails. The bending down of the laminae commonly seen around the entrance of burrow structures is absent, this and the planar penetrative structure of the features suggesting that their origin is inorganic.

In cross section the cracks penetrate to a depth of 7 cm, and are inclined at 70^{o}-90^{o} to the surface of the sandstone bed (Plate 4.17c). The cracks are stained with brown material, probably limonite from present-day weathering. Horizontal brown stained layers open off the main branch, but extend laterally to only 1.5 cm. These follow parallel laminae or ripple laminae (Plate 4.17c). On the surface of the sandstone bed, the brown material spreads out laterally, forming slightly raised areas 1-2 cm wide along the length of the penetrative cracks. The cracks are either straight, or bifurcate at a narrow angle (Plate 4.18a). The longer cracks are sub-parallel to each other and appear to be cut by a later set which tend to be oval rather than linear. It was not possible to obtain any sections through the latter type to see if they were similar in structure to sand volcanoes or not.

Other examples of the linear features do not show lateral spreading over the surface of the sandstone but are raised sharply above the surface to a height of 3 mm. The more prominent forms are also narrower, reaching a maximum of 1 cm in width. These are in two sets which intersect at approximately 90^{o} (Plate 4.18b).

Similar structures are figured by Bajard (1966) from the inter-tidal sediments in La Baie du Mont-Saint-Michele. The banks of the tidal channels in the bay are inclined at a low angle. Desiccation cracks form in the silts and muds exposed at low tide, the cracks remaining open at their upper end (ibid. fig. 131). Lower down, they are filled with lighter-coloured material, and show horizontal branches. Bajard noted that the shrinkage cracks could not have formed had there not been a certain amount of clay in the sediments. Shrinkage cracks form on the slopes of the channels, perpendicular to the mud surface. They are orientated parallel to the length of the channel, the formation of the cracks being facilitated by the lateral creep of the sediments due to gravity. Williams and Rust also figure similar structures initiated by walking on channel banks of thixotropic sediments, often disturbed by silt volcanoes (1969, p.664 and 657).

Similar cracks in the sublithofacies (pE) sandstone are unlikely to have originated simply as desiccation cracks since they occur in clean sandstones with little mud even in the lee of ripples. The orientation of the cracks is not known because no flat, large surfaces are available in situ. On the largest of the surfaces seen, however, the longest cracks are orientated at only a slight angle to each other. Smaller, less regular cracks occur at approximately 90^{o} to the main set (Plate 4.18a and 4.18b) but a polygonal pattern is never developed. It is suggested that these cracks could have formed in the sandstones, at intervals of low water, by the creep of sediments towards the centre of the channel after a thin clay veneer had already been deposited. The cracks at some stage appear to have expelled a fine-grained, watery sediment which exuded across the surface of the sandstone bed. The fluid may also have been impelled along planes in the rock (eg. ripple laminae) since horizontal branches from the main branches are common (Plate 4.17c). It is doubtful whether the watery sediment, which appears to have escaped from the sands, would have been preserved as a feature in relief if the liquid had simply flowed out on to the exposed surface of the bed. It is possible that when movement took place, a thin layer of mud had already been deposited over the sandstone in the waning stages of flow during the drop in water level in the channel. On lateral creep of the sediments, the mud could have yielded plastically, forcing the fluid to expand laterally between the sand/mud interface and along ripple-laminae lower down. Sellwood (1972) notes that sand beds become saturated with water with rising tides, hydrostatic pressure increasing where the beds have been sealed off by clay. Injection of the material could have taken place at this stage. It is not clear in these examples where the material came from, since the cracks rarely approach the base of the bed into the underlying clay. Within the bed, the cracks are picked out by a brown stain which colours the original sediment rather than displacing it, and it is only on the top of the bed that a space appears to have been infilled by red silty material. Where the infilling of the cracks stands out in marked relief on top of a sandstone bed (Plate 4.17c and 4.18b), it is possible that the mud dried out, and desiccation cracks first developed in the mud, initiating the penetrative features of the sandstone bed. Expelled fluid would then have escaped on to the mud surface resulting in sand and silt volcanoes, and would not have been preserved as a lateral injection feature at the interface of the two lithologies.

Trace fossils

Apart from the trace fossils of the infrequent bioturbated beds (p. 275), organic traces are rare, and have never been observed in the typical ripple cross-laminated sandstones. Traces left by any organisms were probably soon obliterated by reworking of the sediments. Tubes (possibly burrows) of similar dimensions to the

Plate 4.17a

Beds associated with sublithofacies pE -- reddened sandstone showing ripple cross-lamination in the lower part. The upper part of the bed has wispy laminae, possibly from bioturbation. Loc. 195.

Plate 4.17b

Base of the same bed showing burrows. A burrow can be seen in cross section near the base of the bed in Plate 4.17a.

Plate 4.17c

Cross section of typical pE bed showing penetrative cracks. Iron-rich areas are shown by the darker colour, and penetrate ripple laminae at right angles to the main crack. Loc. 197.

Plate 4.18a

Upper rippled surface of pE bed showing bifurcating cracks and irregular areas of iron staining, possibly from sand volcanoes. Loc. 195.

Plate 4.18b

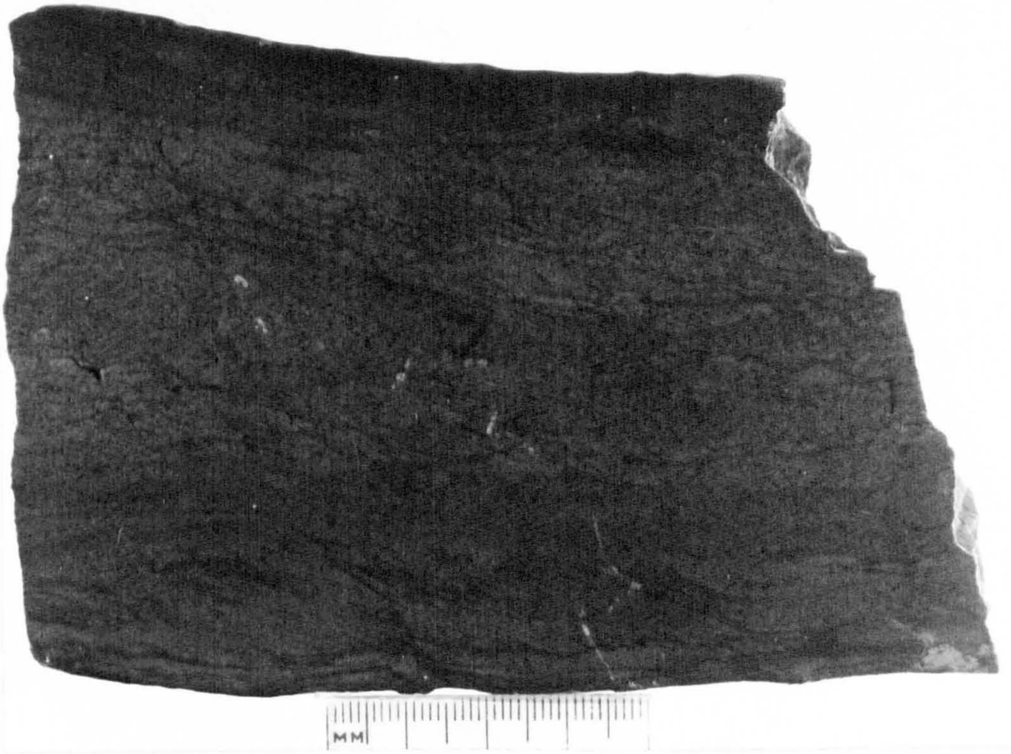
Upper surface of pE bed with cracks preserved in high relief. Two sets intersect. Loc. 197.

Plate 4.19a

pF sandstone showing lower load-casted surface, followed by apparently massive unit. This, on sectioning, shows cross-bedding followed by parallel bedding. The "massive" unit is followed by irregularly bedded sandstone before a second massive unit. Loc. 199.

Plate 4.19b

Basal lag conglomerate consisting of small quartz pebbles and elongated, ochre-coloured pebbles, some of which (top right) may have a concretionary origin. Loc. 198.



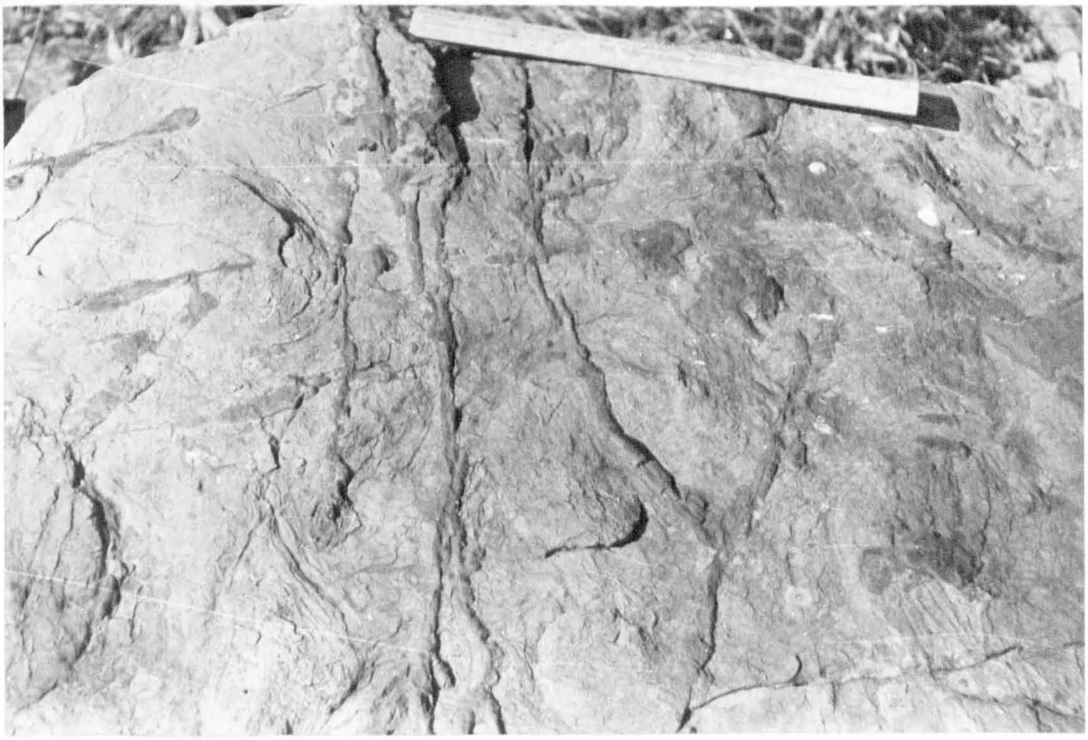
a

b

Pl. 4.17

c

Pl. 4.18



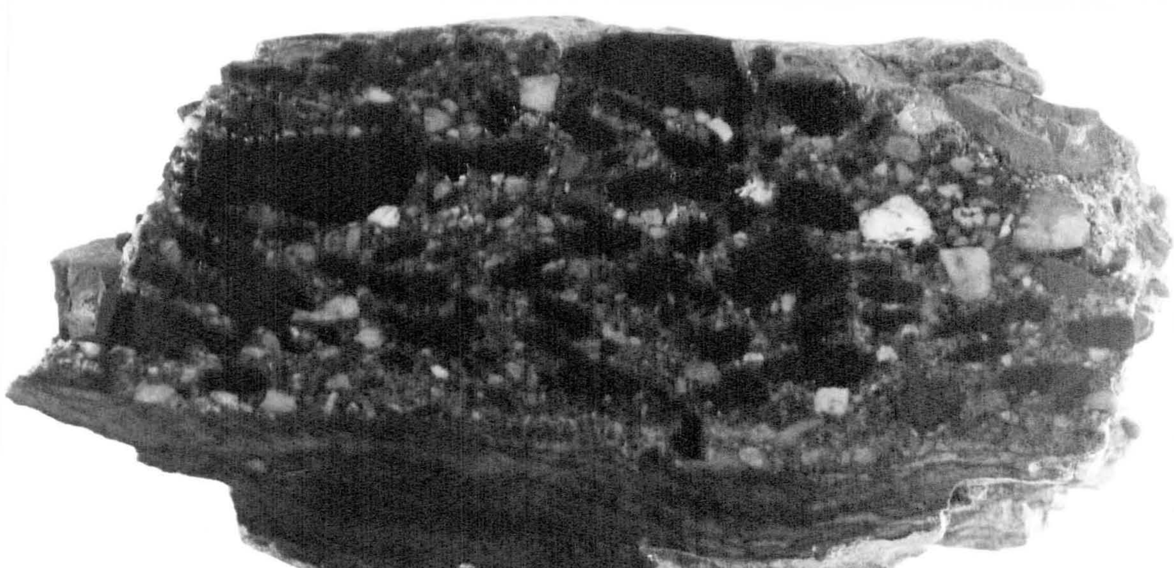
a

b

Pl. 4.19

a

b



pyrite tubes (p. 333) have been found in the silty shales.

SUBLITHOFACIES (pF) -- coarse-grained, cross-bedded sandstones

The bases of the cross-bedded sandstones are invariably load casted where they rest on shales (Plate 4.19a). The sandstones generally form sheets continuous across the width of an exposure and parallel to the bedding of the underlying rock. At one exposure above sandstone-rich (pE) beds, where the rippled sandstones are separated from each other by thin purple shales, it is possible that (pF) sandstones fill a channel cut into (pE) beds. A lag deposit up to 21 cm thick (Plate 4.19b) occurs at the base of the channel. The deposit consists of ochre and red-brown, largely elongated but rounded pellets up to 3 cm in length. The margins of some of these imbricated pellets are entire. They may have formed from desiccated mud flakes, or eroded siderites and siltstones.

Some of the ferruginous particles, particularly those higher in the massive sandstone, appear to be rounder and are also larger. These might have a concretionary origin. Coleman and Gagliano (1965, p.146) found that ferric nodules, between a few millimetres and a few centimetres in diameter, formed on exposure of the Mississippi levees to the air. Such nodules could form as discrete aggregates or around plant and root fragments. These would be hardened in an oxidising environment accounting for the lack of armouring of the particles during transport, unlike the clay inclusions reported by Coleman and Gagliano.

The ferruginous particles of the lag deposit, seen only at one exposure, are set in a sandy matrix with quartz pebbles up to 1 cm in length. The conglomerate rests on rippled sandstones with discontinuous yellow and white finer-grained silty laminae. The yellow colour of the sandstones, and of thin bright yellow lenses which elsewhere precede sandstones interbedded with purple shales, may be due to the formation of jarosite. This develops on present day weathering of pyrite, which could have formed where organic material had accumulated. Johnson and Friedman (1969) also noted pyrite-rich lenses in organic material at the base of channels.

The lag congbmerate is not immediately followed by cross-beds but by a yellow parting and 21 cm of plane beds. These are cut by coarse grained trough cross-bedded sands. Higher, finer grained, massive sandstones contain ferruginous inclusions. It is likely that all of the thicker sandstones are cross-bedded. A massive sandstone with a load casted base (Plate 4.19a) was found, on sectioning, to consist of cross-beds in the lower part, followed by plane bedded sandstones which truncate the cross-beds. The unit passes upwards into unevenly bedded sandstones, which at one locality, have large plant fragments on the upper surface (Plate 4.14b). The sequence in the coarser grained sandstones from lag conglomerate to plane beds, followed by trough cross-bedding suggests deposition of the coarser grained sandstones in meandering channels from successively slower flows (Allen, 1963). Where cross-beds are truncated by plane beds, the coarser grained sandstones may have been formed as crevasse splay deposits entering bays adjacent to the channel.

INTERPRETATION : SUBLITHOFACIES (pA) and (pB)

Deltaic deposits occur in the south of the field area. From the direction of derivation of (pA) and (pB), deduced from sole structures, it is reasonable to assume that the sediment of these turbidites originated from the deltaic area. (pA) is distal to (pB) if both were derived from the delta. (pA) is often thinner bedded than (pB), but maximum bed thickness is greater in (pA). Slumped beds and channels are more common in the distal beds, but c-divisions are more common in the proximal beds than the distal beds where a- and b-divisions predominate. These features need explanation since they are the reverse of what might be expected in proximal and distal beds at similar stratigraphic horizons.

As noted in Chapter 3, (pA) protoquartzites occur at two levels in the R1b succession and are extremely limited in lateral extent, suggesting that they were deposited in the form of tongues from the source area. That the protoquartzites are lenticular in cross section is suggested by smaller sedimentary features, such as channels, which occur at Ballbank and the Blake Brook. These channels are similar to those described by Unrug (1959) from the Carpathian Flysch in proximal deposits. Channels were also recorded by Walker (1969) in the turbidite facies of the Northam Formation, and thought to indicate a more proximal environment than the parallel-sided facies alone. In North Staffordshire, (pA) shows channels more frequently than the more proximal beds, suggesting that the velocity of flow of the turbidites in the distal beds may have been as great as in the proximal beds.

Some of the sedimentary features indicate instability in the sediments soon after their deposition. Formation of pseudonodules would have been aided by the existence of a soft mud bottom and instability in the sediments. Kuenen (1958) reproduced, experimentally, isolated nodules from a sandstone bed by shaking, resulting in the liquefaction of the substrate. Pseudonodules formed in this manner were still attached to the original sandstone by thin strings of sand. This feature has not been observed in the R1b specimens.

That the formation of the pseudonodules is due to liquefaction of the sediment from shock waves, possibly generated by sliding masses of sediment (Terzaghi, 1956) is supported by the occurrence of a sandstone dyke in association with the pseudonodules at one exposure. The formation of such dykes is attributed to the liquefaction of sands, often deeply buried, by earthquake shocks. Shorter sandstone dykes may, however, be formed by the passage of slumped beds (Dzulnski and Walton, 1965, p.162).

Nevill (1967) found that the movement of sediments (in his case, sandstones of deltaic origin) might simply be in the form of rafting of a sandstone bed down a greasy slope, resulting in the breaking up of the sandstone bed into rounded, isolated blocks surrounded by clay. This may account for some of the blocks of sandstone recorded in North Staffordshire as pseudonodules, but slumped beds are often entire and clearly folded. As noted by Nevill, movement of the sandstones and their deformation might not result in the total disruption of the beds, but in plastic deformation into more complex structures. The bases of distorted beds, like those of the folded R1b sandstones of the Blake, never show good sole structures, these having been rounded off during the slip of the sediments. In the R1b sandstones, slumping may have involved more than one sandstone bed at a time, and included layers of partially lithified shales, eg. in the case of a disorientated shale block. The disturbed sandstone beds were covered with layers of clay (now wrapped around the fold structures) which would have aided sliding and cohesion of the sandstone beds.

The slumped beds described by Nevill can be traced for a distance of thirty miles (48km). The slumping occurred simultaneously over the whole area, this and the consistent direction of slumping suggesting that the cause of instability was far reaching. In the case of the slumped protoquartzites, it is not known how far the slumped beds extend. Because of the lenticular nature of the protoquartzites, the existence of the slumped beds may be of a local nature, only in certain portions of the tongue.

The slope of the basin floor may have contributed to local movement of these turbidites after deposition. It is suspected that the distribution of the deformed sediments is related to the massif / basin junction, one expression of which is the reef knoll line of the Upper Dove. Contorted sandstones are known only at three localities in a narrow zone relatively close to and parallel with this knoll line. Unfortunately, no southern exposures (apart from the lenticular turbidites of the Upper Churnet, which are not deformed) are known in order to determine the frequency of slumped beds away from this zone. It is possible that a line of differential movement could have caused local steepening of the basin profile as late as R1b. Potter (1957) described thrust sheets and a breccia thought to have been formed (at independent horizons) by free gravity gliding of a sediment mass. This was induced in Carboniferous sediments in the U.S.A. by activity along a major fault and anticlinal axis which produced sufficient gradient to result in local instability. Holdsworth (1963b) noted that the original increase in differential movement between the negative basin and the positive massif of North Staffordshire could explain the local D1 (B2) reef building episode. By late P2 times, however, the massif / basin distinction appears to have been lost, and argillaceous limestones accumulated over basin and massif alike. After this period, renewed differential movement is indicated in the D1 (B2)-E2 unconformity of the massif margin in the Upper Dove Valley. Nor does the massif / basin topography appear to have been rapidly obliterated, or at least their differential rates of subsidence, as H and R1 protoquartzites appear to be limited in their extent by the massif boundary. It is only as late as Longnor Sandstone times that sandstones derived from the north can be seen to rest on progressively higher levels of the limestone.

Trewin (1969) also described slumped turbidites (from the Croker Hill area) derived from a westerly direction, possibly indicating a steep slope at the western margins of the basin. No channels were noted in these protoquartzites, but slumped strata consisting of shale mudstone and sandstone occur. These contain fragments of pulled-apart sandstones and inverted beds.

Evans _et al_. (1968) found that slumped beds in H at Gawsworth Common occur in a part of the succession where the sediments appear to have "flooded in at a great rate". Hull and Green's (1866) "concretionary sandstones" occur in a nearby area and probably also formed from the slumping of sandstones.

These examples of slumped beds indicate that it appears to have been the slope of the basin floor and the rate of accumulation of the sediments which caused the slumping. Although no deltaic deposits are seen adjacent to the above areas in E2-H2, it seems likely that the deposits could have originated on or near a delta slope.

Sublithofacies (pB) proximal protoquartzites, however, show little indication of slumping in contrast to the more distal sublithofacies (pA). Very little data is available to speculate on the nature and the distribution of the slumped deposits, but it is suggested that slumping occurred more frequently where steep slopes are thought to have existed within the basin. In the case of the E2-H examples, the steeper slopes were near the western edge of the basin, and slumps were probably precipitated by the rapid influx of sediments. In the case of the Rlb examples, however, it is thought that long, steep slopes may not have been developed in the southern part of the basin, as there is little evidence for slumping and the generation of turbidity flows carrying large amounts of material out into the basin (p.292). Slumping in the Rl examples may occur almost exclusively in a zone parallel to the massif / basin junction, and it is thought that either a remnent sharp change in the basin profile, or renewed instability, could have caused slumping of the deposits into a trough in front of the Massif area. A change in the basin's profile may conceivably account for the channels found in these distal turbidites.

The Rlc (pB) sandstone unit appears to have been deposited as a tongue, possibly in a channel. The area over which the sandstone unit is exposed is limited, but the rapid thinning of the unit from 15 m to 9 m in a distance of less than one mile (1.6 km), and the occurrence of only a few thin rippled beds at one locality, suggest that its shape is markedly lenticular. The general direction of movement of the sediment was from the south-west, with some readings from the south and south-east. Sandstones are absent at Meerbrook, 1¾ miles (2.8 km) to the north. Extremely thin representatives of the unit may occur in the Upper Churnet Valley (p.210) but no more northerly representatives are known.

The sandstones of the Rlc unit show many features in common with turbidites. a-, b- and c-divisions are well developed in the thinner beds, a-divisions alone in the thickest beds. Sole marks are abundant on the base of b-division beds, but rare on the sole of a-division beds. Most a-division beds appear to have been deposited from initially strongly erosive currents which tore up mud flakes, now left as disorientated shale pellets at the base of some a-division beds. The soles of such beds show no other structures.

A comparison with Walker's table of proximal turbidite features (1967, Table 2) shows that most features considered to indicate a "proximal" environment are present, but that important modifications occur.

Walker, 1967. Table 2

Proximal turbidites	Sublithofacies (pB)
A. Beds thick.	Considerable range in bed thickness. Thicker (2 m) beds have been observed in (pA).
B. Beds coarse grained.	Only one pebbly bed has been found. This feature has not been noted in (pA), or in (fA)-(fG).
C. Individual sandstones often amalgamate to form thick beds.	Amalgamation, and mud flake conglomerates common.
D. Beds irregular in thickness.	Beds commonly parallel-sided, but some locally swell into erosive channels.
E. Scours, washouts and channels common.	Small channels are common, but do not reach the 2 m minimum depth for Walker's channels.
F. Mudstone partings between sandstones poorly developed of absent. Sandstone:mud ratio high.	Sandstone:shale ratios high in the thickest part of the unit.
G. Beds ungraded or crudely graded.	a-divisions sometimes show grading. Thinner beds can show a-, b- and c-divisions.
H. Base of sand always sharp, top often sharp, many ae sequences.	Sharp bases. ae sequences common, but sharp-topped a/b/c sandstones also occur.
I. Laminations and ripples occur infrequently.	Laminated beds (1-2 cm) occur where the sandstone:shale ratio is low. Rippled tops in sandstone-rich sections are common. Beds consisting of ripples

	alone occur only in the very thin parts of the unit.
J. Scour marks occur more frequently than tool marks.	Tool marks are found only on the base of the thinner beds in the more shale-rich parts of the unit. No flute casts have been noted. Thicker beds usually have irregular lower surfaces incorporating shale pellets.

Minor channels occur in sublithofacies (pA) as well as (pB) and appear to be no real indicator of the distance of the area of deposition from source. Maximum bed thickness in (pA) is also greater than in (pB). In other respects, however, (pB) does have more features generally associated with proximal environments as indicated above.

It is difficult to make an accurate assessment of the distance of the area of deposition from source as exposure is limited. (pB) was deposited at a distance of approximately 3.5 miles (5.6 km) from the top sets of the southern delta, assuming that the area of deposition of shallow water sediments stayed stable during R1b-R2a. This distance compares with a minimum distance of 6.25 miles (10 km) for (pA) from the same point. These measurements do assume that the delta front ran roughly east-west, rather than SW-NE, which might place the (pB) beds in a no more proximal situation than (pA). The lower sandstone:shale ratio and abundance of siderite (nodules and cement) suggest that (pA) is distal to (pB), although the frequency of rippled beds in (pA) compared with (pB) does not. The direction of currents which formed the rippled beds in (pB) is variable, but from the same sector as the currents which deposited the sands. This suggests that the rippled beds were reworked by the tails of turbidites carrying little pelitic material.

The abundance of c-divisions in the more proximal sandstones may be a reflection of the grain size of the material available. As noted earlier (p.268), the (pB) beds appear to have formed from relatively clean material in contrast to the more pelitic distal deposits. Ripples form the top of many of the top-truncated beds. In the thinner parts of the (pB) succession, most of the beds consist of the c-division alone. This abundance of rippled beds may be a result of the shape of the basin floor. If the (pB) beds accumulated in a channel, beds near the margins would have been deposited in a shallower channel depth and at a lower velocity than at the centre of the channel. It may be because of this that c-divisions predominate over a- and b-divisions.

Channels in the Namurian succession of Derbyshire have been described by Collinson (1969, 1970) and Walker (1966b). Those described by Walker were cut into the Grindslow Shales and Shale Grit, and filled with turbidites. Such channels were in the order of 6-50' deep, one example possibly reaching 150' in depth. These channels were envisaged as feeders for the proximal and distal turbidite sheets developed at the break in slope, and were cut into proximal turbidite and delta slope deposits.

The form of the Rlc (pB) protoquartzite body is different from that of the K-feldspathic lithofacies channels noted above. Individual channels described from the protoquartzite sequence are on the scale of the "washouts" of Walker (1966). The whole sandstone unit is thought to be a shallow channel because of the rapid lateral thinning of the beds, accompanied by a decrease in thickness of the beds and abundance of a-divisions, and increase in the number of thin rippled beds. There is no evidence for the cutting of a deep channel which was subsequently filled with successive turbidites. Instead of being cut into prograding deltaic deposits, the sandstone occurs between two marine bands, the upper one of which contains a fauna suggesting shallower and more aerated bottom conditions than in the marine bands to the north. Although protoquartzitic deltaic deposits do occur in the Kinderscoutian, the prograding of the delta was certainly never as active as that of the northern lithofacies. The delta in fact appears to have regressed in time as protoquartzitic sandstones were progressively replaced by the advance of the K-feldspathic lithofacies. Even in the more active phases of the southern deltaic area, less sediment in any one unit between marine bands was supplied to the basin, compared to the amount of detritus contributed to the basin from the north.

The deep channels of the K-feldspathic lithofacies were probably cut by high velocity turbidity currents, possibly generated by the slumping of deltaic material. Only a single slumped bed has been noted in sublithofacies (pB) in contrast to (pA). This distribution may have been controlled by the local configuration of the basin rather than the proximal or distal environments of the sublithofacies. The lack of slumped beds in (pB) suggests that slopes in the proximal area may have been less than 10° since creep and sand flow generally requires even higher slopes (Collinson, 1970).

A large part of the succession is unexposed between (pA) beds and the delta, 3.5 miles (5.6 km) to the south. It is possible that slumping of protoquartzites in channels down the delta slope could have provided material for turbidity current genesis. However, where the succession is seen it is consistently composed of "normal" basin shale deposits. Anything comparable to delta slope deposits is absent, except perhaps at the base of a rhythm in the deltaic sublithofacies where only 2 m of (fC) silts and mudstone rest on channel deposits.

The indications are that the turbidite sequence would pass into a shallow water sublithofacies without any great change in the depth of the basin.

An alternative mechanism for the initiation of turbidity currents is directly from rivers carrying high loads when in flood. Walker (1969) suggested this phenomenon to explain the close juxtaposition of a turbidite and shallow water sequence. In such a situation there is no regional slope facies (so well developed in the Grindslow Shales of the northern delta) and therefore no steep, long slope on which slumps might form and accelerate to form turbidity currents.

If the scale of the southern deltas at this time was on the relatively minor one envisaged (compared with that of the northern complex), this could explain the limited and sporadic nature of the protoquartzite turbidites and lack of deep channels. If only a limited extent of slope and amount of detritus were available to generate turbidity current flow, erosion would not reach the scale of the deep channels, and might be confined to the small scale channels and the erosive bases of proximal turbidites which flowed out over the delta front. The currents would be constrained to flow in a linear fashion because of their discharge from a point at the distributary mouth and by their erosive character. It seems doubtful if such currents could carry a great deal of detritus out into the basin, as their velocity and load would not be as great as currents generated in more active and large scale deltas.

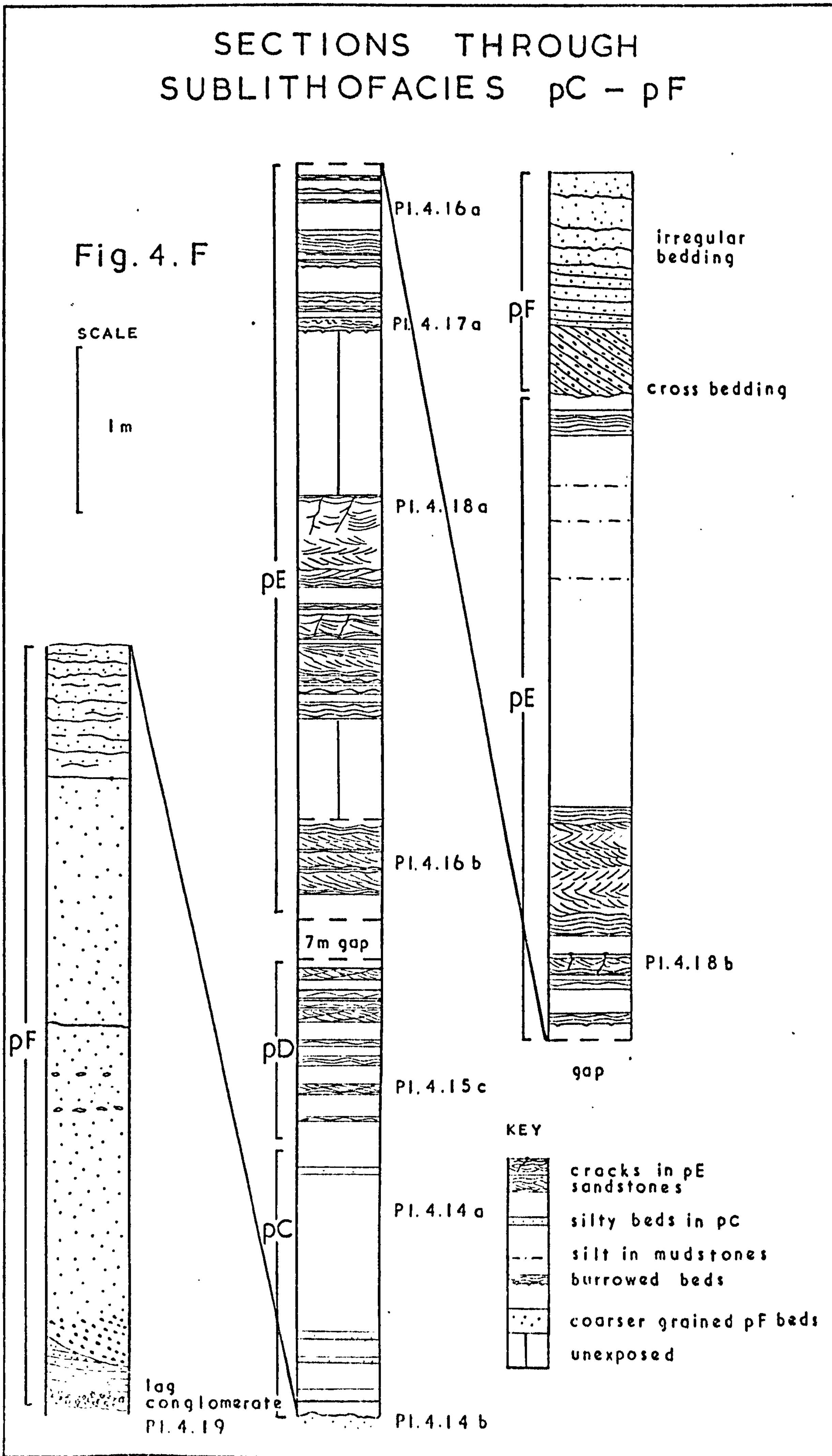
The R1b deposits extend at least 10 km out into the basin, compared with 6.5 km for those in R1c, and still maintain markedly lenticular forms. It could be that the break in slope of the delta was not marked enough to induce the turbidite flows to fan out laterally to form proximal fans and distal aprons. The flow would tend to spread laterally as it travelled down the basin floor, but on the scale of the turbidites envisaged, it is doubtful if extensive sheets could have formed in a distance of only 10 km.

INTERPRETATION : SUBLITHOFACIES (pC) - (pF)

Sublithofacies (pC) - (pF) are interpreted as deltaic sediments although many features of deltaic areas which might have been expected to occur are absent. The restriction of the sublithofacies into only four groups is because of the limited area exposed.

Although no sections show every part of the following sequence, it seems likely that sublithofacies (pC) beds are followed by (pD) which in turn pass upwards into (pE) and (pF) beds (Fig. 4.F). This sequence of mudstones, passing upwards into more sandy beds followed by ripple cross-laminated beds and coarse-grained sandstones indicates a shallowing upwards sequence from foreset silts and clays to fluvial channel sandstones.

As suggested previously (p.292) there is no evidence within the exposed part of the field area for the existence of a regional delta slope, characterised in recent deltas by poorly laminated silts and clays. Where deltas build out into deep bodies of water, the foresets normally accumulate from the fine material deposited from suspension. The sandy topset beds build out across the silts and clays, the sandy material generally being confined to the delta top unless it is removed down channels as turbidity currents. The absence of slope deposits may be due to lack of exposure, but their consistent absence in the Combes area indicates that the delta may have built out sandy deposits rapidly across a shallow shelf without having to construct typical thick delta slope deposits first. The succession


SECTIONS THROUGH
SUBLITHOFACIES pC - pF
Fig. 4. F
SCALE
1 m
pE
pD
pC
pF
7m gap
gap
Pl. 4.16 a
Pl. 4.17 a
Pl. 4.18 a
Pl. 4.16 b
Pl. 4.15 c
Pl. 4.14 a
Pl. 4.14 b
Pl. 4.18 b
Pl. 4.19
irregular bedding
cross bedding
lag conglomerate
KEY
cracks in pE sandstones
silty beds in pC
silt in mudstones
burrowed beds
coarser grained pF beds
unexposed

between the $R1b_i$ marine band and the first sandy beds is not seen, but deltaic deposits appear to closely overlie the marine band. The only possible example of slope deposits occurs immediately above a sublithofacies (pF) sandstone. Here, the abrupt nature of the junction between (pC) and (pF) suggests that the muds and silts represent deposits of renewed transgression and maximum depth of water when the deposition of fluvial sandstones was locally terminated. No bottom set beds have been noted in the Combes area. Bioturbated silts and clays observed in R1c north of the delta, and below $R2b_{ii}$ at Oakamoor (Plate 5.3c) may represent such deposits.

Because only a few scattered exposures are known, it is impossible to determine the geometry of the sandstone beds, or to be exact about sedimentary environments. It is possible to distinguish a coarsening upwards sequence from (pD) - (pF), and a fining upwards sequence within (pF) sediments. All of these beds were deposited in the subaqueous or subaerial top set environment.

Coarser grained sediments are more often reddened and accompanied by purple shales than finer grained rocks. However, (pD) beds which are finer grained than (pE) sandstones can also be interbedded with purple shales. (pE) can be interbedded with either grey silty streak beds or purple shales. The colour of the sediments does not appear to be related to particular structures. The retention of the red colour by the sediments probably depended upon how quickly a particular channel was abandoned so that the sediments would be exposed to the air, or how soon the water table fell so that overbank deposits would remain in an oxidised state. Van Straaten (1954) points out that although the red colour of the sediments of the Condroz does not prove direct evidence for the fluvial supply of sediments ". . . it is probable that before their final deposition the sediments did not undergo marine conditions for prolonged periods or else their colour would have changed to greyish tinges."

Within sublithofacies (pC), current structures and silty laminae are absent, suggesting that the mudstones were deposited from material in suspension. The structureless, more silty beds which occur in the mudstones may have been deposited from suspension during periods of higher discharge. Lamination first appears in beds similar to typical (pD) which overlie the mudstones. Such sandy streak beds often show continuous ripple lamination, and in this respect, as well as in bed thickness, they appear to be transitional between (pC) and typical (pD). The more sandy laminae within a given bed of sublithofacies (pD) frequently have irregular bases which cut out the underlying laminae, the sandy material having been deposited by current action. Symmetrical ripples often occur in the basal layers of the sandy streak beds but are unlikely to have originated from wave action since they pass upwards into climbing ripples, the rippled beds themselves being cut by small washouts filled with sandy streak sediments. Flaser bedding, commonly developed in subtidal and intertidal zones (Reineck and Wunderlich, 1968) is uncommon in the succession as a whole. Structures resembling flasers have been noted in some sandy streak sediments, but flasers can form in a marine delta top environment and are not necessarily diagnostic of inter- and subtidal environments.

The sandy streak beds, which can contain bioturbations, are thought, where grey in colour, to have formed in the subaqueous topset environment either close to distributary mouths or in bays (see also Read, 1965). Where reddened sandy streak beds occur with purple shales, they may be overbank deposits.

Distributary mouth bar deposits typical of those formed by a delta building out into deep water (Fisk, 1960) have not been recognised. Sublithofacies (pE) beds show evidence of the existence of shallow channels with low banks, or bars. The most convincing evidence for the formation of rippled beds in channels is the occurrence of penetrative cracks, thought to have developed on the sides of channels at periods of low water (p.280). Distributaries at their mouths deposit only finer sands and clays. Coarse material is deposited further upstream where the flow velocity is greater. The deposits at the river mouth also vary according to periods of high or low water (Shepard, 1960), clay layers of varying thickness being deposited during low river stage. The clays and silty streak beds of (pE) were probably deposited during low water, the rippled beds during periods of higher discharge.

Structures typical of subaqueous levees, periodically exposed at low water, might be expected to border the channel sandstones if they were deposited at the distal end of the distributary channel, but there are few indications of their existence in the succession. According to Coleman and Gagliano (1965), typical subaqueous levees show several types of convolute lamination, complex cross-laminations and scattered burrows. Very few beds in the (pE) sequence in fact show bioturbations, which might be expected if they were deposited at the distributary mouth. Two beds which do show burrowing and cross-lamination are slightly reddened and may be examples of levees. Convolution in the sandstone generally could be absent because of the formation of penetrative cracks. These would have provided an easy passage way for the escape of water and prevented the formation of some types of convolutions by releasing water pressure within the sediments via the expulsion cracks.

The (pE) sandstones may have been laid down in more than one type of environment. Thicker rippled sandstones often show a clean rippled and reddened central zone and more silty base and top, characteristic of bar sands. Some of the sandstones probably were deposited at the distributary mouth as low bars forming the banks of shifting channels, but others may have been deposited in lagoons when flood waters escaped from the main channel. This explanation seems most likely where a single thick (0.75 m) sandstone occurs below 2.5 m of mudstones, greater thicknesses of which are more common in bays of the Mississippi delta (Shepard, 1960). These sediments are followed by a (pF) cross-bedded sandstone. This has an irregularly load-casted base, probably from having been deposited on soft muds, and appears to form a sheet (see also Plate 4.19a). Elsewhere, (pF) beds may channel into (pE) beds and the channel, showing a basal lag conglomerate, has been infilled with plane beds, trough cross-bedded sandstone and irregularly bedded sandstone (p.283). This fining upwards sequence and the absence of any marine fauna indicates a fluvial origin for the sandstones. The sequence is abruptly terminated by the development of (pC) beds (p.274).

The best exposed part of the succession which has been described, and other fragments both higher and lower in the succession, all fail to show any development of coals or root beds. The part of the succession described probably lay too near the seaward margin of the delta for the growth of vegetation, but higher and lower in the succession sandstones are thicker and coals might be expected similar to those described by Gibson _et al_. (1905). Sandstones lower down consist of sheets of medium grained sandstone. One of these lies approximately 1 m above black shales with _Dunbarella_ (preservation is poor, goniatites could have been present but not preserved). There is no transition from fine grained sediments to the sandstone sheet, suggesting that there was no great difference in the depth of water between the deposition of the black shales and that of the sandstone.

Higher in the succession, there also appear to be sheet sands composed of tabular cross-beds of coarse sand. There are no other known indications of marine incursions, but it is possible that during transgressive phases, or as abandoned parts of the delta subsided, any topset swamp deposits could have been eroded.

Saint George's Land, or the Mercian Land Mass, was not large enough to have developed a large complex delta of the scale of the Mississippi or the Rhone. It seems likely that fringing deltaic sediments could have formed from several rivers which drained northwards from the east-west aligned land mass. The absence of thick delta-slope deposits suggests that these deltaic sediments prograded over a shallow shelf without having to build up a thick foundation of foresets for the topset sands. Distributaries were unlikely to be confined to a few main channels. At the delta front there were probably numerous, small shifting streams depositing sand at river mouth bars. This material could have formed some of the possible sheet sands observed lower in the succession.

The shelf must have gradually subsided to accommodate the 100 m or more of deltaic deposits accumulated between $R1b_i$ and R2a in the south and south-east of the area where the succession seems to be thickest. The situation in the Combes area in R1 is similar to that of the Endon and Stanley area in H where sheets of protoquartzites are known. The western margin of the basin may well have been different as Trewin (1969) found evidence of a steep slope causing instability of the sediments. This situation appears to have persisted into H.

Because the delta never appears to have developed a steep foreset slope in the south, and the geographical extent of the Mercian landmass was limited, little protoquartzite material was contributed to the basin in R1 despite the proximity of the delta. All of this material, deposited in the form of turbidites, was limited to the eastern part of the basin and was probably directly derived from the deltaic deposits exposed in the south-east. In the western part of the area, both deltaic deposits and turbidites are absent.

Protoquartzite deposition was abruptly halted over most of the southern area by the R. gracile transgression. A general deepening of the basin during this transgression, which persisted after the fossiliferous beds had been deposited, may have pushed back the delta front and restricted the area of deposition of the protoquartzites to a few units of limited extent in R2.

CHAPTER V

DISTRIBUTION AND PRESERVATION OF THE FAUNA

DISTRIBUTION AND PRESERVATION OF THE FAUNA

SUMMARY

The *R. gracile* marine band is particularly well exposed in North Staffordshire, and a sequence of distinctive goniatites within the composite marine band can be used for exact correlation purposes. Because of these features, and the extreme variation in thickness of its sediments, partly due to local wedges of sandstone in an otherwise marine sequence, this marine band is described in detail and the origin of the thin *R. gracile* shell bed discussed. Shallower water neritic conditions are thought to have existed in some parts of the area in R2a and R1.

Faunal phases of the basin in simple and composite marine bands are compared with those of the Ashover Boreholes. The localised occurrence of goniatites in R1c may be due to the lack of widespread conditions for good preservation. Barren shales between marine leaves which, in the *R. gracile* marine band can be correlated over a wide area, could also be accounted for by this phenomenon. In contrast to most views, the habitat of the goniatites does not appear to have been restricted to any particular depth range. It seems likely that the goniatites inhabited shallow marine waters for breeding. Fluctuations in salinity in active delta areas may have periodically killed the goniatites, and permanently excluded a shelly benthonic fauna.

VARIATIONS IN THE THICKNESS OF THE R. GRACILE MARINE BAND

The total *R. gracile* fauna is never seen within a simple marine band. Even at the locality of the shell bed at Oakamoor the lower *R.*

retiforme leaf is probably separated from the shell bed. The first occurrence of *R. retiforme* is, however, considered part of the *R. gracile* composite band because it is morphologically indistinguishable from the upper occurrence of the species.

The thinnest marine deposits are to be found in the shell bed, which contains the faunas both of upper and lower main leaves together with that of the upper *R. retiforme* leaf. Protoquartzites in the Felthouse/Parkhouse Wood section are underlain by shales with *R. retiforme* at 10 m from the base of the protoquartzites. As far as can be seen, the section is unfaulted and *R. retiforme* (first appearance) is separated from the shell bed (an example of which was obtained from Parkhouse Wood by the Geological Survey, p.122) by 33-39 m of sediments. This section is markedly different from the one exposed near Thorncliff where *R. retiforme* is separated from the *R. gracilingue* leaf by only 3.13 m of shales. In contrast to the marked thinning of the succession between these two leaves, *R. gracilingue* is separated from *R.* cf. *graciloides* by 37 cm of unfossiliferous shales, although *R. retiforme* (upper occurrence) occurs in the same marine leaf as *R.* cf. *graciloides* (p.129). Elsewhere, *R. retiforme* is always separated from the upper main leaf by sparsely fossiliferous shales without goniatites, eg. in the Upper Shell Brook section and in Brund 5 (Appendix Figure VI).

No indications of shelly horizons are found in the section near Thorncliff, but at Heath Hay Ravines where a thin shelly band does occur there may be a barren interval between the *R. gracilingue* and *R.* cf. *graciloides* faunas (exposure is incomplete). The lower *R. retiforme* leaf may possibly be represented by a lower concretionary horizon at loc. 111 (p.307) but the leaf is absent to the north and west of the Thorncliff area, probably because of the continued deposition of the

Longnor sandstone during this period (p.123). In the area of thickest accumulation of the K-feldspathic turbidites, eg. in Upper Shell Brook, the lower and upper main leaves of the R. gracile sequence are expanded to 4.5 m and 3.92 m compared with 17 cm and 54 cm (including R. retiforme, upper occurrence) in the section near Thorncliff. Thus in areas where turbidity current activity was greatest between marine band episodes, the marine deposits are also correspondingly expanded. The thinnest marine deposits occur in the deltaic area where reworking of material took place but, if the interpretation of the Felthouse / Parkhouse Wood section is correct, deltaic sandstones locally expand the succession between representatives of the R. gracile fauna.

DETAILS OF THE MARINE BAND

1. The succession in Brund Borehole No.5

The total succession in the borehole was thicker than expected from measured sections across the marine band in the Upper Churnet area. The lower R. retiforme leaf is not developed. The total thickness for the lower main leaf is 4.27 m. It is separated from the upper main leaf by 4.8 m of shales which are barren apart from "fucoids" and bioturbated laminae. The upper main leaf is 3.66 m thick and is separated from the upper R. retiforme fauna by 3.3 m of sparsely fossiliferous shales. The total succession of 16.33 m is the thickest recorded in the area. Details of the fauna are given in the appendix to the Palaeontology, Chapter 1.

2. The River Dane area -- Upper Shell Brook (108) and the River Dane (109)

The succession is characterised by a locally thick development of the K-feldspathic lithofacies ($R1c$-$R2b_i$). Loc. 108 exposes 4.5 m of light grey, hard, fissile shales in the lower main leaf (base not seen). The shales are lighter in colour and more brittle than those characteristically developed in the basin. The fauna is sparse on any one bedding plane, probably because of the locally higher rate of sedimentation during the deposition of the lower main leaf. Dunbarella specimens occur as scattered individuals with R. gracilingue.

The barren interval between the upper and lower main leaves is 3.14 m thick and contains four thin sublithofacies (fC) sandstones. This barren interval is succeeded by the upper main leaf, the base of which is marked by black brittle shales (1.35 m) containing R. latelirifer in greater abundance than the goniatites of the lower leaf. Bullions are present at this horizon and contain goniatites, sponges and a few lamellibranch and goniatite spat. Few Radiolaria occur. The R. graciloides horizon is not exposed. The unexposed section (2.57 m) is succeeded by 3 m of sparsely fossiliferous shales, followed by a 15 cm band containing R. retiforme. Total succession: 14.71 m (minimum thickness).

The adjacent section in the River Dane, only 2 miles (3.2 km) away, shows a marked change in the expression of the transgressive phase. The Upper R. retiforme leaf has not been noted, but it is thought that the representative of this leaf occurs near by since R. retiforme was collected from a borehole in the River Dane valley, (p.117).

No goniatites have been retrieved from the locality which exposes the R. gracile band, but it is thought that representatives of the upper and lower main leaves occur. At 29 m below the base of the R. bilingue s.s. marine band, a thick (11.04 m) fossiliferous sequence yields poorly preserved goniatites in the R. bilingue early form band.

Sublithofacies (fD) and (fC) turbidites occur below the R. bilingue early form marine band. At 35 m below $R2b_i$, a shale leaf contains calcareous concretions which have proved barren. A further 2.95 m of (fC) sandstones and shales occur between this and a lower shale leaf 2.94 m thick. The lower shale leaf contains a limestone bed and two layers of calcareous concretions. The concretions contain abundant fish remains -- mats of scales and spines -- and etching of the limestone bed shows a few lamellibranch and goniatite spat, and some small sponges. By extrapolation of the succession from the R. bilingue s.s. and R. bilingue early form marine bands, the two shale leaves containing carbonates are likely to represent the upper and lower main R. gracile leaves.

The abundance of the fauna is radically different from that in Upper Shell Brook. A comparison of the two sections (Appendix Figure VI), however, confirms that the interpretation of the locality in the River Dane as the representative of the R. gracile band is feasible.

3. The Upper Churnet -- loc. 103

Exposures of the R. gracile marine band occur at several localities in the Upper Churnet, but none show the complete succession. Loc. 103 exposes the lower main leaf at 0.58 m above the last R1c sandstone bed. The marine shales are dark, fissile and rather brittle. A bullion found at the base contains Posidoniella only, followed by "solid" specimens of R. gracilingue. A matted Dunbarella horizon occurs above the lowest bullion.

Above the 40 cm containing R. gracilingue, the section is largely unexposed for 1.2 m, but is followed by 30 cm of shales with R. cf. graciloides. The two faunas are sometimes separated by a barren shale interval, but no sandstones are present between the two.

R. retiforme occurs in a thin (6 cm) shale leaf separated from R. cf. graciloides by 0.5 m of sparsely fossiliferous shale. R. retiforme, as at all other exposures noted, occurs in brittle light grey shales. Total thickness of the marine band: 2.46 m approximately.

4. The Thorncliff area -- locs. 117-118

At loc. 117, the lower R. retiforme leaf is developed. It contains large specimens of this goniatite, particularly in the lower part of the leaf (p.116). Fish remains are abundant in the upper part of the leaf, and also scales and spines in the succeeding 1.8 m of otherwise barren shales. In the next 1.33 m of shales, "worm casts" are abundant. This part of the section is followed by a 17 cm black layer, possibly decalcified, containing R. gracilingue. The upper main leaf occurs at 0.37 m above this. The basal black shales rest abruptly on pale grey, faintly laminated clays. The abrupt nature of the contact indicates the rapid nature of the change in bottom conditions. Mats of fish scales and spines are again common in the upper main leaf. R. cf. graciloides occurs in the lower part of the leaf, and is followed in the same leaf by R. retiforme. The upper main and upper R. retiforme leaves have therefore amalgamated in this area. Total R. gracile succession: 5.12 m.

5. Heath Hay Ravines -- locs. 111 and 112

Both localities expose an extremely fossiliferous layer, thought to be at the same level at each exposure. The shelly band, so-called because of the numerous goniatites, contains R. gracile and R. gracilingue. R. cf. graciloides has been identified from the shales which overlie the shelly layer at loc. 112.

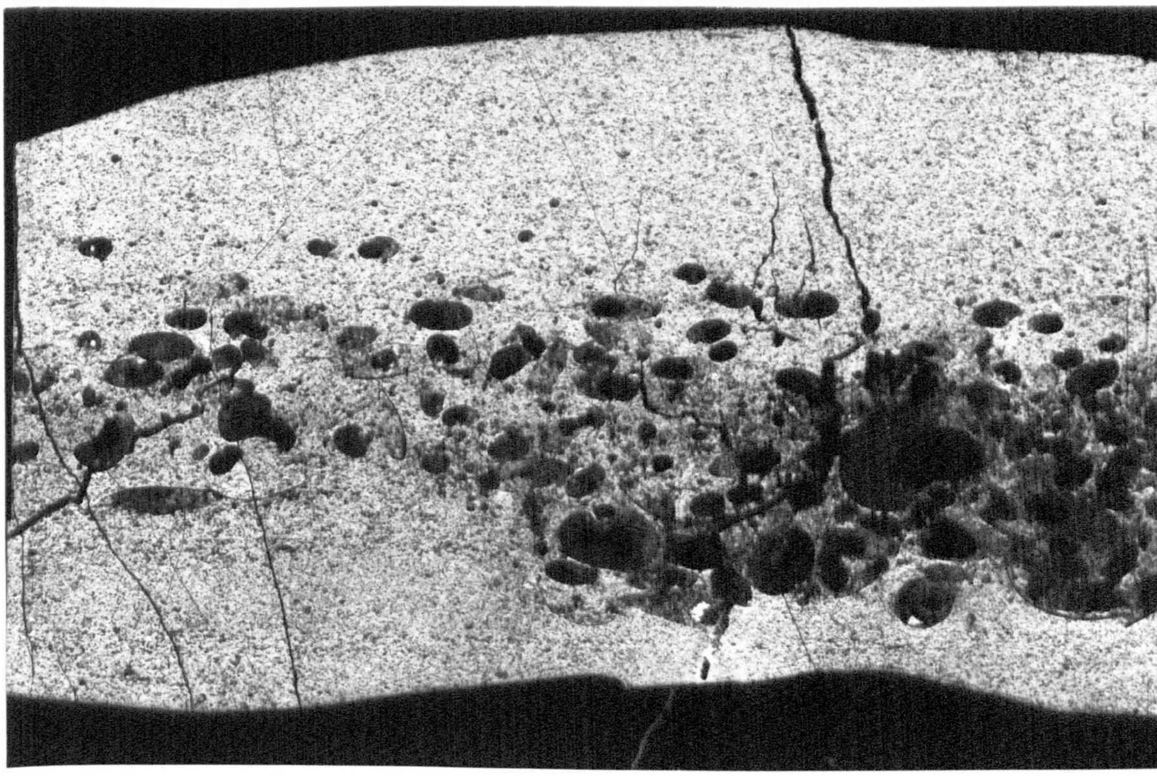
At loc. 111 the shelly layer contains partly crushed goniatites in a red weathering band near the base of the 60 cm of fossiliferous shale exposed. Thinner-shelled goniatites are common and attain up to 2 cm in diameter. At 1.8 m below the base of the fossiliferous shales, a concretionary horizon could represent the lower R. retiforme leaf. No microfauna was present in the concretion.

At loc. 112, the shelly layer occurs in an impure limestone bed. This passes laterally into a shelly bed contained within shales which overlie a limestone bed. The carbonate bed has yielded a few large Reticuloceras specimens. In one of these the siphuncle can be seen on the internal mould of the shell as a dark line at the venter. The siphuncle has not been noted in specimens preserved in the typical black shales. Beneath the shelly layer, 53 cm of the succession is poorly fossiliferous, containing only thin-shelled lamellibranchs and thinner-shelled goniatites. A concretion from this layer is cut by aragonite veins and contains lamellibranch spat and few goniatite spat but no Radiolaria. The concretion is unusual since the laminae, often preserved in bullions, in this case, show some convolution and possible erosion. A red, rounded "marl" pellet has also been noted.

6. Oulton Wood -- loc. 107

A shelly horizon has also been recovered from a bullion at this locality (the marine band is otherwise unexposed) and is tentatively correlated with the same shelly horizon at Heath Hay Ravines since the bullion contains R. gracilingue. The shelly layer within the bullion contains adult Reticuloceras specimens, goniatite and lamellibranch spat and orthocone nautiloids. The rest of the bullion is sparsely fossiliferous, containing a few specimens of R. gracilingue, and scattered lamellibranch spat with sparse Radiolaria. Faint lamination can be seen on the cut surface of the bullion. At a point beneath the shell bed, which varies from 1.25-2.0 cm in thickness, the faint

Pl. 5.1



R. gracile marine band bullion, loc.107

x2

Negative print of acetate peel, stained in Alizarin red-S and Potassium ferricyanide, (acidified).

Lamellibranch spat are found in the matrix of the bullion but are more common in the shelly horizon, where goniatite spat and orthocone nautiloids also occur. The laminae on the left-hand side of the print are cut out by the accumulation of goniatite shells on the right. Radiolaria are uncommon in this specimen and poorly preserved (largely in calcite, little replacement of the skeleton by ankerite).

laminae appear to be truncated by the thicker part of the shell bed (Plate 5.1).

7. Star Wood, Oakamoor -- loc. 114 -- and Felthouse Wood -- loc. 113

The main *R. gracile* leaf in Felthouse Wood could not be found, and is probably no longer exposed. *R. gracile* has previously been recorded from this locality (p.111) and specimens from the same locality are available in the I.G.S. collection at Leeds. The lithology and abundance of the fauna is identical to the red ankerite bed exposed at Star Wood, Oakamoor. The lower *R. retiforme* leaf is also exposed in the Felthouse Wood /Parkhouse Wood section where it occurs beneath a 33-39 m protoquartzite unit. It is thought that this sandstone unit separates the *R. gracile* limestone from the lower *R. retiforme* leaf (p.122).

The *R. gracile* marine band at Oakamoor rests upon light grey shales which pass downwards into purple shales. These contain a trace-fossil fauna of tubes, approximately 3 mm in diameter, which are surrounded by greenish reduction spots. The shales, which are approximately 60-90 cm thick, rest on a sublithofacies (pF) sandstone. Laterally, this is coarse grained and reddened. Small washouts occur within the sandstone. The base of the *R. gracile* band consists of a red 5 cm layer of crushed shelly material in a silty matrix. The fossils are so closely packed that is is virtually impossible to extract any fossils from this horizon. This layer is overlain by a 9 cm red ankerite containing abundant "solid"specimens of the *R. gracile* fauna. The red ankerite is in turn overlain by 15 cm of black, fissile shale containing *R. retiforme*, fish teeth and *Dunbarella*.

The Oakamoor locality was originally described by Alkyns (1923) who obtained a varied fauna from the red ankerite. The fauna included:-

Glyphioceras bilingue (possibly R. graciloides)

Glyphioceras reticulatum (possibly R. gracile)

Gl. davisi, Foord and Crick(R. davisi)

Orthoceras koninckianum, d'Orb

Orthoceras strigillatum, de Kon

Pleuronautilus pulcher Crick (Parametacoceras pulcher {Crick})

Solenocheilus cf. cyclostoma, Phil.

Gastrioceras cf. listeri (possibly R. retiforme, p.120)

Gl. aff. striolatum (Homoceras sp.?)

Morris (1969, p.169) also recorded numerous conodonts from this locality, as well as R. gracile Bisat, R. davisi (Foord and Crick), Solenocheilus sp., ?Endolobus sp. and Dunbarella sp.

Goniatites ranging from R. gracilingue (near the base of the R. gracile succession) to R. retiforme (uppermost occurrence) have also been described in this account. The goniatite fauna includes all species found to occur elsewhere in the basin in the upper and lower main leaves and upper R. retiforme leaf. It is thought that the lower R. retiforme leaf is not, at this point, amalgamated with the main and upper leaf faunas, since the situation at Oakamoor appears to be similar to that at Felthouse / Parkhouse Wood (p.122).

Certain features of the Oakamoor R. gracile ankerite render it unique in the local Namurian succession. The features are listed below.

(i) Nautiloids -- orthocone and coiled -- appear to be abundant from the records of Alkyns and Morris. Only Parametacoceras pulcher has been found by the author.

(ii) Dunbarella is virtually absent. Alkyns recorded only one specimen from the red ankerite. Morris (1969) recorded Dunbarella, but the specimens may have come from the thin leaf of black shale which overlies the ankerite.

(iii) Some of the goniatites are of unusually large size. Alkyns did not refer to the size of the goniatites, but recorded R. davisi, the geronitic stage of Reticuloceras. Specimens deposited at the British Museum by Alkyns show a range in size of Reticuloceras from small specimens to one approximately 8 cm in diameter (ventral). Morris (1969) also recorded a specimen 12.5 cm in diameter. The size of the largest individuals is greater than that noted in the typical black shale marine bands, except for two examples recorded from the R. bilingue early form marine band.

(iv) The abundance of the microfauna, especially the goniatite and gastropod spat, is greater than that recorded elsewhere. Conodonts recorded by Morris (1969) would appear to be abundant, although the author found none in residues from the ankerite which had been digested in acetic acid. Gastropod spat occur in large numbers in contrast to their relatively rare appearance in the typical bullions. Both Bellerophontid and turreted types occur. These are entirely unornamented and are less than 0.5 mm at the maximum dimension. No larger specimens have been noted. Goniatite spat occur as abundantly as the gastropod spat. The specimens are larger -- 1 mm in diameter -- and are distinguished from Bellerophontid gastropods by the beginnings of septa in slightly larger specimens, as well as the bulbous protoconch. Goniatite spat have never been noted in such great numbers elsewhere except in a limestone in the R.

bilingue early form marine band at the same locality. Within the typical black shale marine bands goniatite spat are rare. They were not recorded from the Ashover Boreholes.

Lamellibranch spat are subsidiary in numbers to gastropods and goniatites and have rarely been noted.

Radiolaria have not been found. It is unlikely that the delicate tests would have survived, but they were probably absent since they occur only sparsely in bullion material to the north and west of the area, eg. the Heath Hay Ravines section.

(v) Broken shelly debris occurs within the ankerite bed (Plate 5.2a and b). Typical bullions contain only incomplete but unbroken shells of goniatites, and lamellibranchs. The shelly debris appears to consist of the broken conches of goniatites.

(vi) Preservation of the goniatite shells is better than in the bullions of the black shales where only a small part of the living chamber is preserved. The only exceptions to this are in a few gerontic shells. Goniatites from the red ankerite frequently show that the living chamber consisted of at least a whole whorl of the conch, (Plate 5.2a). The living chamber of the goniatites in the shell bed is filled in by material similar to that of the matrix, consisting of spat, shell debris and silt cemented by ankerite. The last septum of the shell is usually unbroken, and the matrix does not penetrate the camerae. In a few examples the living chamber has not been entirely filled with sediment since the end of the chamber nearest the septa is filled with ankerite rather than ankeritic matrix.

The internal structures of the shells are well preserved. The septa can be seen clearly and are exaggerated by the growth of early formed ankerite which grew on and thickened the structures. The siphuncle has not been noted in many specimens, but has been seen on etched surfaces to consist of a thin tube preserved in brown material. It seems unlikely that the siphuncle was ruptured or destroyed in many specimens or the camerae would have been infilled with sediment. Goniatites from the red ankerite frequently have black bituminous material preserved in the camerae where they have not been entirely filled with ankerite (Plate 5.2a). This material is solid and probably represents the less volatile content of the original oily deposit often found in freshly broken bullions within the goniatite cavities. The lighter hydrocarbons have probably escaped on present-day weathering of the ankerite which appears to be more porous than the calcite bullions. This is probably due to the greater amount of shelly debris and detrital minerals in the ankerite.

(vii) Woody material is abundant as fragments within the ankerite, and is in a poor state of preservation. Large pieces of wood are occasionally found at the nucleus of bullions but scattered fragments have not otherwise been found. Preservation in the bullions also tends to be better.

(viii) The grain size of the detrital minerals is greater than that of the typical black shales and bullion limestones where detrital quartz cannot be seen as individual grains by the naked eye. Quartz grains up to 0.5 mm have been obtained from acid-insoluble residues from the ankerite. These grains are coated with a film of red material, probably an iron oxide.

(xi) The ankerite is dark red in colour. X-ray diffraction charts of the ankerite bed show only the carbonate and some quartz

Plate 5.2a

Surface of loose slab of ankerite from Star Wood, Oakamoor. Larger goniatites show good preservation of the length of the living chamber which, in some specimens, is penetrated by other fossils in the matrix. Bituminous material can be seen as dark areas in the paler ankerite filling the camerae. Goniatite spat occur as white spots in the matrix.

Plate 5.2b

R. gracile ankerite

As above, x13

Section showing abundant shelly debris, whole goniatite shells and goniatite and lamellibranch spat.

Plate 5.3a

Planolites

x10

Loc. 085, 1.43 m below base of the Longnor Sandstone. Horizontal tubes are also present at the same horizon, (see S. van der Heide, 1955, Pl.A Fig 3 for Planolites opthalmoides Jessen).

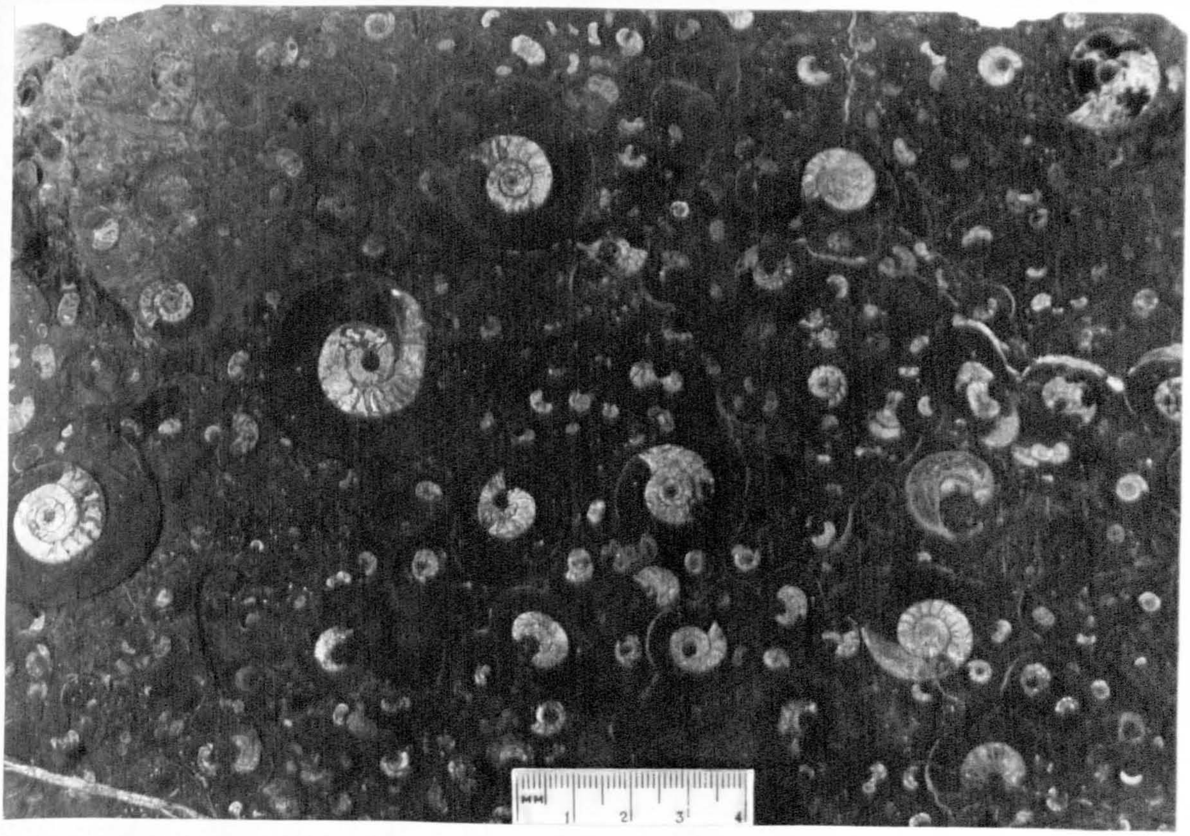
Plate 5.3b

Pyritised "worm casts". x 2, loc. 097 (R1c)

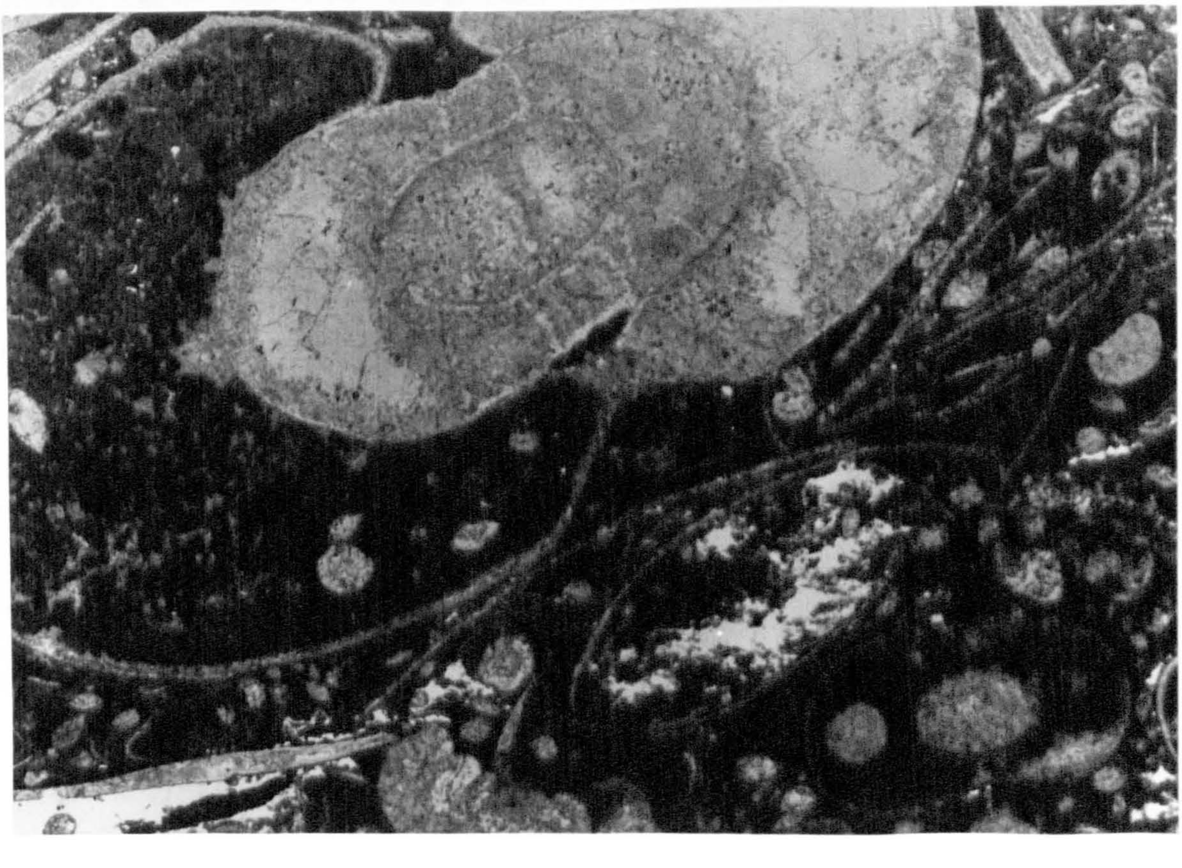
Plate 5.3c

Burrowed, laminated sediments in ankerite concretion $R2b_i$, Star Wood, Oakamoor, loc. 165.

Pl. 5.2

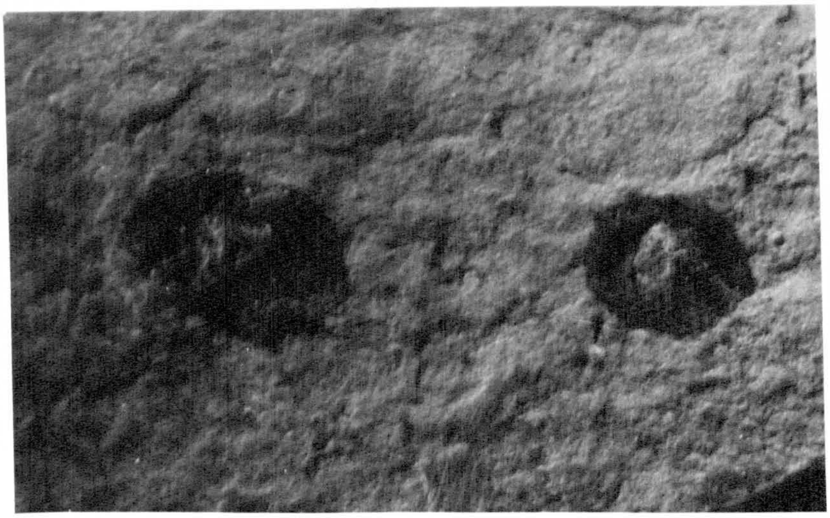


a



b

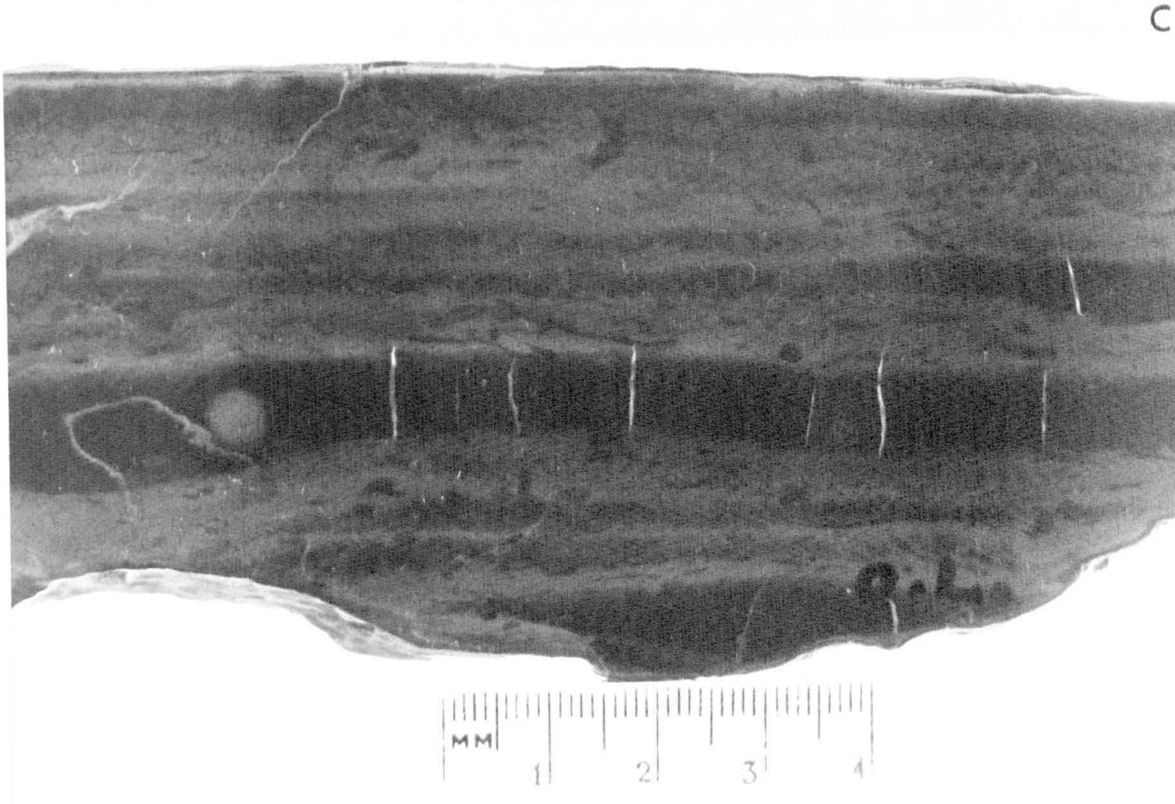
Pl 5.3



a

b

c



present. The red material, although colouring the rock, may be present in amounts too small to be detected in the presence of the ankerite.

In the black shale leaf overlying the ankerite, a fine grained red mineral (similar in its habit to jarosite) coats the shales and fossils. X-ray charts of the mineral were poor but suggested haematite. If this is correct, the presence of the iron oxide in the black shales indicates a redistribution of the mineral after lithification of the sediments. This could have taken place as a result of the cover of Trias, or as a result of present-day weathering. The red colour of the ankerite and red coating on the black shales is unique in the local Namurian succession. Carbonates from the *R. bilingue* early form marine band exposed immediately above the *R. gracile* marine band are unaffected, suggesting that it was probably the original content of the shell bed which has determined the colour of the rock.

OTHER MARINE DEPOSITS IN THE DELTAIC AREA

Other examples of shell beds are unknown in the field, except for a similar (?)Kinderscoutian type of lithology exposed at Rownall Farm. The base of the exposure shows a sandstone with the quartz grains set in a calcareous sparry matrix. Fish debris, seen in thin section, occurs as scales and spines. This lithology is unique in the area covered. The sandstone (about 30 cm exposed) is followed by grey and purple shales (1 m) which contain calcareous bullions. These are purple on the outside. The badly weathered shales, which pass up into grey shales, have yielded occasional *Dunbarella* and specimens tentatively identified as *Reticuloceras*. The shales with bullions are overlain by a 10-15 cm badly weathered red layer which is friable and appears to have been decalcified. Dermal denticles (Petrodus) and scales are abundant, and rare gastropod spat occur. The decalcified band contains numerous quartz grains coated in red material, similar in grain size to those obtained from the R. gracile ankerite.

ORIGIN OF THE R. GRACILE SHELL BED

A strikingly different marine band lithology occurs in R2a at Oakamoor, where goniatite shells are so abundant that the ankerite can be called a shell bed. The Russian Treatise on Ammonoids (Ruzhencev, 1962, p.80, English translation) described ". . . massive aphanite limestones and dolomites deposited in bays and estuaries . . ." where the carbonates are extremely fossiliferous and of a completely different character from the black shales. These estuarine deposits are thought to have collected in shelly lenses, and they contain a large number of fossils, of which the Ammonoids are the most abundant, followed by Bactritids, and orthocone nautiloids which appear as isolated specimens. The Treatise notes that benthonic forms are virtually absent, but that large amounts of seeds, wood and lignite occur. These Upper Carboniferous and Lower Permian shelly accumulations are limited to estuarine sediments. They are bordered by washouts of gravelly material deposited by fluvial agents. Large amounts of detrital matter and shells in all stages of growth are explained by natural disasters. The plant remains are thought to have been brought down by rivers in flood which killed off the cephalopods by ". . . the massive and continuous influx of fresh waters which desalinated the estuarine waters.".

The description of the shell beds corresponds in many respects with features of the R. gracile ankerite. The preservation of the fauna and the growth stages of the goniatites are also similar. The

Treatise (*ibid.* p.80) notes that the shells of the Ammonoids vary from whole specimens to detritus, the distribution of the material being uneven and disorientated. This latter feature contrasts with the orientation of the larger, whole goniatite shells in the *R. gracile* ankerite. The Russian deposits do, however, include specimens in all stages of growth from "larval" and adolescent to fully mature, smaller shells predominating. Unfortunately, preservation in the ankerite does not permit analysis of the size frequency distribution of the goniatites. Smaller shells and goniatite spat do appear to predominate numerically over larger (2 cm ventral diameter, or more) individuals.

Although the ornament of the goniatites is well preserved, they are coated in red material and never show any original colour. Nor are any anaptychi preserved in the red ankerite (or typical bullions). These features are in contrast to examples of mass killings described by Waage (1964) where fossiliferous concretions, which could be traced over at least 1,500 square miles, preserved such delicate features as the ligaments of bivalves and the anaptychi of ammonites. The preservation of these features and colour banding suggested rapid fossilisation after death. Anaptychi and radulae have been found with goniatites only where concretions formed soon after the death of the animal (Closs, 1967a,b,c). The absence of features associated with rapid fossilisation after death suggest that the R2a goniatites were not all killed, buried and preserved by the same episode. The state of preservation of the shells suggests considerable reworking of the material rather than its formation by a single, short-lived event.

Although the total area of the *R. gracile* shell bed and its relationship with the deltaic protoquartzites is imperfectly known, the closely underlying sublithofacies (pF) sandstones do suggest that the shell bed was deposited in the deltaic area in relatively shallow water. Since goniatites are generally associated with deeper, non-coastal waters, a problem arises in their occurrence in sediments deposited in a deltaic area.

Goniatites have been reported from a number of environments besides that of black shales. Quinn (1966) described Reticuloceras from conglomeratic layers with pebbles of siltstone, shale wafers and lenses of limestone in an environment attributed to the seaward flank of a reef mound. Gordon (1965) also found lenses of Pennsylvanian cephalopods in sandstones, but he concluded that cephalopods avoided coastal waters which were more turbulent and were generally absent in near-shore deposits. Reyment (1957) points out that ". . . cephalopod occurrences as opposed to those of other molluscs, give only rarely an idea of the original habitat of the animal.". For example, Tertiary Nautiloids in Japan are to be found in embayments possibly because they floated there after death rather than having inhabited that environment. Similarly, Spirula is frequently found stranded with littoral species. The abundance of cephalopods in strand-line deposits depends largely on the flotational properties of the conch. Nautilus, especially in more inflated specimens, floats easily and could therefore be distributed over large areas of the ocean, according to the currents.

The R. gracile shell bed might conceivably have accumulated from specimens which had floated over long distances and were deposited at the strand line. Two features of the bed suggest, however, that the goniatites could have lived in or near the area of deposition of the bed. Within the R. gracile ankerite, large shells of goniatites are relatively abundant (compared with the typical black shales) and numerous goniatite and gastropod spat occur. Similarly, in the overlying R. bilingue early form marine band at Oakamoor, spat and bioclastic debris commonly occur in the lower limestone horizon, although adult goniatites are rare. This suggests that at this point, similar conditions to the environment of the R. gracile shell bed obtained at no great distance from the area. Large specimens of R. bilingue early form have been found further north and in the west near the thin succession of Congleton Edge, and also suggest unusual conditions.

Observations on the possible mode of life of goniatites by Currie (1957) suggest that they were nektobenthonic. This hypothesis was also supported by Heptonstall (1964). He found that the average size of goniatites decreased as the G. cancellatum marine band was traced out into the basin away from proposed shorelines. This trend was attributed to a regional difference in the community, and was best explained by a nektobenthonic life for the goniatites. A similar trend existed for the size frequency distribution of Caneyella, for which a nektobenthonic or nektonic mode of life was proposed.

The collection of statistical data from the R. gracile marine band in particular would be interesting in view of Heptonstall's results, because this marine band exhibits extreme variation in thickness and in the occurrence of its fauna. In the absence of a detailed analysis, however, it is suggested that the occurrence of larger goniatites in the southern part of the area, where deltaic sediments are known to have periodically encroached, is related to more favourable conditions for the goniatite fauna. Bottom conditions may have been more suitable in nearer-shore areas compared with the soft muds of the typical black shale marine bands, or food more abundant nearer to estuarine waters.

Another important feature of the R. gracile shell bed (and the overlying R. bilingue early form marine band at the same locality) is the abundance of goniatite spat. Spat may have drifted after death for long distances on currents, but this is thought to be unlikely because spat are not commonly found in the typical black shale marine bands. Where spat do occur in such conditions, they are relatively scarce and virtually restricted to marine bands which show unusual faunal and/or petrographic features, ie. the R. paucicrenulatum, R. bilingue early form and R. gracile marine bands. The R. gracile marine band, recorded as a dark brown shelly limestone from the Eakring borehole (Falcon and Kent, 1960), may be similar -- from the description of the lithology -- to the R. gracile shell bed at Oakamoor. The Duke's Wood borehole also records the R. gracile marine band, and specimens of a limestone at this horizon (I.G.S. B2 2135-2138) show goniatite spat although in normal grey bullion materials. Both localities of the boreholes are in a situation which during R. gracile times was marginal to the areas of maximum subsidence (ie. at the eastern extension of the Edale trough, and north of the Widmerpool Gulf -- see also Kent, 1967).

Although few exposures show an abundance of goniatite spat, it is thought significant that the examples known occur in relatively stable Massif areas (Eakring), or in an area of deposition of deltaic sediments. In the Ashover Boreholes (Ramsbottom et al. 1962), the gastropod and lamellibranch spat phase alone was attributed to the drifting of the planktonic early stage into areas of unsuitably low salinity, or unfavourable bottom conditions, when the larvae completed the planktonic stage. This interpretation may also apply where goniatite spat and gastropod spat are common but adult goniatites rare (ie. the R. bilingue early form marine band limestone at Oakamoor). The occurrence of goniatite spat in the R. gracile ankerite may not mean, however, that the area was generally unsuitable for population by the goniatites. Mortality rates in marine larval stages are high even in favourable conditions, although some of the spat and adult goniatites may have been killed off by periodic desalination of the waters (see below). The abundance of goniatite spat in specific situations indicates an original distribution for this stage. It seems unlikely that goniatite spat would be entirely absent from most of the typical black shale marine bands, and the marine bands of the Ashover Boreholes, if goniatites bred in those areas. The mortality rate is unlikely to have been nil.

That spat were more common in shallower waters nearer deltaic or marginal areas is supported by the known breeding habits of modern dibranchs and tetrabranchs. Reyment (1957) cites examples of seasonal migration (from Tinbergen and Verwey, in Reyment, p.169) where migration occurs only among mature forms. Loligo vulgaris migrates seasonally into coastal waters, the temperature of the warmer summer months, and normal salinity, being more important factors than the depth of the water. Spawning occurs on entering coastal waters, and reproduction is virtually unknown elsewhere (Reyment 1957, p.108-9).

Because of the distribution of the goniatite spat in the marine bands studied, and the breeding habits of modern cephalopods, it is suggested that goniatites could have periodically entered coastal waters for breeding. The occurrence of larger shells of goniatites may be connected with migration of more mature individuals, or could be (as suggested earlier) because conditions in these areas were more favourable than in the parts of the basin where fine black muds were deposited.

If goniatites were periodically, or generally, more abundant in coastal waters there would be no necessity for the shells to drift over large distances to form abundantly fossiliferous deposits. The shells could have been derived from individuals which died within the area and were either stranded on the beach or incorporated within the sediments in the littoral or shallower neritic zones. The virtual absence of *Dunbarella* from the red ankerite suggests that the goniatite shells either floated into the area which was unsuitable for *Dunbarella*, or that the goniatite shells sank and were buried in an environment favourable for themselves during life, but not for the pectinoid. Since Heptonstall (1964) found that *Dunbarella* could apparently live in the bottom conditions of the black shale marine bands, it is possible that bottom conditions in the area of the formation of the shell bed were well aerated and agitated and unsuitable for *Dunbarella* which otherwise survived well on bottoms with a higher organic content.

Ruzhencev, in the Russian Treatise, considers desalination of coastal waters to have played a major part in the formation of estuarine shell beds. Sheldon (1965) also suggested that some seasonal variation is likely to have produced the multi-modal size frequency distribution obtained from goniatites in the *Ct. nititoides* - *E. rostratum* marine band. Such a multi-modal frequency would tend to be more marked if a high mortality rate occurs either during a short period or during a period of no or little growth, at the same time each year. Periods of catastrophic death could have taken place during the deposition of the *R. gracile* marine band. Further west and north of the Star Wood shell bed are two areas of exposure of the same marine band (locs. 111, 112 and 107) where exposures show further differences from the typical black shale marine bands. Loc. 112 of Lask Edge, near to the thinned succession of Congleton Edge, shows, in the basal bullions of the goniatite-bearing part of the black shale marine band, some features attributable to current action (p.307). Above this bullion layer is a thin, laterally impersistent impure limestone which, at three localities in the area, contains numerous specimens of *R. gracilingue* and occasional *R. gracile*. An abundantly fossiliferous horizon in the lower main leaf (loc. 107) occurs 2.5 miles (4 km) to the north-east. This may be the same horizon as at loc. 112. Within the loc. 107 bullion there is some evidence for the erosion of indistinct laminae beneath the shelly layer, again suggesting current action. Such abundantly fossiliferous layers within black shales occur only in the *R. gracile* marine band and in the *R. paucicrenulatum* marine band in the Combes where a goniatite spat and brachiopod fauna is common. It is tentatively suggested that these fossiliferous layers might have formed during periods of high fluvial discharge when desalination of the coastal waters might have locally killed off the marine fauna and produced extremely fossiliferous bedding planes.

If periodic mass killing through desalination did in fact take place, more pronounced multi-modality in the fossil population might be expected in near-shore sediments where both mature and spat-sized individuals were at least periodically present. Pott's diagram of variation in the size frequency relationships of *Gastrioceras* in populations taken from across the width of the marine band (in Heptonstall, 1964, fig. 51) shows that multi-modality in the fossil population is less marked in the centre of the band, and that it is smaller (though not spat-sized) individuals (1-8 cm in diameter) which predominate. Heptonstall (*ibid.*, fig. 43) also found that the mean size of *Gastrioceras* decreased as the band was traced away from shorelines, and that the increase in carbon content tended to correlate with the decrease in goniatite mean size from the top to the middle of the G. cancellatum marine band at Orchard Farm (ibid., p.199). Heptonstall did not consider that this latter feature had any ecological implications, and thought that the increase in mean size of goniatites at the top and bottom of the marine band (or at localities nearer proposed shorelines) was a result of the better swimming ability of larger individuals in more turbulent waters. As far as the author is aware, no mention was made of spat-sized goniatites in Heptonstall (1964) yet spat-sized goniatites have been found by the author in siderite concretions at the top of the G. cancellatum band at Orchard Farm. Although it is possible that the mean size of goniatites is dependent upon the degree of turbulence, the relative decrease in mean size of goniatites away from shorelines might be explained either by impoverished conditions of food supply, or by the migration of mature individuals for breeding (p.319) leaving only immature individuals in the open sea conditions. If migration and breeding took place at the same time each year when food was abundant in estuarine regions but periodic flooding could cause catastrophic death, both spat-sized and mature goniatites would be affected. Further from shore, larger goniatites may have been absent because of a migratory period, or (less likely) the effects of desalination were simply sufficiently mitigated to affect only the less mature individuals.

Records of shell beds produced by reworking of sediments already containing dispersed shells are numerous. Greensmith (1966) recorded shell beds containing Naiadites from the Carboniferous of Scotland; these were formed in a similar manner to those described by Greensmith and Tucker (1965, 1967). Van Straaten (1956) also described shelly beds formed in a similar manner by the concentration of shells by wave action on the upper beach, and by current action in gulleys. Pavements of shells can also be produced in deeper waters by the action of tidal streams (Scruton, 1960). Shepard (1960) also found that some inlet (straits between a delta and shoals or an island) samples consisted of shells evidently reworked from older beds. He remarked that such inlet environments ". . . would probably appear stratigraphically as a zone of local shell concentration and perhaps local erosion wherever the currents were strong enough to remove some of the underlying sediments.".

Though evidence for reworking of goniatite-bearing sediments in the Namurian is slight, the early Holmfirth and Glossop Memoir (Bromehead *et al.*, 1933) recorded reworked nodules, embedded in the top of a sandstone, at the base of the *R. gracile* marine band. Other examples are unknown. Since the *R. gracile* marine band is commonly split into four marine leaves, it is possible that periods of active reworking took place in minor regressive phases which in other areas resulted in the deposition of unfossiliferous shales between marine leaves.

Certain features of the preservation of the goniatite shells in the red ankerite contrast with goniatites of the typical black shale marine bands. "Solid" goniatites from the shell bed are preserved in ankerite and can show living chambers up to 360° in length. Currie (1957) recorded that the living chambers of Carboniferous genera are not often preserved. Specimens rarely show living chambers greater than 360° in length, but examples of *Gastrioceras subcrenatum* are known to have living chambers of 380°.

Even though some mechanical breakage of the conch may have taken place in the R2a specimens with the longer living chambers, the presence of this feature is in marked contrast with the goniatites of the bullion limestones in the black shales. On the death of a goniatite, the loss of the soft parts and radula (never found in the conch) would have left exposed the interior of the living chamber. Solution of its interior by organic and carbonic acids within the muds (solution taking place before bullion formation) would have decreased the length of the living chamber and made the shell wall thin. In contrast to this, the septate part of the shell was protected by septae which would have to have been progressively dissolved to destroy the shell, since its exterior was protected by a periostracum. The periostracum of goniatites within the black muds should have been well preserved (as indicated by the detail of impressions) because chitinoclastic bacteria are less active in oxygen-poor than oxygen-rich conditions (Hecht, in Zobell, 1939).

If the R. gracile shell bed were deposited as a shell pavement, considerable mechanical breakage of the shell material would have taken place, explaining the large amount of shelly debris present and its absence in the bullions. Pavements of shells have also been noted in the Wash (Love, 1967) where lamellibranch shells accumulated in creeks, having been washed out from the sediments. The shells within the sediments, particularly those in the darker layers, were blackened and etched. Shells of the R. gracile ankerite, however, show remarkably good preservation of the shell ornament but only rarely any sign of perforation of the shell which could have been caused by etching. Love (ibid., p.347) found that in the sediment mass as a whole, microscopic and large shells were to be found and that the pH was not ". . . lowered sufficiently to dissolve calcite extensively (which begins at pH 7.8) . . .". The shells in the creeks were strongly iron stained, indicating either deposition of iron from the water, or oxidation of iron on the shells. The red colour of the R. gracile ankerite strongly suggests the presence of iron in an oxidised state at the time of formation of the shell bed since the red colour is restricted to this bed alone in the succession. Although reddening could have taken place during subsequent weathering, (p.313), it is thought that the colour is an original one as a similar lithology from the Eakring borehole was described as a "brown" shelly limestone.

It has already been proposed that the goniatites of the shell bed could have become stranded or buried in shallow water neritic deposits, and that the red colour of the bed suggests reworking of the shell material, concentrated in gulleys, where iron oxides form a coating on shells. Van Straaten also noted that of all the species recorded in the Arcachon (France) mud flats, only small numbers of open-sea shells were carried into the area. If the goniatites did in fact enter shallow, coastal waters and were stranded in beach deposits, this may well explain their abundance and the rarity of Dunbarella.

It is not known how much of the thickness of the succession in the black shale facies the Russian shell beds represent. In the example of the R. gracile shell bed, a maximum thickness of 16 m, where the marine band is composite (excluding a lower R. retiforme leaf) is reduced to only 29 cm of shelly debris and black shale. This demonstrates that the succession at Oakamoor is remarkably thin in contrast to the underlying succession (Appendix Figure VI).

Because the thin marine band at Oakamoor includes the whole of the R. gracile fauna, apart from the lower R. retiforme leaf, the shell bed cannot have been formed by a single, catastrophic event.

Had catastrophic death occurred, only a small part of the fauna of the marine band's total duration would have been found. The shell bed must therefore consist of reworked material, originally deposited in an environment where shell accumulation could have taken place. This shell material may have been derived from a series of thin, shelly layers within the sediments, the shelly layers having been formed from numerous episodes of catastrophic death.

OTHER INDICATIONS OF SHALLOWER NERITIC CONDITIONS

Deposits similar to the *R. gracile* shell bed have been found only in the southern part of the area at Rownall Farm (loc. 099). The origin of the reddened decalcified bed (p.311) is problematic in that it has characteristics in common with the *R. gracile* shell bed, but overlies shales with *Dunbarella*, goniatites and bullion limestones. The occurrence of this fauna and lithology between the lower calcareous sandstone and the upper reddened bed suggests a transgressive - regressive sequence, the goniatite-bearing shales having been deposited at the acme of transgression. The reddened bed is similar to the *R. gracile* shell bed since it contains reddened quartz grains, which are more numerous than in the R2a shell bed, and a small number of spat-sized gastropods. The nature of the original carbonate cement is unknown. The rare goniatite fauna (unidentifiable) and greater amount of quartz and fish remains suggest that the bed at Rownall Farm was subjected to more prolonged or active reworking of the original material than the *R. gracile* shell bed. Accumulations of fish debris in the lower calcareous sandstone suggest that this is a marine sandstone formed during the transgressive phase.

The exact stratigraphic position of these beds is unknown since only poor goniatites, tentatively identified as *Reticuloceras* have been recovered from the soft, weathered shales, and thinner-shelled goniatites and Homoceras sp. from the bullions. Because Homoceras is extremely abundant locally in Rla_2 and Rlb_{ii}, the band at Rownall Farm may correlate with either of these.

Goniatites occur in both the Rla_2 and Rlb_{ii} marine bands only 3.2 miles (5.1 km) away at Badderly Edge Golf Course. Here, there is no evidence of near-shore conditions in the fauna or the lithology of these two marine bands, except that the higher of the two does contain large specimens of Caneyella (see the comment from Heptonstall, p.317). It is possible, however, that marked changes in faunal content of the marine bands can take place within short distances. The Rownall Farm locality lies between two protoquartzites (p.203) suggesting that if this band is R1, it is more likely to be Rla_2 because deltaic sandstones overlie this marine band at the Golf Course section. Unusual features in the marine band at the Combes (p.328) also indicate that "shell bed conditions" existed not far from that area -- possibly to the south-west near the Rownall Farm locality.

The Combes locality exposes numerous bullions which, at some levels in the marine band, have an abundant fauna which tends to be concentrated on certain planes. Goniatite spat is common (though less so than in the R. gracile shell bed) and is accompanied by a brachiopod, adult gastropod and nuculid fauna (p. 37, Plate 1.3a and b). In the Upper Manifold Valley, the Rla_2 marine band also yield some goniatite spat, gastropod spat slightly larger than normal, Crurithyris (Holdsworth, 1966b) and sponges for which Holdsworth suggested a benthonic mode of life.

These indications of benthonic faunas, and the Rla_2 productid fauna of Congleton Edge (Evans et al., 1968) suggest a relative northerly migration of the shorelines of the basin at this period, compared with other marine episodes. Hind (1901) concluded that the occurrence of nuculid and Nucula-like genera indicated nearer-shore conditions than goniatites alone. Nuculids, Orbiculoidea and Lingula were recorded by Lambrecht and Charlier (1956) in marine bands in Belgium. They considered that the appearance of these genera indicated diminished marine characteristics (presumably lowered salinity) compared with the environment of the goniatites. The appearance of the brachiopod/nuculid fauna may be less influenced by salinity, however, than by the change in depth of waters and bottom conditions. Cälver (1969) considered that the productid facies (intermediate between the Myalina and pectinoid facies) probably included the nuculoid facies recognised in the Ruhr. Further work, he suggested, might distinguish a nuculoid facies from the productoid facies. Apart from horny brachiopods, elements of the productoid fauna are unknown in the basin in the Kinderscoutian and Marsdenian, except for the productoids in the $R1a_2$ succession on Congleton Edge (p.327) where the succession is thin and marginal to the area of greater subsidence.

There are some indications that the brachiopod fauna of the Combes is allochthanous. Goniatites and other elements of the fauna tend to be concentrated on certain bedding planes within the bullions, and it has been suggested (p.321) that fossiliferous layers (referred to elsewhere as "seams" of goniatites, Holdsworth 1966b) might be the result of intermittent periods of flooding when a large proportion of the local fauna could have been killed. The fossiliferous layers could have been exaggerated by winnowing associated with these conditions, or by normal bottom currents in localities in the south nearer the deltaic area. Evidence for bottom current activity has been noted in the R. gracile marine band (p. 307) and is also suggested in the R. paucicrenulatum marine band by the absence of the one kaolinised ash band (known to occur elsewhere) at localities in the west of the area (eg. Heath Hay Ravines and Dingle Brook) and in the south of the area (the Combes). Slight bottom current activity is also suggested by the splitting of the kaolinised ash band into two layers (possibly by a pulse of sediment as the ash settled from suspension) as far north as the Upper Churnet (loc. 021). The incorporation of thin wisps of mud into the ash bands of the R. circumplicatile horizon in the Dingle Brook section again suggests bottom current activity during marine episodes.

Although the nuculoid specimens of the Combes may have been transported, it seems doubtful that the brachiopod fauna, identified in the Upper Manifold (Holdsworth 1966b) and in the Grindsbrook section (Stevenson and Gaunt, 1972) could have been distributed over such large distances by the transportation of dead shells. It is possible that during the period of the $R1a_2$ transgression, when the nuculoid and productoid elements of the fauna suggest nearer shore conditions, a benthonic fauna was able to establish itself in an area normally populated only by thin-shelled lamellibranchs and goniatites.

During the R. gracile transgression, shell beds indicate shoreline conditions but there is an apparent lack of benthonic faunas (excluding Dunbarella in the black shales). The only known situation transitional between the red shell bed and the typical black shale lithology is that of a shelly layer within a black shale marine band at Heath Hay Ravines and Oulton Wood (p.307 and Plate 5.1). In both examples, the shelly layer is accompanied by indications of bottom current activity which might have contributed towards the formation of the shell accumulation and resulted in both firmer and better oxygenated bottom conditions. Despite this, there is a lack of a benthonic fauna at these two exposures. In view of the indications of a benthonic fauna in Rla_2, it is possible that such a fauna did establish itself in the area during the period of the *R. gracile* transgression and that it is simply not seen due to the unexposed area between Oakamoor and Thorncliff. The association of the *R. gracile* shell bed with deltaic deposits suggests, however, that conditions for a benthonic fauna did not obtain in areas where the delta was most active. The abundance of gastropod spat and complete absence of larger individuals in the shell bed testifies to the unsuitable nature of the environment in the area in which the fossils were buried. It is possible that the greater mobility of the goniatites, associated with their breeding habits, enabled the cephalopods to inhabit areas marginal to the delta. Brachiopods, gastropods and lamellibranchs, which would have needed more time than goniatites to colonise an area, probably preferred areas where salinity was more constant --away from distributary mouths -- thus explaining their absence at least the area of accumulation of the shell bed.

FAUNAL PHASES

FAUNAL PHASES OF THE ASHOVER BOREHOLES

Detailed analysis of the fauna of the Ashover Boreholes led Ramsbottom *et al.* (1962) to conclude that faunal phases of six distinct types tended to occur in a definite order and reflected the cyclic nature of deposition of the sediments. Not all of these phases are represented in the succession studied in North Staffordshire. Phase 3 (*Lingula*) occurs only in R2c although a few *Lingula* specimens have been recorded in Rla_2 with goniatites. The most commonly developed phases are 5 and 6, ie. the thinner- and thicker-shelled goniatite phases. Dunbarella bands are included in phase 5 since the appearance of Dunbarella marks a sub-phase 5b in contrast to 5a where sporadic Caneyella or Posidoniella also occur with thinner-shelled goniatites. Phase 4 (mollusc spat) has rarely been recognised with certainty, nor the second phase of Planolites. A fish phase (1) is virtually absent since the majority of fish remains have been recovered from marine bands in association with goniatites. Phases 1-6 were taken by Ramsbottom et al. (1962) to indicate increasing salinity and depth of water, a view elaborated upon by Holdsworth (1966b).

FAUNAL PHASES DEVELOPED IN THE NORTH STAFFORDSHIRE BASIN

Phases 5 and 6

The thicker-shelled goniatite phase is well represented in the $R1a_2$--$R1b_v$ marine bands. Goniatites occur only locally in R1c but are again distributed over the whole area in the Marsdenian marine bands. The $R1a_1$ succession is characterised by horizons with Reticuloceras specimens but less fossiliferous parts may be interrupted by spat phases.

Phases 5a and 5b are absent at the base of some of the typical bullion-bearing marine bands at particular localities. For example, the $R1a_2$ marine band can begin with Reticuloceras only, or with Homoceras. Homoceras also occurs almost to the exclusion of Reticuloceras in $R1b_{ii}$, and frequently in Dunbarella-bearing shales ($R1a_2$--$R1b_i$) of the Brund Boreholes. Because Homoceras occurs in situations where Anthracoceras / Dimorphoceras might have been expected, this goniatite may be more akin to the thinner-shelled goniatites than Reticuloceras in its habits.

Dunbarella bands are best developed in R1b where they occur at the base and top of marine bands, and also within marine bands in the Brund Boreholes. The Brund Boreholes provide the best evidence for the existence of faunal phases 5a and 5b in the R1b succession. Within $R1b_i$--$R1b_{iv}$, *Dunbarella* alone occurs in matted bands but *Dunbarella*, *Caneyella*, thinner- and thicker-shelled goniatites can all occur together. *Dunbarella* and/or *Caneyella* and less commonly thinner-shelled goniatites precede and follow *Reticuloceras* horizons. Thinner-shelled goniatites alone occur at the top of the $R1b_v$ marine band.

Phase 4 -- spat

This phase is common, judging from the records of the Ashover Boreholes. It is, however, difficult to recognise in weathered shales and its absence or presence is best determined from etched surfaces of concretions. Rare calcareous concretions obtained from grey shales (between marine bands) which lack a macrofauna or contain only fish, have never yielded spat. Nor have any siderite concretions although such concretions from marine bands generally preserve a microfauna, visible in thin section. A calcite, fish-bearing concretion at 1 m below the $R1b_v$ marine band in Swint Clough is barren, as is also a concretion at 1.8 m below the *R. gracile* marine band at Heath Hay Ravines. The phase has been recognised, however, in bullions immediately preceding shales with a marine macrofauna. Bullions containing sparse goniatite and lamellibranch spat occur at the base of the *R. gracile* band (loc. 113). A spat phase, with one seam of *Posidoniella* in the bullion, also precedes the *Dunbarella* band at loc. 104.

Phase 3 -- Lingula

Lingula alone (phase 3) has not been noted until R2c, where it occurs at the base of the R. superbilingue marine band at the Roaches and at Foxt. Lingula has been found with goniatites and other brachiopods and gastropods at the Combes in $R1a_2$.

Phase 2 -- Planolites

Planolites (Plate 5.3a) has been found at only one exposure just below a thin impure calcareous band -- probably the horizon of R. sp. nova (R1c). At this locality, Planolites occurs with tubes of pyrite which are 2 mm in diameter and generally not more than 2 cm in length. No branching has been observed. The association of these tubes (probably burrows) with Planolites, and their occurrence in the Ashover Boreholes in otherwise barren shales and, in a few instances, with Planolites suggest that the organism which formed the tubes and Planolites are indicative of the same type of environment. The two types of trace fossil may even have formed by the same organism (see also Jessen in van der Heide, 1955, p.75).

The "pyrite tube" fauna has also been found beneath the R. gracile shell bed at Oakamoor where reduction spots (greenish) occur around the tubes in the otherwise purple shales. Traces of a burrowing fauna also occur between the two main leaves of the R. gracile marine band in Brund 5 and as "pyritised worm casts" (Plate 5.3b) between the lower R. retiforme and R. gracilingue leaves in the Thorncliff area.

Burrowed sediments have been recognised between marine bands in siderite concretions where silty and clay-rich laminae alternate (Plate 5.3c). No burrows can be recognised in the shales at the same level as the concretions, suggesting that in areas where bioturbated beds were found the shales might commonly have contained a burrowing fauna.

Phase 1 -- Fish

Teeth, dermal denticles and spines are the most common fish remains in both marine bands and the fish phase of the intervening grey shales. Large mats of scales are virtually confined to the marine bands, probably because of the better conditions of preservation in the less well aerated conditions. Mats of scales found in an R1c band (loc. 098) are probably referable to Acanthodes. Acanthodian spines and odd palaeoniscid scales commonly occur in grey shales in the Thorncliff area but fish remains are most common in R1c-R2a marine bands in the Thorncliff and Oakamoor areas. This distribution may reflect the proximity of the deltaic areas since food supplies for fish would probably have been best near to estuarine waters.

Dermal denticles of Petrodus (Ford, 1964) and odd scales are abundant in a thin, red, decalicified limestone and calcareous sandstone within the deltaic area. This probably reflects the relatively condensed nature of these deposits (p.326).

Composite marine bands

Composite marine bands show, in each marine leaf, a similar sequence of changes to that exhibited by a simple marine band. In an exposure of the R. bilingue (?)s.s. in the Upper Churnet, Dunbarella is abundant at the base of the first and second marine leaves and at the top of the second. It also occurs within each of the three marine leaves exposed at certain levels. Thinner-shelled goniatites can occur at any position in the marine leaves but tend to be smaller where Reticuloceras is most abundant and Dunbarella absent. A few

Reticuloceras specimens occur with *Dunbarella* within and at the base and top of marine leaves. The intervening grey shales have only fish scales and, on occasion, pyritised "worm casts". Brown patches occur in the shales between the *Dunbarella*-rich bands and the grey shales. Spat and "worm casts" follow the goniatites of the top marine leaf.

DISCUSSION

Faunas characteristic of phases 1-6 were thought by Ramsbottom *et al*. (1962) to occur in a definite order which reflected the cyclic change in the environment. Examination of the borehole records shows that examples of *Lingula* and *Planolites* phases in particular are few, and fish phases are concentrated in certain parts of the succession (Holdsworth, personal communication). The greater part of the fossiliferous succession is contained within phases 4-6. The spat phase is the most common, and often precedes phase 5, or phase 6 where 5 is absent. The explanation of the spat phase was that the lamellibranch and gastropod spat drifted into waters where either the bottom conditions (after the planktonic early stage) were unsuitable, or salinity of the area too low. Heptonstall (1969) deduced that *Dunbarella* was benthonic and *Caneyella* nektobenthonic (p.317), these genera being entirely replaced by the nektobenthonic goniatites as marine episodes progressed towards their acme and bottom conditions became unfavourable. Lamellibranch spat associated with goniatites alone would therefore have died because of unfavourable bottom conditions. The death of those associated with the few large lamellibranchs which occur in the spat phase may be the result of the normal mortality rate of the spat (cf. the abundance of goniatite spat in the areas where goniatites bred) or may have died due to unfavourable bottom conditions since the spat probably needed different bottom conditions from the larger lamellibranchs. The absence of goniatites in the spat phase, which preserves other molluscs well, indicates their absence from that environment or extremely low numbers.

The prevalence of phases 4, 5 and 6 in the North Staffordshire basin and the Ashover Boreholes, suggests that although the Ashover Boreholes were situated on the more stable block where the succession is relatively thin, the environments, with respect to the marine faunas, were virtually the same. The boreholes were situated at the western extension of the block near to the more rapidly subsiding trough, and it is suggested that the water depth and distance from land of this area -- for most of the period -- made conditions during marine transgressive periods suitable only for phase 4 onwards. Even phase 5, as in some parts of the basin, can be absent. This is explained by the area at certain times being too far removed from coastlines and firm bottom conditions for colonisation by lamellibranchs. Holdsworth (1966b) suggested a model using salinity and depth as controls on the fauna, indicating that goniatites alone might occur in the deeper part of the basin, and that nearer shorelines lamellibranchs and thinner-shelled goniatites might colonise the area. The author partly agrees with Holdsworth's findings -- parts of the succession ($R1a_2$) which lack sandstones and are situated furthest from the deltaic areas lack thinner-shelled goniatites and lamellibranchs at the base of marine bands and it is only later, in upper R1b, that thinner-shelled goniatites became abundant.

No complete cycles of phases 1-6 are known in North Staffordshire. At the furthest point out in the basin, spat and goniatites (4 and 6) might be expected, followed nearer shorelines, where benthonic lamellibranchs could establish themselves, by phases 4-5-6. None of the other phases are sufficiently abundant to comment upon their relationship to faunal phases 4-6.

Remains of a burrowing fauna (pyrite tubes and "worm casts") are particularly common in R1c-R2a. The abundance of a burrowing fauna at any one horizon is not necessarily reflected over the whole area. For example, R. sp. nova (R1c) is common in the Blake Brook section, but only a burrowing fauna occurs high in R1c in the south of the area (around Thorncliff). Conversely, goniatites are known in lower R1c in the south and west, but only burrows above late R1b protoquartzites in the north, suggesting an antipathetic relationship between goniatites and "worms".

The paucity of the R1c goniatites may be apparent rather than real. No sequence of phases 4-5-6 can be demonstrated in the north where goniatites in the highest R1c band occur locally. Their absence at certain localities may be due entirely to lack of preservation since goniatites occur quite commonly at this high R1c horizon only in a thin, decalcified limestone where it is present, but through 45 cm of shale at the Blake locality where the limestone is absent. Adjacent to the limestone in which R. sp. nova has been found, the shales frequently reveal pale brown markings which, both in this case and in the Brund Boreholes, are thought to represent the remains of molluscan periostraca. Either conditions within the muds were so acid that all the calcium carbonate was dissolved, or bottom conditions were oxygenating and encouraged bacterial attack of the chitin, with concomitant solution of the shell (p.324).

The relationship of the burrowing fauna with areas of deposition of protoquartzites -- they occur closely above protoquartzites both around Longnor and Thorncliff -- suggests that the deposition of a tongue of protoquartzites in a certain area subsequently either affected the salinity or the depth of the basin. That the burrowing fauna flourished in areas of shallower water is indicated by its absence from the typical black shale marine bands, and its abundance in areas adjacent to deltaic deposits as well as immediately above fluvial sandstones. It seems more plausible, however, that conditions in R1c did not exclude goniatites, but that the generally shallower water conditions and deposition of both K-feldspathic and protoquartzite sandstones resulted in firmer bottom conditions and better oxygenation of the bottom waters during marine episodes. Remains of burrowing animals within the sediment were well preserved, but goniatites and lamellibranchs (well preserved in the black shale conditions) left no evidence of their existence other than pale brown markings on shale surfaces (p.337). Only occasionally were they preserved where carbonate precipitation was sufficiently rapid to contain them, or local pockets of less oxygenated muds preserved the shells.

BARREN SHALES BETWEEN MARINE LEAVES

In areas where K-feldspathic turbidites are well developed the *R. gracile* sequence usually occurs as a lower main leaf with *R. gracilingue* dominant, and an upper main leaf with *R. graciloides* separated from *R. retiforme* by sparsely fossiliferous shales. The persistence of a barren shale leaf between these two faunas suggests that the formation of such barren intervals may have been controlled by at least a basin-wide influence rather than simply local variation in the rate of sedimentation.

The Highoredish Borehole (Ramsbottom *et al.*, 1962, p.100) records an *Anthracoceras* / *Dimorphoceras* phase of 1' 3" between *R.*

gracile (early) and R. gracile. Similarly, a 2½" band with Dunbarella and spat occurs at Uppertown and is reduced to 1" at Tansley. In the R. gracile sequence of the Rombald's Moor district, Deans (1934) found an increase in Anthracoceras and Nautiloids at the top of the two marine leaves which are separated from each other by shales with ostracods. In the North Staffordshire basin the marine band contains a barren interval between the R. gracilingue and R. graciloides faunas except at two localities. The exposure at Heath Hay Ravines may have a continuously fossiliferous sequence, but the faunal phases are not known in detail. The shell bed at Oakamoor has no barren interval but it is unlikely that one would be recorded since the deposit is condensed. Apart from these examples, the distribution of the sediments and fauna does suggest a basin-wide influence of the control (or controls) over marine leaf formation -- possibly a minor regressive phase, which may well have contributed to the reworking of the shelly deposit.

Barren leaves within marine bands consist, in some instances, of grey shales only. But in areas where turbidites are well represented in the succession, thin sandstone beds also occur in the barren interval. In the River Dane section two carbonate horizons, lacking goniatites, have been correlated with the main leaves of the R. gracile marine band (Appendix Figure IV). The lack of goniatites is enigmatic; their apparent absence could be due to the poor fissility of the shales rather than shell solution since R. retiforme was obtained from a nearby borehole. The carbonate beds in this section, and the main leaves in an adjacent section, are separated by shales which contain thin turbidite sandstones. Fossiliferous shales do not occur in immediate contact with the sandstones, in contrast to localised examples recorded by Hind and Stobbs (1904) of Reticuloceras

("*Glyphioceras*") *reticulatum* between individual beds of the Mam Tor Sandstones. A pebbly sandstone bed also occurs within sparsely fossiliferous $R1b_i$ marine sediments above (pE) deltaic sediments. In areas marginal to the most active parts of deltas supplying large amounts of detritus to the basin, trasgressive phases do not always seem to have resulted in complete inundation of the delta and concomitant inhibition of turbidity current genesis. But minor regressive phases, resulting in a higher rate of sedimentation may have determined the formation of barren shale and shale/sandstone leaves in composite marine bands where these leaves can be correlated over wide areas.

Coalescence of marine leaves in the $R2b_i$ marine band can be demonstrated. 5 m of the composite band where the succession is relatively thick (9-18 m from $R2a$-$R2b_i$) is reduced to a 1.8 m band where the succession is thin (2.54 m from $R2a$-$R2b_i$). Splitting of marine bands is related to areas of higher rates of sedimentation and it is possible that this factor, resulting in coarser grain size of the sediments and more oxygenated bottom conditions (a burrowing fauna can occur between the two main *gracile* leaves) contributed largely to the absence of any other fossils. The coalescence of marine leaves within the field area indicates that a fauna existed at no great distance from the area of deposition of a barren leaf. Although it is possible that water of low salinity may have excluded the goniatite/lamellibranch fauna from certain areas nearer the deltas, it is unlikely that further out into the basin, where the composite marine bands occur, areas of lower salinity should have persisted. That a goniatite/lamellibranch fauna did inhabit the area of the split marine bands during the period of deposition of the barren intervals, but were not preserved, is suggested by the occurrence of a few

Reticuloceras and Anthracoceras specimens in the Dunbarella-rich bands (p.335), and the existence of pale brown markings between shales with Dunbarella and those with annelid remains at one locality (p.335). The pale brown markings are probably an intermediate stage between good preservation in the black shales and non-preservation in the now barren part of the succession.

DEPTH RANGE OF THE GONIATITES

The South-West England province and certain parts of the Namurian succession in the Midland province (Calver, 1969 {Westphalian} and the R. gracile and the R. paucicrenulatum marine bands) indicate that the Ashover Borehole succession is not typical of the whole area of deposition. The controls influencing the total fauna, which includes many benthonic elements, vary according to the geography of the basin. Variation in such parameters as depth and bottom conditions did not necessarily affect, to the same extent, all elements of a particular biofacies.

Calver (1969) recognised the following "faunal facies" which contain more faunal elements than Ramsbottom's (1962) faunal phases. In contrast to Ramsbottom's phases more than one of the facies contains a "fully marine" phase.

facies a	Myalina
facies b	productoid
facies c	pectinoid
facies d	goniatite

These facies were based upon the relative abundance of faunal elements rather than the most "marine" fauna because, for example, both brachiopods and goniatites can occur in facies b. This mixing of faunal elements has also been illustrated by Ramsbottom (1970) who recognised three faunal facies, two of which are subdivided. Thicker-shelled goniatites are shown to have inhabited only the deepest-water part of the shelly benthonic facies range (productoids typical) but thinner-shelled goniatites also range into the nuculoid/gastropod facies. From the limited amount of material available from North Staffordshire, however, it seems that the nuculoid and gastropod elements are not incompatible with the thicker-shelled goniatites. Nor do the Lingula and Crurithyris elements (shallow water benthonic facies) necessarily exclude goniatites since Bloxham (1969) found goniatites could live in the same environment as Lingula, and Crurithyris occurs as a benthonic form with goniatites in North Staffordshire. The only facies of Ramsbottom (1970) from which goniatites are totally excluded appears to be that of Planolites, although the stunted Lingula facies of Bloxham and Thomas (1969) could also be included.

The concept of a generalised faunal facies does reflect the abundance of faunal elements, but the deduced depth zones do not necessarily exclude the possibility of the thicker-shelled goniatites having inhabited shallow marine waters. The R. gracile shell bed was formed during a period of inundation of the delta top when a shallow water environment over a muddy, but oxygenated, bottom appears to have been favourable (at least locally) for the population of the area by goniatites. Similar conditions may have led to the occurrence of "minute goniatites" mentioned by Prentice (1960) in a marine band overlying paralic deposits. Similarly, goniatite "fry", rarely mentioned in the literature, have only been noted between the two main leaves of the R. gracile band (associated with ostracods, Deans 1934) and in the R1 succession immediately above its unconformable base with the Lower Carboniferous limestones in Eastern England (Edwards, 1967, p.45). Spat also occur in the brown shelly bed recorded by Falcon and Kent 1960, see p.318 of this account).

Despite the shelf conditions in Eastern England in the R1 succession there is a paucity of a benthonic shelly fauna in the area, apart from Lingula which makes its appearance only commonly in R2. One productoid fragment is recorded close below the "Kinderscout Grit" in the information in Edwards, 1967. This situation is in contrast to the brachiopod facies of the South-West Province, and the indications of a shelly fauna in bioclastic debris (R1 and E) in Lancashire (Magraw and Ramsbottom, 1956, Kent, 1947). This indicates that conditions under which goniatites lived and bred were often unfavourable for shelly faunas -- though these were not deep-water conditions. It may have been only during certain periods in situations nearest coastlines that conditions in shallow waters became highly suitable for the more mobile goniatites. Sessile benthonic organisms may never have been able to colonise such areas, possibly explaining the paucity of a shelly fauna in Eastern England and the absence of brachiopods in the R. gracile band in the field area. In contrast to this, in a shelf area where stable conditions of salinity obtained, ie. away from active deltaic areas, brachiopods could have locally established themselves with the goniatites and periodically, when bottom conditions were suitable, have colonised the basin, eg. during $R1a_2$.

The lack of records of goniatite "fry" or spat in south-west England* (apart from Prentice, 1960) is surprising in view of the abundant evidence of shallow water conditions, inferred from the benthonic faunas. It is possible that a significant factor in the appearance of goniatites in shallow waters was either the nature of

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* see errata

the bottom profile or the exposure of the coast. Both of these factors could have influenced the turbulence of the waters. Goniatites may not have been able to tolerate turbulent near-shore conditions of exposed coastlines or, perhaps more likely, needed extensive areas of shallow waters (eg. over inundated delta-tops)for breeding grounds. If this were the case, goniatites might have appeared with benthonic faunal elements near-shore and off-shore, but alone (or with fish and some gastropod spat) in bays and estuaries periodically affected by desalination.

Falling sea levels in regressive phases associated with the exposure of the delta-top deposits and destruction of breeding areas, may have contributed as much towards the disappearance of the goniatite fauna as changes in salinity.

APPENDIX

List of fossil localities and kaolinised ash bands

H2 -- *Homoceratoides prereticulatus*

Locality Number	Grid Reference	
001	(0221,6092)	Base of shale scar, left bank of stream.
002	(9660,6389)	Stream near Bentend.
003	(9468,6607)	Ankerite at stream level, Upper Shell Brook.
004	(9273,6128)	Dingle Brook, near Rushtonhall.
005	(9090,5931)	Right bank of stream, Heath Hay Ravines.
006	(0118,5838)	Base of shale scar in bank above Thorncliff stream.

$R1a_1$ -- *R. circumplicatile* subzone

007	(0220,6091)	Ankerite lenses in shale scar, left bank in tributary of Churnet. 5 kaolinised ash bands, 007_{1-5}.
008	(0266,6173)	Shale scar in right bank in tributary of Churnet, near Strines. 2 ash bands, 008_4 and 008_5.
009	(0652,6688)	Left bank of River Dove, near stream level. Bullions with *Albaillella* and *R. circumplicatile*. 2 ash bands (?)3 and (?)5.
010	(0410,6698)	Right bank of Upper Manifold. 3 ash bands, 010_3, 010_4, 010_5.
011	(0466,6600)	Ankerite bed in right bank, tributary of Manifold.

012	(0617,6117)	Ankerite bullions, left bank of Blake Brook. 2 ash bands, 012_3 and 012_4.
013	(9667,6396)	R1 shales at stream level, near Bentend.
014	(9630,6340)	Left bank of tributary to Dane, Little Hannel, near Bearda. 3 ash bands, 014_3, 014_4, 014_5.
015	(9471,6613)	Limestone bed in _R. circumplicatile_ subzone, Upper Shell Brook.
016	(9470,6612)	Ankerite bed with _R. circumplicatile_ group, Upper Shell Brook.
017	(9273,6128)	Shales and impure limestones, right bank of Dingle Brook near Rushtonhall. 2 ash bands, 017_{4-5}. Immediately downstream from 004.
018	(9274,6128)	Left bank of Dingle Brook. 018_{4-5}.
019	(9089,5909)	Right bank of tributary stream, Heath Hay Ravines.
020	(0115,5843)	Shale scar high in left bank of Thorncliff stream. 2 ash bands, 020_{4-5}.

$R1a_2$ -- _R. todmordenense_ subzone

021	(0262,6172)	Left bank of tributary to Churnet near Strines. 1 ash band (bullions in stream).
022	(0653,6685)	Right bank of River Dove.
023	(0539,6363)	Rotten limestone at stream level, right bank Oakenclough.
024	(0407,6698)	Right bank of Upper Manifold. 1 ash band.
025	(0477,6583)	Right bank of Upper Manifold. Bullions.
026	(0474,6590)	Right bank of Upper Manifold.
027	(0619,6117)	Left bank of Blake Brook.
028	(0441,6903)	Shale scar, right bank of stream at Brand Side. 1 ash band.

029	(0512,6857)	Shale 3-4 m above stream level at Brand End.
030	(9685,6392)	(?)Rla_2. Left bank of stream near Bentend.
031	(9629,6362)	Shale scar near Little Hannel, left bank of tributary stream to Dane at Bearda. 1 ash band.
032	(9462,6612)	Bullions and shales at stream level, Upper Shell Brook.
033	(9447,6420)	Bullions and shales at stream level, middle reaches of Shell Brook. 1 ash band.
034	(9274,6128)	Dingle Brook, left bank near Rushtonhall. Immediately upstream from 018.
035	(9089,5932)	(?)Rla_2. Left bank of stream, Heath Hay Ravines.
036	(9187,5125)	Shale scar in right bank, tributary stream at Endon Golf course, Baddeley Edge.
037	(9602,6095)	Right bank of tributary stream, Fairboroughs Wood.
038	(0043,5242)	Bullions and land-slipped shales, The Combes valley. (Morris 1966a, loc. 60).
039	(0040,5237)	Septarian nodules at base of band, bullions with R. aff. umbilicatum and the R. adpressum/dubium horizon, The Combes valley. (Morris 1966a, loc. 92).
040	(0117,5845)	Shales near stream level, left bank Thorncliff main stream.
041	(8643,5849)	Rla_2 shales -- near head of Limekiln Brook, Congleton Edge.

The R. nodosum zone

Rlb_i–

042	(0407,6698)	Right bank, Upper Manifold Valley.
043	(0621,6118)	Shales in left bank, Blake Brook.

044	(9628,6361)	Shales to left of stream, near Little Hannel.
045	(9185,5115)	Low in left bank of tributary stream, Golf Course, Badderly Edge.
046	(0041,5234)	High in shale scar, left bank of stream, The Combes,
047	(0115,5845)	Left bank of Thorncliff main stream. (?)Rlb_i shales (slipped) above Rla_2. Overlain by shales with Hd. ornatum alone.

Rlb_{ii}—

048	(0622,6118)	Left bank of Blake Brook. Shales with impure limestones.
049	(0622,6118)	Bullions, (?)Rib_{ii} near small fault.
050	(9185,5112)	Right bank of tributary stream, Golf Course, Badderly Edge.
051	(0113,5846)	Shales at stream level, right bank of Thorncliff main stream.

Rlb_{iii}—

052	(0156,6033)	Left bank of tributary stream to Upper Churnet.
053	(9628,6336)	Small tributary (left bank) near Little Hannel.
054	(9466,6612)	Left bank, Upper Shell Brook.
055	(9085,5930)	Left bank, limestone and bullions, Heath Hay Ravines.
056	(0112,5847)	High in shale scar above 051.
057	-	Right bank of stream, Swint Clough. See Hudson and Cotton, 1943.

Rlb_{iv}—

058	(9627,6342)	Left bank of stream, near Little Hannel.
059	(9410,6392)	Right bank of River Dane below confluence with Shell Brook.

060	(0112,5846)	Left bank Thorncliff main stream, immediately below $R1b_v$.
061	(9706,6406)	Left bank of stream from Swythamley Hall. Thinner shelled goniatites only.

$\underline{R1b_v}$

062	(0259,6173)	Left bank of tributary stream, Upper Churnet. 1 ash band.
063	(0621,6131)	Left bank of Blake Brook at stream level.
064	(0640,6118)	Right bank of Blake Brook at stream level.
065	(,)	Probably $R1b_v$ shale scar in field.
066	(0433,6912)	Stream below Brand Side near Fairthorn Farm.
067	(9626,6342)	Left bank of stream near Little Hannel.
068	(9476,6500)	Right bank of stream, middle reaches of Shell Brook. 2 ash bands.
069	(9410,6392)	Right bank of River Dane below confluence of Dane and Shell Brook. 2 ash bands.
070	(9083,5930)	Left bank of stream, Heath Hay Ravines.
071	(9706,6407)	Left bank of stream from Swythamley Hall.
072	(0111,5845)	High in shale scar, left bank Thorncliff main stream. 2 ash bands.
073	( )	Right bank of shale scar, Swint Clough. 2 ash bands. See Hudson and Cotton, 1943.

<u>R1b marine bands -- not specifically identified</u>

074	(0623,6118)	Blake Brook, ankerite with thinner-shelled goniatites.
075	(0511,6860)	Right bank of stream at Brand End.
076	(9085,5910)	Left bank of stream, Heath Hay Ravines.
077	(9087,5932)	Left bank of stream, Heath Hay Ravines (?)Rib_i.

078	(9599,6094)	Left bank of tributary stream, Fairboroughs Wood. $R1b_{ii}$ or $R1b_{v}$.
079	(0032,5220)	Left bank of Combes Valley, Dunbarella band, (?)R1b.
080	(0112,5817)	Left bank of stream south of Thorncliff (Morris 1966a, loc. 55, R. circumplicatile subzone).

The R. reticulatum zone

081	(0203,6095)	Rotten nodules, left bank of Churnet (?)R1c.
082	(0643,6121)	Left bank of Blake Brook, R. sp. nov.
083	(0643,6118)	Right bank of Blake Brook. Lower R1c, no thicker-shelled goniatites.
084	(0567,6367)	Right bank, Oakenclough. (?)R1c, lamellibranchs only.
085	(0760,6462)	Right bank of Manifold. (?)R. sp. nov. horizon, lamellibranchs and Planolites.
086	(0586,6510)	Right bank of Manifold.
087	(0605,6511)	Left bank of Manifold. Thin weathered carbonate below Longnor sandstone, (?)horizon of R. sp. nov.
088	(9475,6520)	Right bank of Upper Shell Brook, (?)R1c, Dunbarella and Homoceras.
089	(9471,6468)	Identified by Evans et al. (1968) as R1c.
090	(9482,6558)	Identified by Evans et al. (1968) as R. cf. reticulatum.
091	(9082,5913)	Left bank of stream, Heath Hay Ravines, (?)lower R1c.
092	(9083,5912)	Left bank of stream, Heath Hay Ravines, (?)R1c, fish.

093	(0033,5780)	Tributary stream near Edge-end Farm.
094	(0029,5752)	Siderite band at stream level, tributary to Thorncliff stream.
095	(0105,5815)	R. reticulatum group, (?)lower R1c.
096	(0070,5713)	Annelid traces, (?)R1c.
097	(0070,5713)	Siderite concretion, burrowed beds. (?)R1c.
098	(9998,5823)	R. reticulatum group, (?)lower R1c.

(?)Kinderscoutian marine band

099	(9501,4995)	Rownall Farm, near Bagnall. Old proto-quartzite and "marl" pits.

The R. gracile marine band, R2a

100	(0180,6086)	Left bank of Upper Churnet, shales about 3 m above stream level. Preservation poor.
101	(0154,6051)	Tributary stream to Churnet, immediately above bridge.
102	(0166,6064)	Tributary stream to Churnet, in stream bed. Base of upper main leaf only.
103	(0215,6360)	At confluence of Churnet and tributary near Stake Gutter, R2a or $R2b_i$.
104	(0245,6208)	Right bank of Upper Churnet. Bullions with R. gracilingue at stream level. R. retiforme exposed higher in the succession a few metres further upstream ($81a_3$).
105	(0289,6141)	Shale bank in left bank of Upper Churnet.
106	(0260,6251)	R. retiforme, in tributary gulley.
107	(0672,6130)	Right bank of Blake Brook at footbridge, Fernyford.
108	(9281,6267)	Bullion at stream level, Oulton Wood.

109	(9485,6714)	Headwaters of Shell Brook, Butterlands.
110	(9507,638)	Fish-bearing concretions and limestone bed. Probably lower main leaf. Left bank of River Dane in turbidite section.
111	(9508,638)	Calcareous concretions. Possibly upper main leaf, same section.
112	(9074,5917)	Heath Hay Ravines. Left bank of stream. Shelly layer crushed in shale.
113	(9074,5922)	Right bank of stream: bullions with spat at stream level, shelly layer in impure limestone, followed by unexposed portion, then shales with R. cf. graciloides two metres further downstream. Left bank: opposite R. cf. graciloides exposure, limestone bed with a few adult goniatites overlain by shelly layer crushed in shale.
114	(9800,5030)	Shales at stream level below protoquartzites, Parkhouse Wood.
115	(0610,4610)	Shelly layer crushed in shales and ankerite shell bed. Stream level, right bank, Star Wood, Oakamoor (Morris 1966a, loc. 112).
116	(0027,5815)	Loose bullions, Solomon's Hollow, Thorncliff stream.
117	(0058,5830)	Loose shale blocks with R. gracile fauna.
118	(0004,5874)	Lower R. retiforme leaf, Stream draining past Troutsdale Farm into Tittesworth Reservoir. Black shales with R. retiforme on left bank at stream level, grey shales with R. retiforme a few metres further downstream on the right bank (0001,5876).

119	(0004,5874)	R. gracilingue and R. graciloides/R. retiforme leaves exposed in shales scar (left bank) above 117.

The R. bilingue early form marine band, R2b$_i$

120	(0161,6064)	Shales at stream level, tributary stream to Upper Churnet, WSW of Hurdlow.
121	(9998,6029)	Left bank of stream draining to Reservoir, Middle Hulme, Meerbrook. Siderite bullions.
122	(0257,6341)	Shale/sandstone scar on right bank of Stake Gutter, R2b$_i$ or R2b$_{ii}$.
123	(0258,6335)	Shales near stream level, right bank of Stake Gutter, Upper Churnet.
124	(0246,6216)	High in shale scar, right bank of Upper Churnet.
125	(0245,6229)	Shales near stream level, left bank of Upper Churnet. (?)R. bilingue early form marine band.
126	(0246,6258)	Left bank of Upper Churnet.
127	(0243,6244)	Left bank at stream level. Lamellibranchs only.
128	(9494,6692)	Shales at confluence of stream, headwaters of Shell Brook.
129	(9492,6698)	Left bank of stream, headwaters of Shell Brook.
130	(9489,6704)	Left bank of stream, headwaters of Shell Brook.
131	(9520,6383)	Left bank of River Dane west of Feeder Cottage. Shales with bullions.
132	(9261,6133)	Dingle Brook, south-west of Rushtonhall.
133	(9307,6117)	Dingle Brook, south of Fold Farm.
134	(9073,5917)	Right bank of stream, Heath Hay Ravines.
135	(9070,5920)	Thinner shelled goniatites only, (?)R2b$_i$.
136	(9840,5012)	Right bank of stream, lower Parkhouse Wood, R. bilingue (?)early form.

137	(0611,4609)	Right bank of stream, Star Wood, Oakamoor (Morris 1966a, loc. 110).
138	(0043,5823)	Shales and bullions at stream level. Bullions on right bank higher upstream.

Marine leaf above $R2b_i$

139	(0243,6231)	Upper Churnet, right bank of stream.

The *R. bilingue* s.s. marine band

140	(0168,6067)	Shale scar, left bank of Churnet.
141	(0131,6056)	Siderite bullions (?)*R. bilingue* s.s. (Morris 1966a, loc. 103, *R. bilingue* late form).
142	(0156,6071)	Right bank of tributary to Churnet.
143	(0145,6062)	Shales at stream level along tributary to Churnet.
144	(0253,6302)	Contorted beds and *R. bilingue*.
145	(0225,6165)	Sheared band (?)*R. bilingue* s.s. Also at (0215,6145).
146	(0231,6175)	Shales in right bank of Churnet near confluence with tributary, (?)*R. bilingue* s.s.
147	(0363,6828)	Right bank of River Dane, west of Brand Top.
148	(9276,6255)	(?)*R. bilingue*, Oulton Wood.
149	(9538,6388)	Bullions and shales on both banks of River Dane.
150	(9632,6451)	Shales and siderites with *R. bilingue*, left bank of River Dane in slipped material, probably near fault.
151	(9072,5921)	Thinner-shelled goniatites only (?)$R2b_{ii}$.
152	(9590,6064)	*R. bilingue* s.s. Right bank of stream, Fairboroughs Wood.
153	(0611,4577)	Left bank of stream, Star Wood, Oakamoor.

154	(0611,4589)	Right bank of stream, high in shale scar. (?)R. bilingue s.s.
155	(0589,4675)	Right bank of stream at water level, just north of Cotton Dell.
156	(0043,5822)	Left bank of stream, high in bank above R. bilingue early form.
157	(0052,5824)	Shales and siderites in shale scar.
158	(0058,5830)	Steeply inclined shales and siderites with R. bilingue.

Other R2 exposures

R. eometabilingue (R. bilingue late form) marine band.

159	(0241,6298)	Right bank of gulley below Ramshaw School, Upper Churnet.
160	(9221,6270)	R. eometabilingue or R. metabilingue. Lee Wood, Woodhouse Green.
161	(0617,4640)	R. eometabilingue, Cotton Dell, Oakamoor (Morris 1966a, loc. 109, R. metabilingue).
162	(0037,5862)	R. eometabilingue / R. metabilingue. Stream draining to reservoir.

R. metabilingue

163	(0381,4810)	Left bank of gutter, Upper Cotton, (?)R. metabilingue.

R. superbilingue

164	(0379,4809)	Shirley Hollow, Foxt. (Morris 1966a, loc. 108).
165		R2 burrowed beds, below R. bilingue, Oakamoor. A few yards upstream from loc. 155.

Addenda

166	(9742,6447)	Tributary stream to Swythamley section.
167	(9790,6437)	*R. graciloides*, R2a.

LIST OF SECTIONS REFERRED TO IN SEDIMENTOLOGY

Locality Number		Grid Reference	Sublithofacies
168	Megarhythm 1-3, River Dane R1c-R2bi	(9483,6370)-(9538,6388)	fA-fD
169	Swythamley, R1c	(9706,6411)	fA
170	Archgreave, ?R1c-R2a	(9440,6948)-(9448,6940)	fB/C
171	Upper Shell Brook, R1c	(9483,6640)-(9483,6656)	fB/C
172	River Churnet Northern section R1c	(0247,6204)	fE
173	River Churnet Middle section R1c	(0220,6135)	fE
174	River Churnet Southern section R1c	(0170,6074)	fE/fA
175	Near Meerbrook, R1c	(9985,6028)	
176	Blake Brook, R1c	(0645,6125)	fF
177	Ballbank, R1c	(0585,6511)	fF
178	Thirkelow, R1c	(0490,6866)	fF/G
179	Hollins Hill, R1c	(0595,6715)	fF/G
180	Cistern's Clough, R1c	(0407,6935)	fG
181	Right bank of R. Dove near Hollins Hill, R1c	(0613,6684)	fG

For location of above sublithofacies see Figure after p.

182	Blake Brook, Lower R1b protoquartzite, typical section	(0623,6118)-(0630,6120)	pA
183	Blake Brook Upper R1b protoquartzite	(0642,6117)	pA
184	Oakenclough Lower R1b protoquartzite	(0542,6367)-(0551,6365)	pA
185	Ballbank	(0562,6517)	pA
186	Upper Manifold Lower R1b protoquartzite	(0392,6707)-(0399,6704)	pA

187	Upper Manifold Upper R1b protoquartzite	(0349,6693)- (0359,6697)	pA
188	Upper Churnet, R1b	(0234,6122)	pA
189	Thorncliff stream, R1c Typical section	(0025,5783)- (0012,5809)	pB
190	Thorncliff stream, R1c	(0102,5842)	pB
191	Tributary to Thorncliff stream, R1c	(0095,5814)- (0104,5815)	pB
192	Tributary stream ?R1c	(0089,5719)	pB
193	The Combes, R1b	(0016,5166)	pC/D
194	The Combes, R1b	(0033,5223)	pD
195	The Combes, R1b	(0014,5162)	pE
196	Endon Golf Course, $R1a_2$	(9184,5116)	pE
197	The Combes	(0000,5153)	pE/F
198	The Combes	(0044,5180)	pF
199	The Combes	(0038,5217)	pF
200	Oakamoor, R2a	(0612,4606)	pF
201	Felthouse/Parkhouse Woods, R2a	(9767,5020)- (9800,5030)	pF
202	Rownall farm	Same as loc. 099	
203	Dry Stones, Upper Churnet ?H	(0305,6258)	

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Errata

p.121 The number of spirals in Hd. ornatum is reduced higher in the succession in R2 (W.H.C. Ramsbottom, personal communication). The existence in R2 of two levels, containing an identical thicker shelled goniatite, separated by fossiliferous levels containing related forms but not the recurrent species, is probably a unique case.

p.132-133 In early accounts, the strata between the Coal Measures and Carboniferous Limestone were classified as the Millstone Grit, and Pendleside or Yoredale Group. Hester (1932) restricted the name "Pendleside Series" to "... the limestone and grit occurring towards the top of the Lower Carboniferous in Lancashire" (see also Fig. 25 in Ramsbottom, p.70 in "The Geology and Mineral Resources of Yorkshire", Ed. Rayner and Hemingway).

The "Pendleside Series" of Crick (1904) referred to the typical Yoredale rocks of Yorkshire. The locality of the holotype of P. pulcher is unknown. Crick states that it is from the "Carboniferous Pendleside Series: probably Yorkshire". It seems likely that the specimen came from Hebden Bridge since "... the precise locality whence it was obtained has not been recorded, but the matrix agrees with that of the other examples which are from Hebden Bridge".

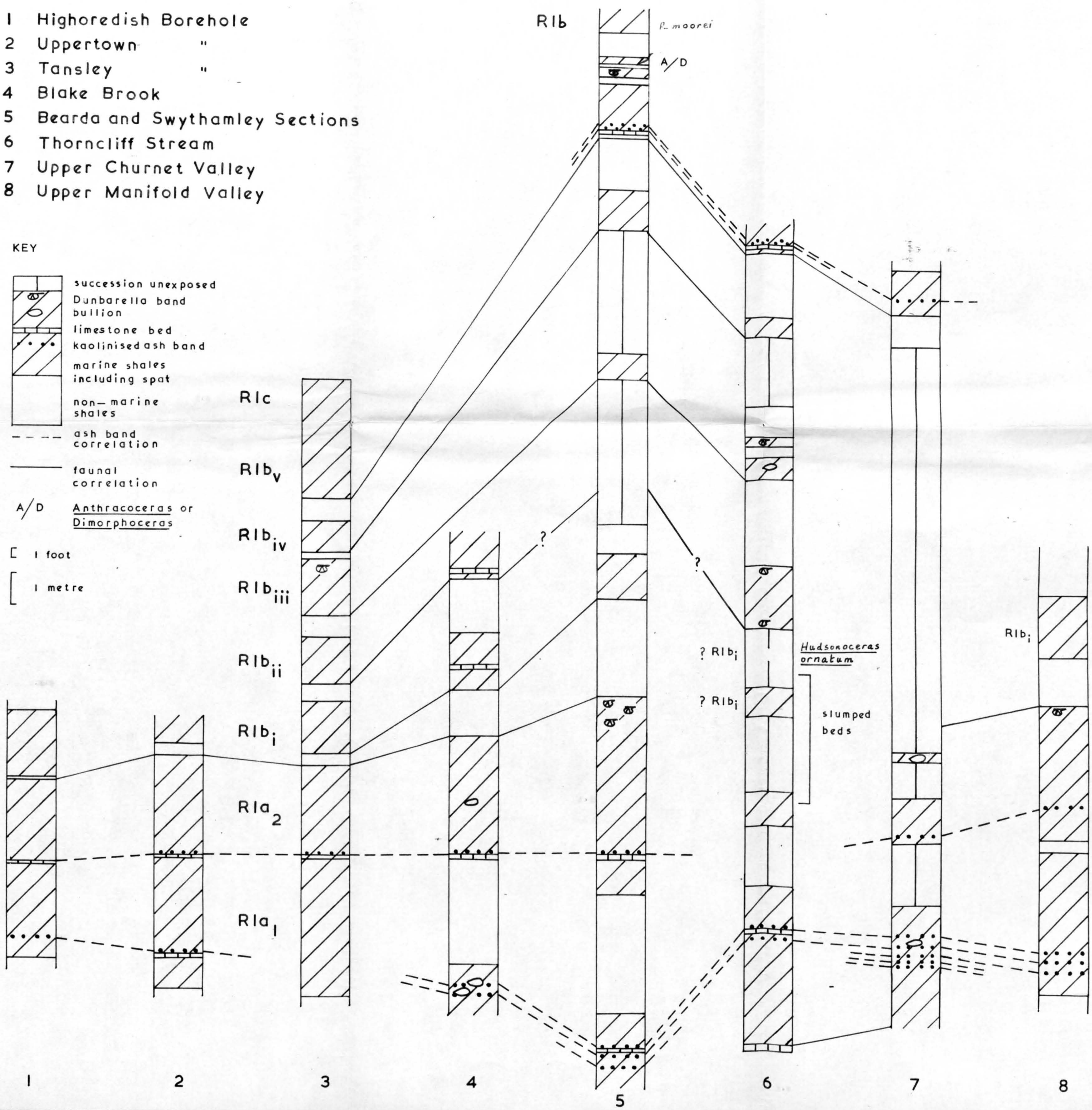
If the holotype is from Hebden Bridge, it is from R1c and there is no simple progression of characteristics from H to R2, contrary to the information on p.132-133.

p.343 The shelly benthonic facies of Ramsbottom (1970 Fig. 4.B) shown to stretch across S.W. England in the Namurian is only inferred from brachiopods in the Bampton area in E2, indicating an easterly edge to the basin. It is therefore unlikely that goniatite spat would have been found until the establishment of paralic conditions, described by Prentice (1960).

I

Appendix Figure I

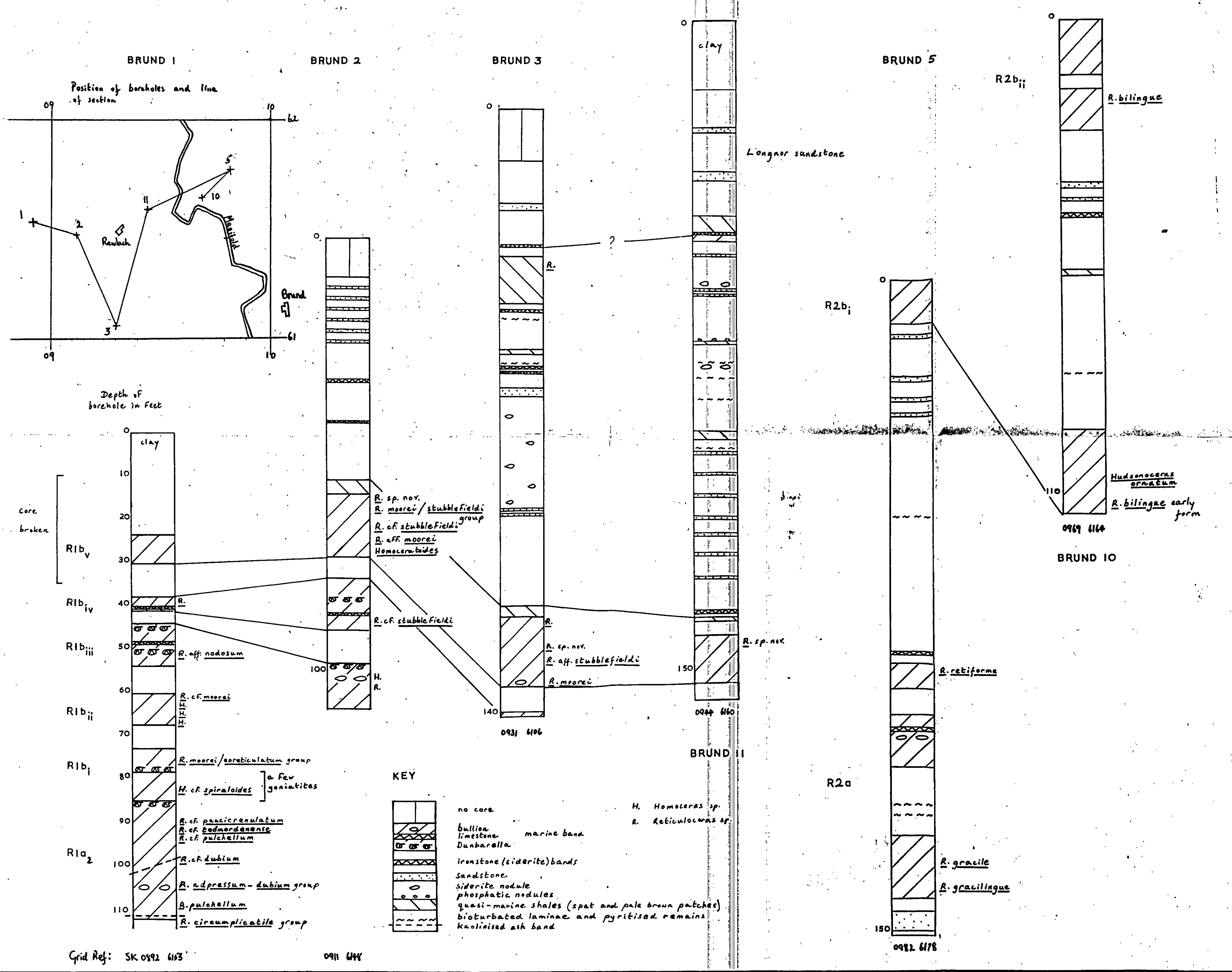
R1a–R1b KAOLINISED ASH BANDS IN THE ASHOVER BOREHOLES AND NORTH STAFFORDSHIRE



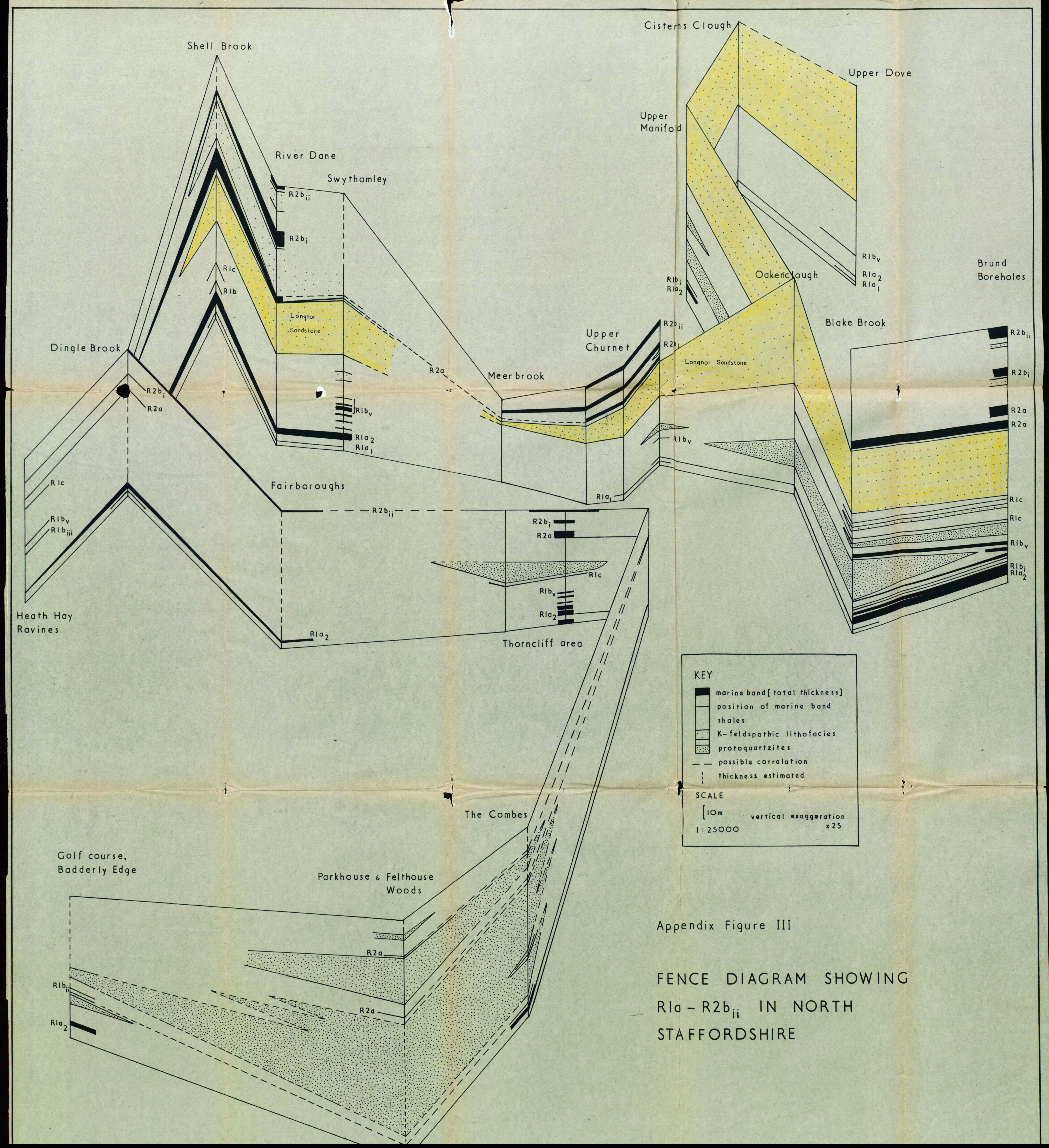
II

Appendix Figure II

CORRELATION OF THE BRUND BOREHOLES



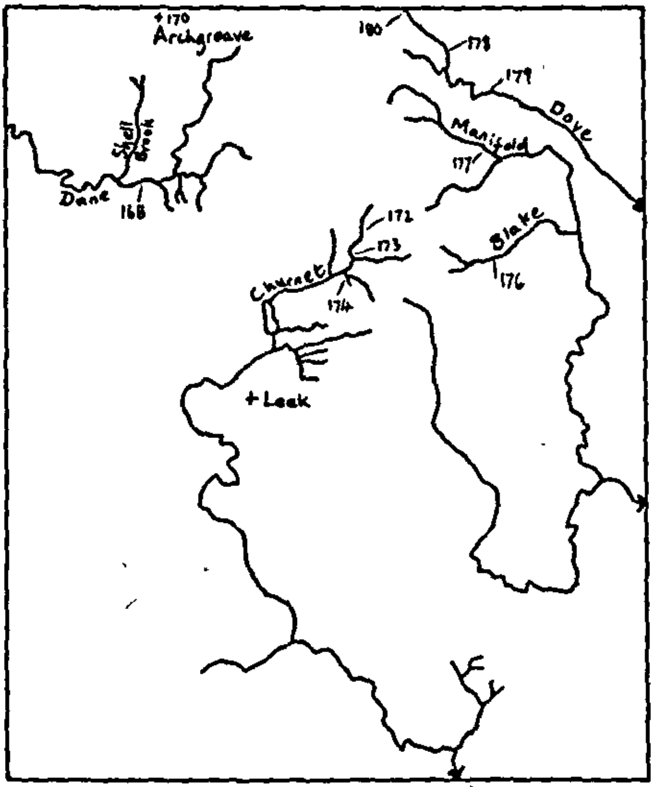
III



Appendix Figure III

FENCE DIAGRAM SHOWING $R1a - R2b_{ii}$ IN NORTH STAFFORDSHIRE

IV

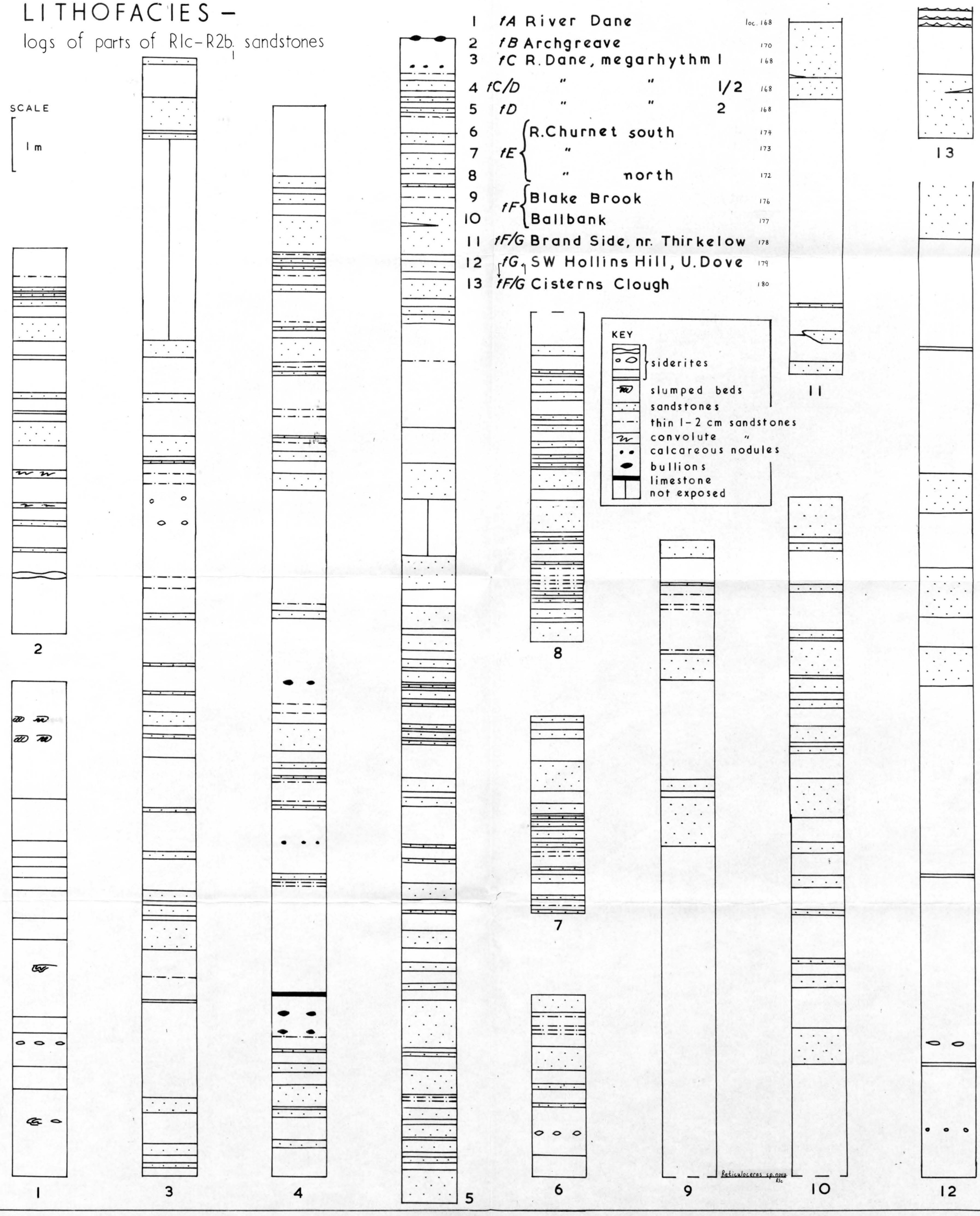


000 locality number (see also figure p.247)
for sections

Appendix Figure IV

K-FELDSPATHIC LITHOFACIES –

logs of parts of R1c–R2b1 sandstones



V

Appendix Figure V

RHYTHMS IN SUBLITHOFACIES fC/fD TURBIDITES - MEGARHYTHM TWO, RIVER DANE

VI

Appendix Figure VI