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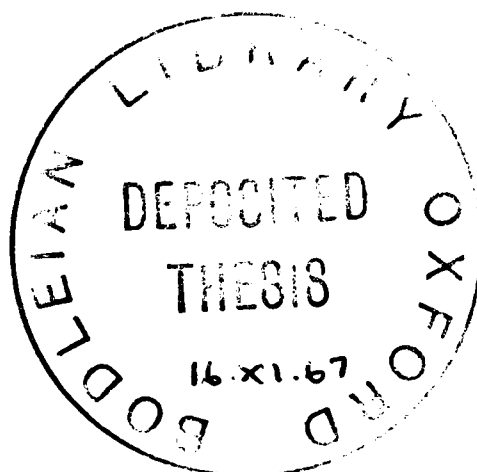
SEDIMENTATION OF THE SOUTHERN PART OF THE GRINDSLOW SHALES
AND THE KINDERSCOUT GRIT.

Volume 1

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ABSTRACT

The aim of the research has been to determine the environments of deposition of the Grindslow Shales and Kinderscout Grit in an area north of the Derbyshire Dome. These units overlie the Mam Tor Sandstones and Shale Grit, which are thought to be turbidites showing increasing proximity to source. The Grindslow Shales had been interpreted as the slope down which the turbidity currents were generated. Little was known of the depositional environment of the Kinderscout Grit, though shallow water conditions had been suggested. The sequence, from the base of the Mam Tor Sandstones to the top of the Kinderscout Grit, falls within the zone R_{1c} of the Namurian.

The outcrops of the Kinderscout Plateau, Derwentdale and Longendale have been mapped and numerous sections measured.

In all, 17 facies have been recognised, described and interpreted in hydrodynamic terms on the basis of their internal evidence. Three siltstone facies and one of silty sandstone are thought to be largely deposited from suspension, while fine sandstone, showing ripples and cross-lamination, is interpreted as showing lower flow regime conditions. Parallel laminated fine sandstone is interpreted as an upper flow regime deposit. Facies 8, Massive Bedded Coarse Sandstone, is not,

in the first instance, interpretable in hydrodynamic terms. Facies 9, Parallel Bedded Coarse Sandstone, is interpreted as an upper flow regime deposit, while Facies 10, Medium Scale Cross-Bedded Coarse Sandstone is attributed to the lower flow regime along with Facies 11, Medium Scale Cross-Bedded Fine Sandstone. Facies 12, Large Scale Cross-Bedding, consists of single tabular sets of cross-bedding up to 40 m. thick, mainly of very coarse sandstone. These are ascribed to the advance of delta-like sedimentation units into bodies of standing water. Other facies, of minor importance, are Sharp-Based Clean Sandstone Beds, Orthoconglomerates, Seat Earths and Coals, Mudstone Melange and Turbidite-like Sandstones.

Three types of trace fossil have been recognised, though it is concluded that they are probably of little environmental significance.

Five facies associations are recognised, in which facies succeed one another with variable predictability.

The Major Channel Association involves Facies 8, 9 and 10, Massive, Parallel and Cross-Bedded Coarse Sandstones, resting in channels up to 40 m. deep. Other details of channel geometry are not clear, though widths of 300-400 m. have been calculated. There is a preferred upwards facies sequence within the channels of Erosion Surface $\rightarrow$ Facies 8 $\rightarrow$ Facies 9 $\rightarrow$ Facies 10. From

hydrodynamic considerations of the sequence, it is suggested that the Facies 8 Massive Bedded Sandstone was deposited by currents flowing in the upper part of the upper flow regime, the whole channel sequence representing a waning flow.

The Large Scale Cross-Bedding Association involves Facies 12 and 10, the medium scale cross-bedded sandstone being separated from the underlying Large Scale set by an erosion surface. It is suggested that the Association represents delta cones which advanced into bodies of standing water, subsequent to sudden deepening.

The Fluvial Channel Association is a fining upwards sandstone sequence with a horizontal erosion surface at its base. Facies 10, Medium Scale Cross-Bedded Coarse Sandstone forms the bulk of the association, though thin beds of Orthoconglomerate and mudflake conglomerate may occur above the erosion surface. In the top of the association, the cross-bedded sandstone passes into parallel or ripple laminated fine sandstone and sometimes into silt earths and coals. The association is interpreted as the result of the lateral migration of a fluvial channel, probably of the meandering type.

The Slope Association, which has limited stratigraphical position, is a broadly coarsening upwards siltstone and silty

sandstone sequence. Thin turbidites occur in the base and burrows become abundant towards the top. It has occasional large channels, filled mainly with turbidites. The association is interpreted as the prograding slope of a coastline receiving abundant sediment supply.

The Interdistributary Complex Association is a random sequence of predominantly fine grained facies, showing a variety of flow conditions. It is interpreted as forming in shallow water conditions, probably in interdistributary areas of a delta top.

An analysis of the relationships of the facies associations throughout the area gives the following generalised sequence:-
'Gracile' Marine Band.

Fluviatile Channel Association

Slope or Interdistributary Complex Upper Kinderscout Grit

Butterley Marine Band

Fluviatile Channels and

Interdistributary Complex Association

Large Scale Cross-Bedding Lower Kinderscout Grit

Major Channels

Interdistributary Complex Association

Grindslow Shales

Slope Association

From a consideration of this sequence, it is concluded that the Grindslow Shales represent the main southwards advance of the delta slope and delta top environments across the area. The major channels which erode into the Interdistributary Complex Association sediments of the top of the Grindslow Shales were non-migrating distributaries which underwent frequent diversion and cut-off. They had high flow regime currents and were possibly associated with a period of eustatically falling sea level. A subsequent eustatic rise led to the ponding up of sediment on the delta top with the formation of delta cones. Above the delta cones, meandering river channels and interdistributary areas were the main features of the palaeogeography. The Butterley Marine Band and its overlying unit of Slope Association suggest a further eustatic rise of sea level. The Upper Kinderscout Grit is thought to be the deposit of laterally migrating rivers.

Comparison with the succession further north gives additional evidence of eustatic changes of sea level and suggests ways in which the palaeogeography might have responded to these. It is suggested that the turbidity currents in the basin possibly originated as high flow regime traction currents in the major channels on the delta top, at times of flood.

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CHAPTER 1. INTRODUCTION.

Statement of Problem.

The Kinderscout Grit forms the upper part of a broadly regressive sequence which passes upwards from basinal mudstones, through turbidites to shallow water sediments. Few such sequences have been described and a study of the southern part of the Kinderscout Grit will complete the investigation begun by Walker (1964).

The lowest sediments of the sequence, the Edale Shales, are thought to be deep basinal mudstones (Reading, 1964) and the overlying Mam Tor Sandstones to be largely the deposits of turbidity currents flowing into the basin (Allen, 1960). Reading (1964), in a regional review of Namurian sedimentation, thought that the overlying Shale Grit and Grindslow Shales were the 'off-shore delta front' deposits of an advancing delta, the Grindslow Shales representing the delta slope. Walker (1964, 1966a) interpreted the Shale Grit as a formation of proximal turbidites, overlying the more distal Mam Tor Sandstones. In the Grindslow Shales, he found no evidence of traction currents and suggested that their depositional environment was the 'slope' on which the turbidity currents were generated. Above the slope was thought to be a shelf

area, ambiguously referred to by Walker as the 'delta platform', over which advanced the Kinderscout Grit 'delta'. The widespread erosion at the base of the Kinderscout Grit was considered to be due to a eustatic fall of sea level after the deposition of the Grindslow Shales.

Reading (1964) had previously contrasted the absence of regular paralic cycles in the southern Kinderscout Grit with their presence in time equivalents to the north in Wharfedale. He suggested a 'near-shore or coastal plain' environment within an uninterrupted regressive sequence. Later (pers. comm.), he noted that the coarse sandstone in the lower Kinderscout Grit lacked normal fluviatile characteristics.

From the previous work, therefore, several problems emerge. Was the depositional environment of the Grindslow Shales the actual delta slope, as suggested by Reading, or a separate slope in front of the delta, as Walker imagined? Following from this is the question of whether the turbidity currents of the Mam Tor Sandstones and Shale Grit originated at the mouths of delta distributaries or are the result of resedimentation of material initially deposited on a shelf. What also was the depositional environment of the Kinderscout Grit? Is its erosive base a consequence of uninterrupted regression or is it due to a eustatic lowering of sea level or other controls?

Thus, the aim of the present research is to describe the southern part of the Grindslow Shales and Kinderscout Grit, to deduce some of the processes that operated during sedimentation and to reconstruct the environments of deposition. By placing these in a regional context, a reconstruction of the history of sedimentation can be attempted and at least partial solutions to the above problems be thereby offered.

Area Studied.

Boundaries.

The area studied is in the north of Derbyshire and Cheshire and the south of the West Riding of Yorkshire. The area is bounded to the south by the Vale of Edale, to the west by the grid line SO 50 and Crowden Great Brook, to the north and east by the limits of outcrop (Fig.1). With exceptions of small areas west of Bleaklow and east of Hathersage, all the area is shown on the geological and locality maps presented in the thesis.

The area is covered by Ordnance Survey 1" Sheets 102 and 111 and by the "Peak District" Tourist Map. The Geological Survey Sheets (New Series) 86, Glossop (1932) and 99, Chapel-en-le-Frith (in press) cover the area.



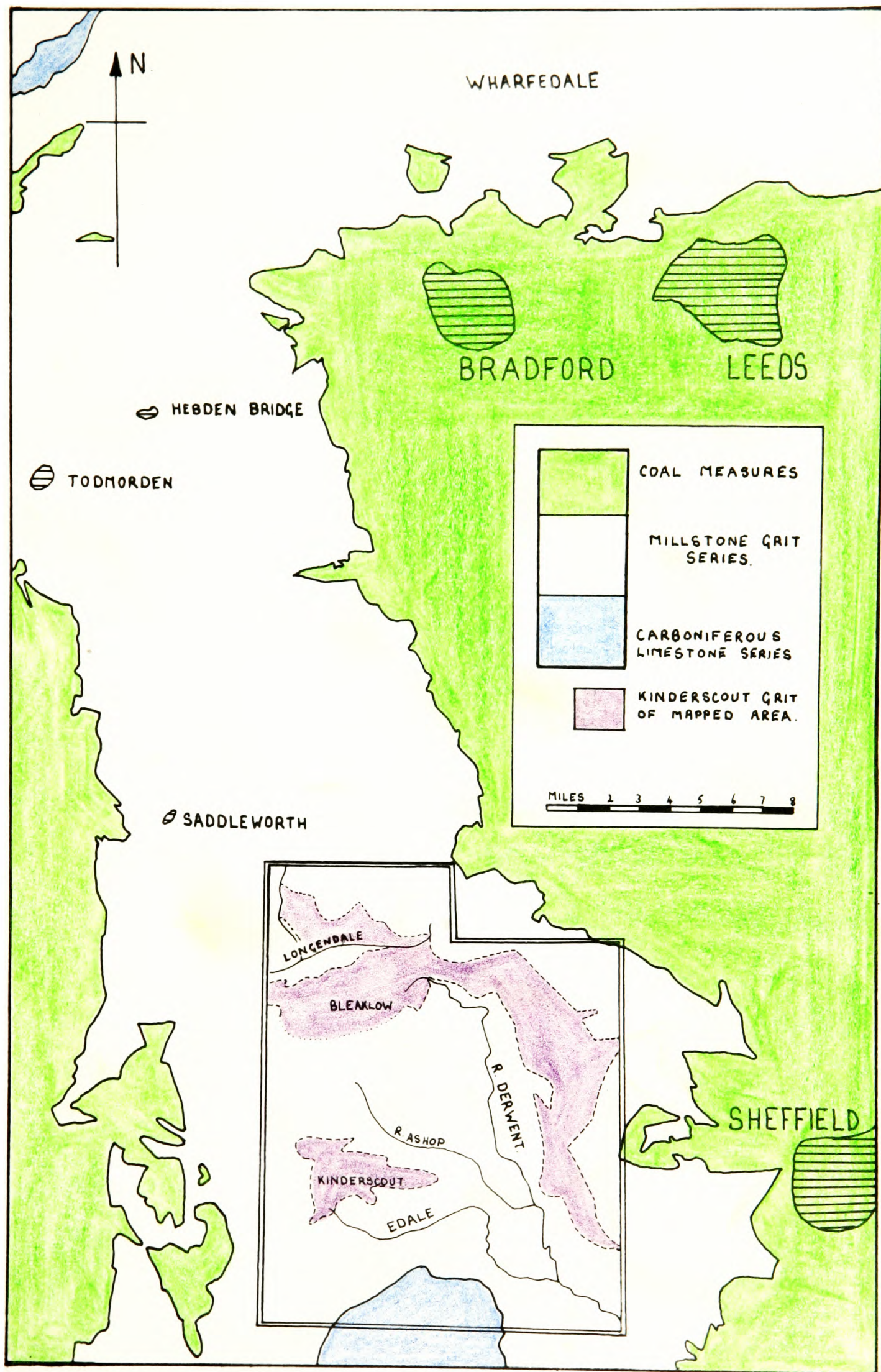


FIGURE 1.

Topography.

The Kinderscout Grit is the dominant controller of the topography, forming the tops of the highest hills so that with the exception of north Longendale and the Ladybower areas, it always outcrops above the 1000 ft. contour. The highest areas are the Kinderscout and Bleaklow Plateaux, both over 2000 ft. at their highest points.

To the north of Longendale, the Kinderscout Grit forms steep scarp slopes, cut by steep-sided valleys such as Crowden Great Brook. To the north and east of the Derwent Valley, the Kinderscout Grit forms the steep, topmost scarps with extensive dip slopes behind, forming the catchment area of the headwaters of the River Don. The Bleaklow and Kinderscout Plateaux are surrounded by steep scarp slopes which often show the development of 'edges', steep, often nearly vertical walls of rock giving good, though often inaccessible exposure. (Photo. 1). On dip slopes and plateau tops, peat is often thickly developed, though isolated tors protrude. (Photo. 2). Most of the area is heather covered moorland or rough grazing, though more profuse vegetation grows in sheltered valleys along the eastern margin of the area.

Landslides, often of huge dimensions, are found on the western and southern sides of Kinderscout and on the northern side of Bleaklow.

Access.

Two major roads cross the area in an east-west direction. The A628, in the north, follows the River Etherow along Longendale and the A57 follows the River Ashop up the Woodlands Valley, giving access to the northern side of Kinderscout. The southern side of Kinderscout is reached by means of the minor road to Edale. The southern part of the Derwent Valley is served by the A6103, between Ladybower and Bamford, but access to the northern part of the Derwent Valley is more difficult. A public road follows the western side of the valley nearly to the upper end of the Howden Reservoir. The valley can be crossed below the Derwent dam and private roads of the Derwent Valley Water Board extend to the upper end of the Howden Reservoir on the eastern side. These were used during the present research by kind permission of the Board's Chief Engineer. The dip slopes to the east of the Derwent are reached by the minor 'Strines' road, linking the A57 at Moscar with the A616 at Langsett.

It is never necessary to walk more than 5 km. from a road to reach any exposure. The area is within the Peak District National Park and is well served with footpaths. Most of the area is 'Open Country' to which the public have right of access though some of the dip slopes east of Derwent are private moors, and permission from gamekeepers is advisable.

History of Previous Research.

The name Kinder Scout Grits (sic) was first used by Green, Foster and Dakyns (1869) for the two lowest units of the Millstone Grit, the Fourth and Fifth Grits.

The term Millstone Grit is itself of great age, going back at least to Mawe (1802). The present stratigraphical nomenclature of the succession above the Carboniferous Limestone north of the Derbyshire Dome was proposed by Jackson (1927).

The area was remapped by officers of the Geological Survey on Sheets 86, (1932) and 99 (in press) with a memoir to Sheet 86 (1933).

There has been no specifically sedimentological investigation of the Kinderscout Grit, though Sorby (1859a) and Gilligan (1920) probably included observations from the Kinderscout Grit in their broader studies. Wright (1959, 1964) in a general study of Millstone Grit sedimentology recorded some specific though isolated observations from the Kinderscout Grit.

C. T. Walker (1955) worked on time equivalents of the Kinderscout Grit in Wharfedale, 50 km. to the north of the present area.

The present phase of sedimentological research began with the recognition, by Allen (1960), of the turbidite

nature of the Mam Tor Sandstones. Reading (1964) reviewed regional aspects of Millstone Grit sedimentation in the Pennine Basin. This was followed by Walker's detailed investigation (1964, 1966a and b) of the Shale Grit and Grindslow Shales.

Stratigraphic Palaeontology.

The first description of the Namurian palaeontology of the area was Jackson's account of the succession below the Kinderscout Grit in the Edale area. This information is included in Figure 2.

Work by Bisat, Cotton and Hudson on the Reticuloceras faunas led to a scheme of zones and sub-zones (Hudson, 1945).

STAGES.		ZONES (Bisat, 1928)	SUB-ZONES (Bisat and Hudson, 1945)
Marsdenian.	R ₂	<u>R. gracile.</u>	{ <u>R. gracile.</u> <u>R. aff. gracile.</u>
	R _{1c}	<u>R. reticulatum.</u>	{ <u>R. co-reticulatum.</u> <u>R. reticulatum.</u>
Kinderscoutian.	R _{1b}	<u>R. eoreticulatum.</u>	{ <u>R. nodosum.</u> <u>R. dubium.</u>

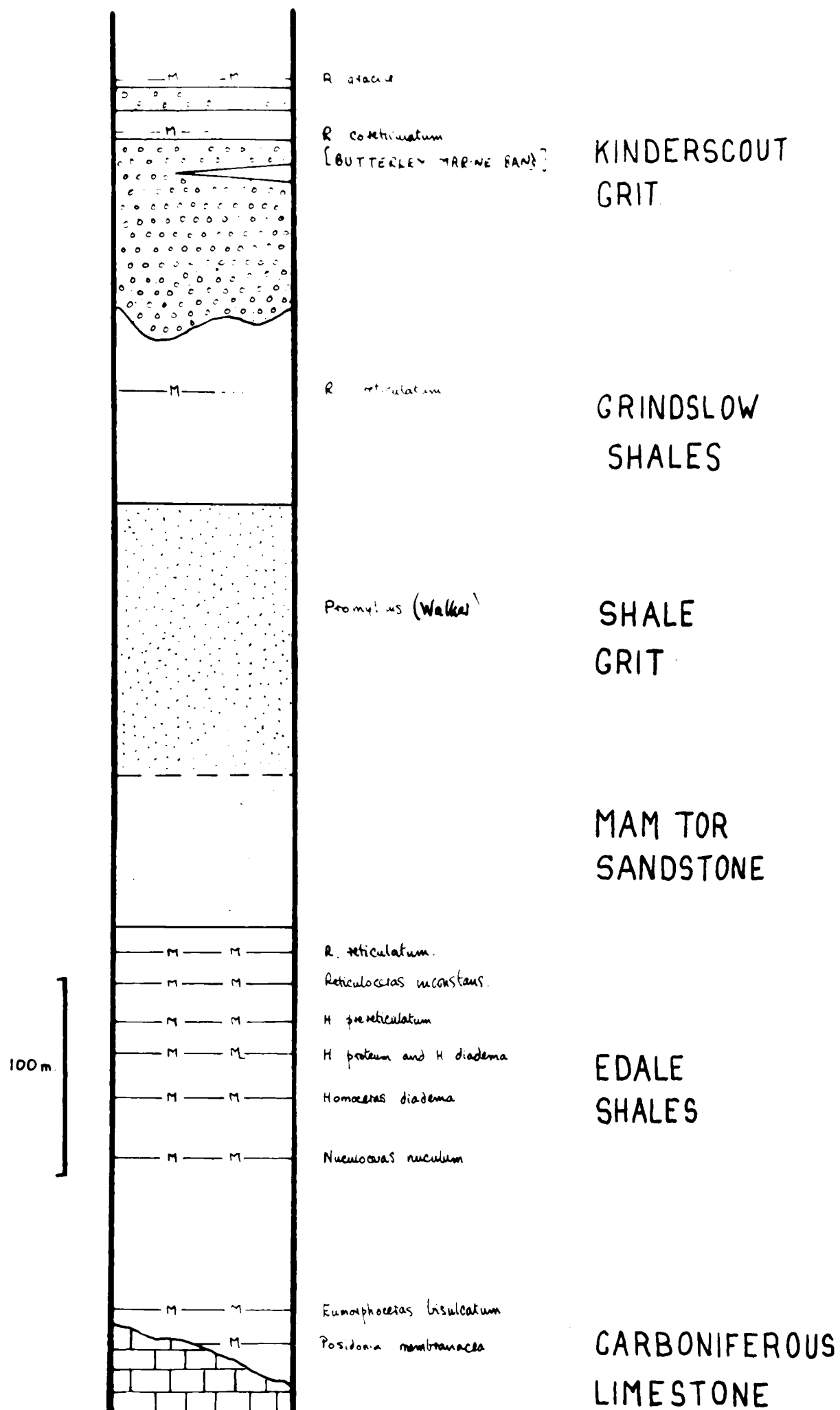


FIGURE 2.

The highest faunal horizon below the base of the Marn Tor Sandstones contains R. reticulatum s.s.. The shales of the Marn Tor Sandstones contain goniatites of R_1 age including Reticuloceras, Homoceras and Dimorphoceras (Hudson and Cotton, 1945).

No diagnostic fauna has been found in the Shale Grit, though Walker (1964) found the bivalve Promytilus in Blackden Brook.

Goniatites were found in the Grindslow Shales by Holroyd and Barnes (1896) at a now obscured locality in the Greenfield Valley, about 4 km. west of Crowden Great Brook. These were identified by Jackson as R. reticulatum s.s. (in Bromehead et al., 1933, p. 145), though Bisat regards them as an early mutation of R. gracile (Bisat and Hudson, 1941). Ramsbottom (pers. Comm.) now doubts the authenticity of this occurrence, the specimens having been lost. R. reticulatum s.s. has been found in the Upper Sabden Shales below the Kinderscout Grit in the Todmorden and Crimsworth Dean areas, 20 or 30 km. north of the present area (Bromehead et al., 1933, p.144). Around Marsden, to the north of the present area, the Kinderscout Grit is subdivided into upper and lower parts by a persistent mudstone and siltstone horizon. This, where seen, contains the Butterley Marine Band, which has mainly a non-diagnostic fauna of Lingula, bivalves and bellerophontids. To the south,

goniatites are found both at the base of the band and in a slightly lower horizon. Bromehead et al. (1933) state that the marine band wedges out in the region of Crowden, Longendale and that no fossils are found to the south. Recent work by the Geological Survey indicates that the mudstone horizon and marine band persists over the whole of the Kinderscout Grit outcrop. At Rushy Flat Dyke (N.G.R. SE 215922) the marine band contains mainly goniatites with an upper band containing Lingula. These goniatites are probably an undescribed form of R. reticulatum though R. coreticulatum is found in the same horizon to the north in the Clitheroe and Leeds areas (Ramsbottom, pers. comm.).

The persistence of a fine grained unit with a marine band near its base, below the topmost sandstone of the Kinderscout Grit can be extended over the whole of its area of deposition southward from Wharfedale, where the Upper and Lower Kinderscout Grits have time equivalents in the Bramhope and Addingham Edge Grits respectively. (Ramsbottom, 1966).

The top of the Kinderscout Grit is defined by a marine band containing R. reticulatum mut. α (= gracile) and late mut. α , Bisat (Bromehead et al., 1933) which places it in the base of the R_2 Marsdenian Stage.

The succession from the base of the Mam Tor Sandstone to the top of the Lower Kinderscout Grit falls within the R_1c

zone. This part of the succession has time equivalents in Wharfedale in the Caley Crags and Addingham Edge Grits. Ramsbottom (1966) suggests direct correlation of the Shale Grit with the Caley Crags Grit and of the Lower Kinderscout Grit with the Addingham Edge Grit. Detailed paleontological evidence for this correlation is, however, not certain.

The Upper Kinderscout Grit lies between marine bands containing R. coreticulatum and R. gracile and has time equivalents in Wharfedale in the Bramhope Grit.

Structure.

Folding.

The area is structurally simple, rocks being folded in broad gentle folds with dips seldom exceeding 10° . The major anticlines are the Derbyshire Dome-Edale Anticline, the Alport Dome and the Pennine Anticline. Between these are the Kinderscout Syncline and a possible syncline in Longendale.

The Kinderscout Syncline has its axis east-west through the Kinderscout Plateau. The Alport Dome has its centre in the Alport-Westend area giving a large plateau of Shale Grit with Edale Shales exposed in the core in Alport Dale and Ashop Clough. The Kinderscout Grit dips away to the west, north and east giving scarp features. Southern-dipping Kinderscout Grit forms the northern scarp of the Kinderscout Plateau. The

scarp to the east of the Derwent Valley extends to the south, beyond the influence of the Alport Dome, and in the Bamford-Hathersage area is controlled by the Derbyshire Dome.

North of the Alport Dome, the Kinderscout Grit, dipping north-west and north, forms the highest ground of the Bleaklow Plateau and the dip slopes east of the Black Cloughs. West of the Alport Dome, the dip steepens gradually towards the Blackshaw Fault, just east of Glossop. North of Longendale, the beds are rather flat lying, though there is a tendency for the beds to dip to the south-east around Crowden, while east of Heyden Brook, the dip is to the north-east. The south-easterly dip may be due to the Pennine Anticline to the north-west and suggests the possibility of a syncline in Longendale. Faulting makes confirmation of this impossible.

Faulting.

Most of the faulting in the area seems normal and two major directions are seen, NE-SW and NW-SE. There are also at least two major east-west faults. The rocks are frequently cut by vertical joints, which are particularly abundant in the vicinity of faults. Most of the faults in the area have been named (Bromehead et al., 1933), and this nomenclature will be followed here. Faults in the area of the unpublished Chapel-en-le-Frith Sheet and those thought to differ from the inter-

pretation shown on the Glossop Sheet are described below, from south to north.

The Kinderscout Plateau is virtually free of faulting, the only fault of any significance being a NE-SW trending one, downthrowing to the south-east by about 30 m., at the north-western corner of the plateau.

In the Ladybower area, a NW-SE trending fault downthrows to the north-east by at least 40 m., dying out rapidly to the south-east. The relationships in this area are rather obscure and more detailed mapping may show the need for a NE-SW fault to fully explain them.

The Crowden Fault, trending east-west along the Longendale Valley, is shown by the Geological Survey to downthrow to the north. In the vicinity of Crowden, a throw of about 100 m. is suggested, based on the base of the Kinderscout Grit. However, at the junction of Far Small Clough with the River Etherow, (N.G.R.SK 134996) the fault must downthrow to the south by about 20 m.. It must be questioned whether these two throws are the result of a rotation along one fault plane or whether two faults are present, both dying out rapidly. Until this pattern of faulting is more clearly understood, correlation between the dip slope stream sections, between the Black Cloughs and Far Small Clough, will be doubtful.

Age of Movements.

The folding and faulting are probably broadly contemporaneous, the faulting possibly being a response to torsional stresses set up by the folding. The movements affect beds up to the Coal Measures outside the area and the Carboniferous is overlain unconformably by Permian and Triassic beds. This suggests that movement was probably early Permian in age. Some of the faults affect both Carboniferous and Permo-Trias, suggesting later movements, probably along reactivated older faults.

CHAPTER 2. METHODS.

Field Methods.

Section Measuring.

The basis of any sedimentological study of this type is the measured section, a record of the thicknesses, lithologies and relationships of the beds and of the nature and orientation of their sedimentary structures. Sections have been measured mainly in scarp slope streams, where the greatest vertical thickness is exposed over the least horizontal distance. Where exposure warranted it, sections have also been measured in edges, landslip backscars and in dip slope stream sections. In this last case, only short sections could be measured in stream banks but a series of these enabled lateral variations to be established. The measurement of sections in edges and landslip backscars was greatly aided by the use of panoramic photographs, taken from the ground, and of oblique aerial photographs, taken from a privately chartered aircraft. These photographs were also of great use in understanding the larger-scale structures and their lateral variations.

Measurement of sections was mainly by tape, to the nearest 1 cm., though gaps in exposure and thick units were measured with a small Abney level set to the dip of the rocks. Grain size was judged with the aid of a portable scale of grains of

different sieve sizes, corresponding to a Wentworth scale.

The following system of grain-size nomenclature was used:-

Diam.mm.	ϕ	
4-2	-2 to -1	Extremely coarse sandstone.
2-1	-1 to 0	Very coarse sandstone.
1-0.5	0 to 1	Coarse sandstone.
0.5-0.25	1 to 2	Medium sandstone.
0.25-0.125	2 to 3	Fine sandstone.
0.125-0.062	3 to 4	Very fine sandstone.
less than 0.062	> 4	Siltstone. (Subjective qualifying adjective)

Directional structures were measured with a prismatic compass to the nearest 1° . Measurements were recorded in the field in a 'single cash' notebook, the columns of which were used in the following way:-

①	②	③	④	⑤
0.35	Medium - cs. siltstone in lam parallel beds with gradational boundaries. A few horizontal burrows	G	22	
0.20	Fine - medium silty sandstone, Parallel horizontal bedding but rather disturbed by vertical burrows	S		164

FIGURE 3.

Column 1. Bed Thickness.

" 2. Description of lithology, structures and directions.

" 3. Nature of upper bed boundary: S=Sharp. G=Gradational.

GS=Sharply gradational.

" 4. Specimen Number.

" 5. Photograph Number.

The data were transferred to strips of graph paper, as a column, usually on the scale of 50:1 though when exposure was poor, 200:1 was used. At 50:1, a 2 cm. bed can just be shown. The type of boundary, noted in column 3 above is shown symbolically:-

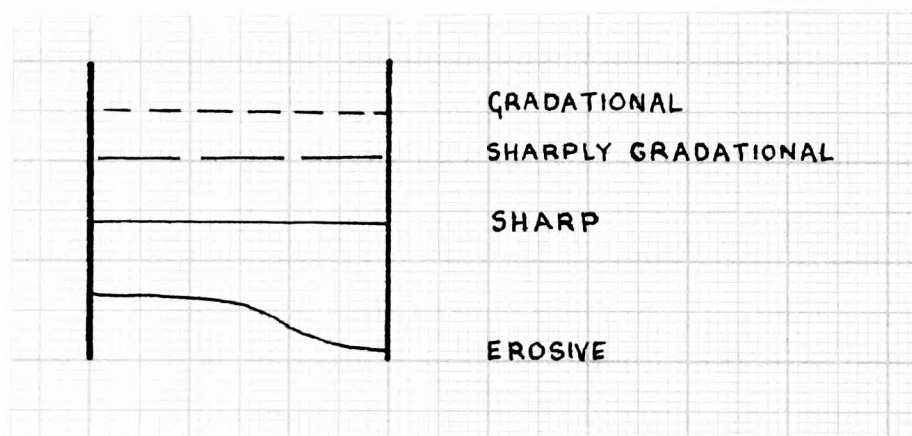


FIGURE 4.

The descriptive features noted, in column 2 (Fig. 3), are transferred directly to the right-hand margin along with the numbers of specimens and photographs. Palaeocurrents are noted; [19], specimens; [18], and photographs; [12]. This section is simpler than Bouma's graphical method (1962) both

to draw up and to read. (Fig. 5)

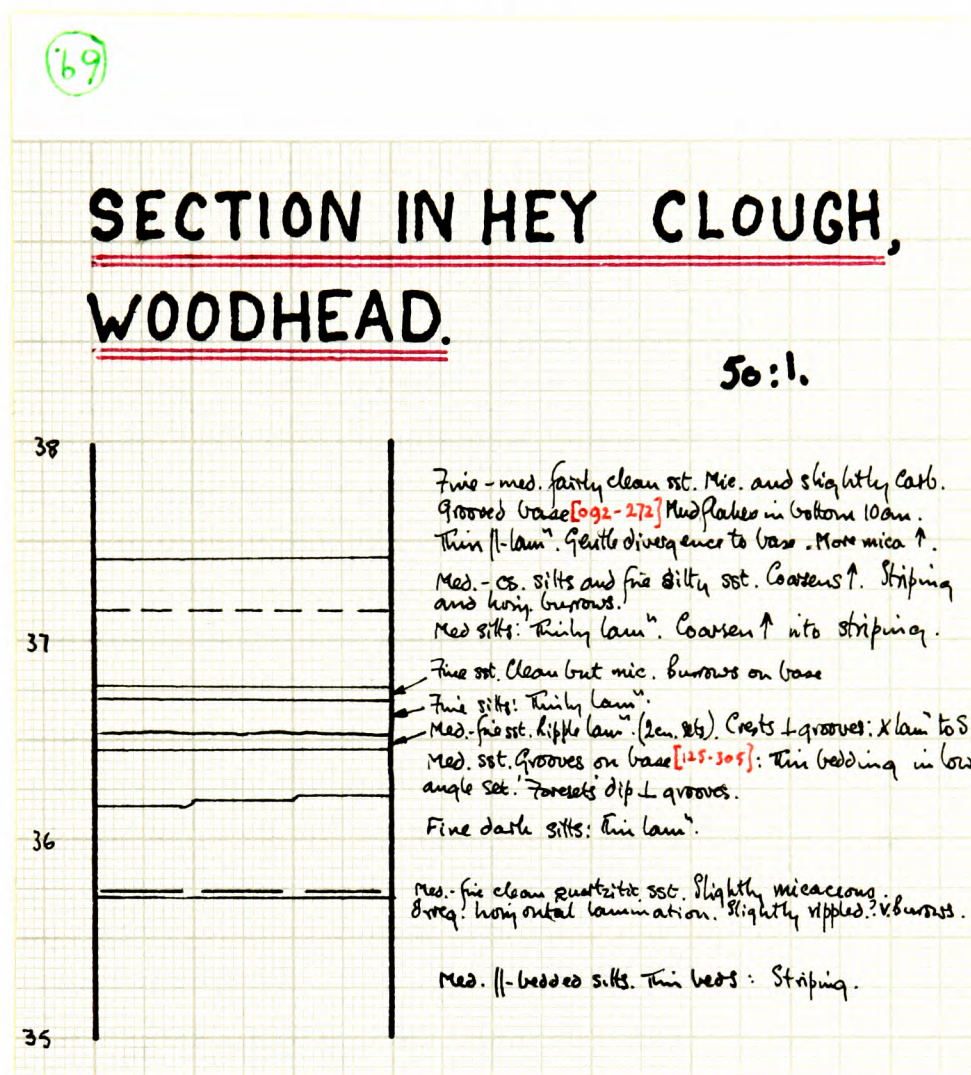


FIGURE 5.

Mapping.

The aim of mapping is to establish the relationships between measured sections, topographic features and any isolated exposures not included in measured sections, thereby establishing lateral facies variations. Coarser grained units can be shown on scarp slopes, to form steep features, while finer grained horizons form gentler slopes. On dip slopes, flat, dipping surfaces are formed by the tops of coarse units while

the finer beds occur in the bases of steep features capped by coarser rock. (Fig. 6)

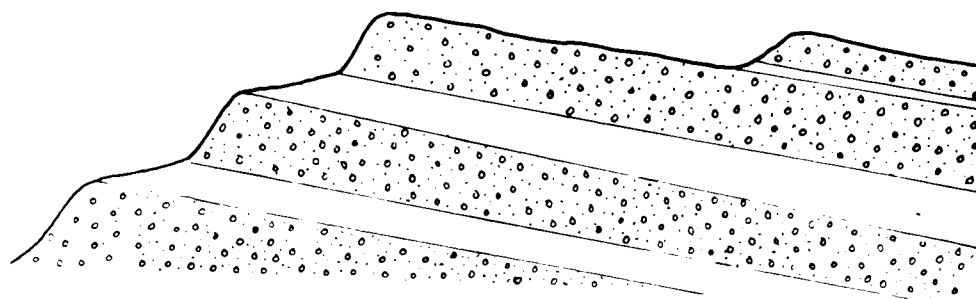


FIGURE 6.

The area has been mapped on the scale of 1:10560 (6" to 1 Mile) from ground observation and the study of vertical and oblique aerial photographs. The map has been reduced to a scale of 1:25000 for presentation in the thesis. It shows the solid geology of the Grindslow Shales and Kinderscout Grit and the topographic features on which the geology is based.

Photographic.

As well as oblique aerial and panoramic photographs, an extensive series of photographs was taken of sedimentary structures and lithological relationships. These were of value in the allocation of some horizons to a facies and a representative selection is presented in Volume 2 of the thesis.

Palaeocurrent Measurement.

Current directions were measured on sole marks and internal structures. All current directional features found were measured and a grid sampling system was not used (Potter and Pettijohn, 1963, p. 253). Measurements were made in the field with a prismatic compass and in the case of foreset dips, with the aid of a small Abney level used as a clinometer. As most tectonic dips are small, no attempt has generally been made to reorientate palaeocurrent measurements. It has only been done for planar foreset dips when the tectonic dip is known with confidence.

Linear structures, such as grooves and primary current lineation, were recorded without suggesting the sense of movement. Ripples were only measured in plan view, when their crests or a 'rib and furrow' (microtrough cross-lamination) were seen. Similarly, trough cross-bedding directions have only been measured in plan view. The directions of trough axes were estimated by eye for direct measurement and no attempt was made to measure and plot out the poles of foresets around troughs (Potter and Pettijohn, 1963, p. 73). Only in the case of apparently tabular sets was a foreset dip direction held to be representative of the whole set (Meckel, 1967).

Local relationships of current direction may often be environmentally diagnostic. In this thesis, palaeocurrents

are more often used in a local interpretative way, rather than for basin analysis. However, maps are presented of the regional distributions of palaeocurrents from several facies associations.

Laboratory Methods.

Analysis of Field Data.

The measured sections were re-examined and each bed allocated to one of a number of facies, and coloured according to a facies colour code. The sections and mapping information were combined to produce lateral facies variation diagrams for sub-areas where correlation was good. These are discussed in Chapter 5.

Petrographic Methods.

Specimens collected in the field from all facies were examined in the laboratory. Thin sections of most types were cut and several polished surfaces prepared. The latter were used for the examination of the smaller sedimentary structures and for the measurement of grain orientation in the coarsest sandstones. Three types of measurement were made on the thin sections:-

i) Point Counting. Thin sections were point counted for quartz,

feldspar, mica, carbon and matrix. No 'rock fragment' category was recognised because of the difficulty of distinguishing originally polycrystalline grains from diagenetically associated, single grains. Material which could not be resolved was assigned to the matrix category. It includes primary and diagenetic clay minerals as well as the products of recent weathering of the feldspars. Where clay minerals are seen to pseudomorph or only partially replace feldspars, the point has been counted as feldspar. Both potassium and plagioclase feldspars are present but no attempt has generally been made to separate them in the point counting.

ii) Grain-Size Measurement. Because of diagenesis, it was found impossible to disaggregate specimens for analysis. All grain-size measurements have therefore been done from thin sections. These were projected on a 'Shadomaster' at known magnification and the lengths of the longest grain dimension measured directly with a ruler. A 1 cm. sample grid was used. Grains which fell on more than one point were recorded for each point to give a closer approximation to a weight distribution. The measured grains were allocated to ϕ classes and plotted as cumulative curves.

iii) Grain Orientation. For the coarsest specimens, sections were cut parallel to the bedding or in the case of cross-bedded sandstone, parallel to the foreset surface. The orientations

of the thin sections were noted. The sections were projected by 'Shadomaster' and the long axes of obviously elongate grains drawn on a tracing paper overlay. The axial directions were then measured and plotted on circular histograms with either 10° or 20° classes. A few vertically cut thin sections were measured in a similar way.

Grain size analyses and compositions, plotted on triangular diagrams, are presented in the Appendix. Point counting and orientation results are noted in Chapter 3.

CHAPTER 3. FACIES.

Introduction.

The term 'facies' is used here in a descriptive sense, for a group of rocks differing from others by virtue of their field aspect. This is controlled by parameters such as grain-size and composition of sediment, geometry and size of sedimentary structures and influences of biological activity.

Many facies are intergradational and, for reasons of expediency, separation is often subjective. Familiarity with the variety of rock types present leads to reasonably consistent attribution.

There is always the possibility of further subdivision of facies. The approach here, however, has been to define as few facies as is consistent with showing the range of processes that has operated. The range of variation within a facies is indicated in the description below.

One inconsistency in this approach has been to eliminate trace fossils from the criteria of subdivision and to deal with them under their own heading. This avoids a proliferation of facies names due both to the multiplicity of trace fossil types and to the wide range of lithologies in which they may occur.

Most facies, from their internal features, indicate only

the processes that have operated on a sediment during and after its deposition and have little absolute environmental significance. In this chapter, each facies will be described and the processes that have operated inferred from the internal evidence.

Facies 1. Mudstone with Marine Fossils.

Description.

This facies is confined to two distinct stratigraphical horizons, the 'Butterley' and 'Gracile' Marine Bands. It consists of very fine grained, grey or black, commonly sulphurous mudstone or siltstone. No petrographic data are available though comparison with Walker's Facies F, Paper-laminated mudstone (1966a, p. 103), suggests that clay minerals and carbonaceous material form the bulk of the sediment, the former occurring as small lenticles. When fresh, the mudstone is rather massive but in a more weathered state, it is highly fissile, showing a paper-thin, parallel and horizontal lamination. There is no evidence of current activity.

On the planes of the lamination are flattened fossils. These are commonly Lingula, Pterinopecten, and Orbiculoidea. In the 'Gracile' Marine Band, the goniatite, Reticuloceras reticulatum, mut. (= gracile) is found. Heptonstall, (pers. comm.) working on the 'Cancellatum' Marine Band, found evidence

of the preferred orientation in those Gastrioceras, preserved in an upright position. He looked for a similar feature in the 'Gracile' Marine Band without success. Reticuloceras has a flattened form and is therefore less likely to be preserved in an upright position.

Interpretation.

The fine grain size, parallel lamination and lack of evidence of current activity, suggest that the mudstone was deposited in extremely quiet conditions, by the accumulation from suspension of fine grained material. The fauna is diagnostic of a marine environment but no depth connotation can be placed on the facies.

Facies 2. Mudstones and Siltstones.

Description.

This facies is gradational with Facies 1, Mudstone with Marine Fossils, Facies 3, Striped Siltstones, Facies 4, Silty Sandstone and Facies 5, Siltstone with Sandy Laminations and Ripples. It consists of mudstones and siltstones, lacking sand-sized particles except for large mica flakes and carbonaceous fragments.

At one extreme, this facies consists of fine, black, thinly-laminated mudstone, sometimes sulphurous, and distinguish

from Facies 1 only by the absence of fossils. It then corresponds, to some extent, to Walker's Facies F Mudstone (1966a, p. 103). There are all gradations between this extreme and very fine sandstone.

All grades can appear massive though thin, parallel bedding and lamination are more common, the actual appearance generally being governed by weathering condition. (Photo 3). Lamination is largely due to the horizontal orientation of the mica flakes and carbon fragments, though high carbon content often gives irregularities in the lamination.

This facies, in the Grindslow Shales, is sometimes associated with thin graded sandstones and with thin 'inter-laminations' which distinguish Walker's Facies D3 Mudstone (1966, p. 101).

Ripples, cross-lamination and primary current lineation are all absent. Trace fossils, generally horizontal burrows, are found in the coarser members of this facies and associated with sandy 'interlaminations'. Parts of Walker's Facies D1, 2, 3, F, G and H are, to some extent, included in this facies.

Interpretation.

The absence of any features indicating current activity and the fine grained nature of the sediment suggest that this facies was deposited in quiet water by material's falling from

suspension, though it is possible that at a very low flow regime, sediment can be moved on a plane bed without the formation of ripples. There is, however, a disagreement as to whether or not sediment can be transported in this way. (Simons et al. 1965, p. 37).

The sandy 'interlaminations' could be due to bed-load transport, particularly where associated with turbidites. Walker interprets 'interlaminations' as due to deposition or reworking by the thin edges of turbidity currents, though weak traction currents could have the same result. The thin graded sandstone beds are also interpreted as turbidites.

No absolute environmental significance can be attached to this facies which could have been deposited in a wide variety of quiet environments.

Facies 3. Striped Siltstones.

Description.

This facies is gradational with Facies 2, Mudstones and Siltstones, Facies 4, Silty Sandstone and Facies 5, Siltstone with Sandy Lamination and Ripples. The facies consists of sediment from medium silt to fine, very silty, poorly sorted sandstone.

Table 1. Composition of Facies 3. Striped Siltstones.

Specimen No.	Quartz	Felspar	Mica	Carbonaceous Material	Matrix	Points Counted
K.20	41.8	6.4	8.4	2.2	39.3	1040
K.41	50.0	11.0	8.0	2.4	31.0	400

Grain size cumulative curves are presented in the Appendix.

The sediment is bedded in thin, parallel and horizontal beds, normally 1 to 2 cm. thick though up to 4 cm., giving a distinctive striped appearance in the field. Boundaries between beds are gradational, the bedding reflecting slight grain size fluctuations. (Photos 4 and 5). The facies is rich in unresolvable matrix, mica and carbonaceous matter which tend to lie with their platy surfaces horizontal, giving a weak lamination. Larger plant fragments, up to 10 cm., sometimes disturb the bedding and lamination. Rare, cleaner sand laminations are found which may show ripple form and cross-lamination.

This facies is particularly susceptible to the activity of burrowing organisms, both horizontal and vertical burrows occurring, often in great abundance.

The facies corresponds in part to Walker's Facies J, Parallel Bedded Silty Sandstone, Facies H, Sandy and Silty Mudstone and, where bioturbated, Facies G, Sandy and Silty

Mudstone with Horizontal Burrows.

Interpretation.

The general absence of cross-lamination, ripples and primary current lineation suggest that current activity was very weak and that sediment was largely deposited from suspension. The alternation in grain size to give the striped appearance is probably due to fluctuations in current strength, water chemistry or sediment supply. These may be controlled by seasonal factors in a way analagous to the formation of varves.

The occurrence of sandy interlaminations with rare ripples suggests that occasionally currents in the lower flow regime (Simons et al. 1965, p. 36) transported or reworked the sediment-water interface.

No environmental significance can be attached to this facies from its internal evidence. Coleman and Gagliano (1965, p. 147) show that textural, parallel lamination occurs in all the clastic environments recognised by them in the Mississippi Deltaic Plain.

Facies 4. Silty Sandstone.

Description.

The term silty sandstone is used to cover a broad range

of fine to medium sandstones of variable silt content. The facies is intergradational with the coarser Facies 2 Siltstones and with Facies 3 Striped Siltstones, differing in lacking the striped appearance. Carbonaceous material and mica are common, the mica flakes being up to 3 mm. in diameter.

Table 2. Composition of Facies 4. Silty Sandstone.

Specimen No.	Quartz	Felspar	Mica	Carbonaceous Material	Matrix	Points Counted
K.4.	48.0	12.8	1.5	8.0	29.5	400
K.21.	53.5	12.0	1.5	5.3	27.7	400

A cumulative grain size curve is presented in the Appendix.

The sandstone is bedded in parallel, horizontal beds of between 1 and 2 cm. thickness. The mica and carbonaceous material give weak lamination, generally rather parallel, though irregular when carbon content is high. Any grain size changes are gradational. Large plant fragments, up to 15 cm. in length are found. Ripples, cross-lamination and primary current lineation are absent.

Burrows, usually of the vertical type, are common and often completely destroy the bedding. (Photo 6).

The facies corresponds, in part, to Walker's Facies J Parallel Bedded Silty Sandstone and Facies K, Parallel Bedded

Carbonaceous Sandstone. (1966a, p. 104).

Interpretation.

Absence of current-formed features suggests that the sediment was deposited from suspension in quiet water or possibly by weak currents below the strength needed for the formation of ripples. The latter seems rather probable in this case as grain size is rather high for transport in suspension without ripple formation. Fluctuation in grain size reflects fluctuation in supply or current strength. The site of deposition was probably similar to that of Facies 3 Striped Siltstones.

Facies 5. Siltstones with Sandy Lamination and Ripples.

Description.

This facies is gradational with Facies 2 Mudstone and Siltstone, Facies 3, Striped Siltstone and Facies 6, Ripple-laminated Fine Sandstone. It is distinguished by a clear separation of clean, fine to medium sandstone from siltstone. (Photos 7, 8, 9). The siltstone is of medium to coarse grade, often rich in mica and carbonaceous material, which give a weak lamination, generally horizontal, but more variable in close proximity to sandstone ripples.

The sandstone, which is also rather micaceous, occurs

in thin, horizontally and ripple cross-laminated bands, 2 mm. to 5 cm. in thickness. The upper limit of thickness is arbitrary, being the smallest thickness that can be conveniently shown on a measured section. Above 5 cm., ripple-laminated sandstone is assigned to Facies 6, Ripple-Laminated Fine Sandstone.

The thin horizontal laminations can be continuous, as in Walker's Facies D3 Mudstone, or discontinuous to give thin lenses of sand. When more sand is present, it occurs as ripples, which may be isolated or in horizontal beds. When horizontal beds are one ripple thick, the rock resembles Walker's Facies D4 Mudstone, though isolated 'biscuit ripples' (Allen, 1959, p. 294) may also occur in this facies. Isolated ripples are normally, however, not confined to discrete horizons and are randomly scattered through the siltstone matrix. Isolated ripples sometimes are loaded into the underlying siltstone with deformation of the siltstone lamination. (Fig. 7).



FIGURE 7.

Lamination in the ripples, both isolated and in cosets of up to 5 cm., is defined by mica and carbonaceous material. The lamination is in cross-laminated sets (McKee and Weir, 1957) and in the thicker units in cosets. The mica and carbonaceous material show a tendency to be more abundant in the bases of sets and the cross-laminae tend to be concave upward. (Fig. 8).

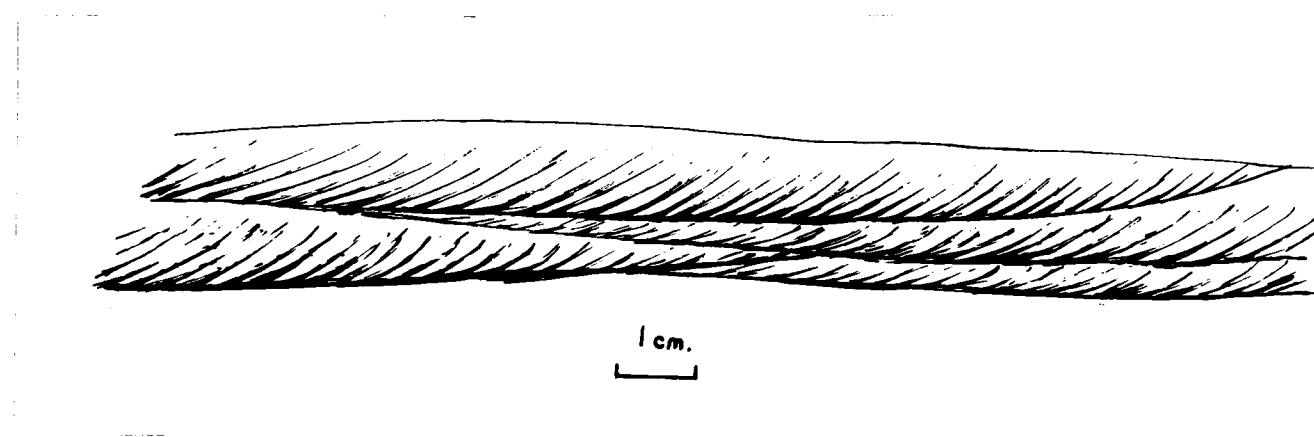


FIGURE 8.

The cosets often show stoss-side erosion between sets and the unit then corresponds to Walker's Type 1 Ripple Drift (1963). Most of the ripple forms seen are asymmetrical and show unidirectional cross-lamination, though occasionally symmetrical forms are seen with laminae passing over them.

Large plant fragments are common and are sometimes associated with deformational structures in the overlying sediment. In Crowden Brook, Edale (N.G.R. SK 095873) a plant fragment of 4 cm. width lies on a bedding plane and the overlying 2 cm. of sediment is buckled down. (Photo 9).

Burrowing, both vertical and horizontal, is common.

Normally the sand bodies within the siltstone are of a ripple scale (i.e. 1 to 2 cm.), but at two localities, dune forms are found. They are described below as they are genetically related to this facies though not fitting the thickness criteria laid out above.

In Crowden Brook, Edale, (N.G.R. SK 096872), a dune of 10 cm. height and 1 m. wavelength, of medium sandstone, is isolated in coarse siltstone. Internally the dune shows cross-lamination, consistent with the asymmetry of the structure though some modification seems to have taken place and irregular laminae roughly parallel the stoss-side slope. The lamination on the stoss-side is disturbed by a vertical burrow, filled by overlying siltstone. (Photo 10).

In the northern bank of the River Etherow (N.G.R. SK 117996), asymmetrical dune forms of very coarse sandstone, with internal cross-bedding, are isolated in siltstone. The dunes have heights of up to 20 cm. and wavelengths of up to 20 m. (Photo 11).

Interpretation.

The sorting of sediment into two distinct lithologies and the formation of ripples and, more rarely, dunes, suggests that currents in the lower flow regime (Simons et al., 1965)

were operating. According to McKee (1965, p. 73) asymmetry and symmetry of ripple form are not diagnostic of current and wave formed ripples. Coleman and Gagliano (1965) and Campbell (1966) accept that lamination passing over a symmetrical form is indicative of wave oscillation. The random nature of exposures makes recognition of ripple type difficult, though when both cross-lamination and symmetrical lamination are seen within one ripple, it is probable that a current formed ripple was reworked by later wave activity.

The presence of isolated sand ripples in a finer grained sediment is indicative of a depleted supply of the coarser sediment (Allen, 1959, p. 293), and probably of variable current activity.

Deformation, associated with plant fragments, (Photo 9), is interpreted as due to the collapse of rotting plants during subsequent sedimentation.

The facies resembles sediments found in recent tidal flat environments (Van Straaten, 1959, Fig. 3, after Hantzschel, 1936; Evans, 1965, plates 5, 6, 8, 9, 10; Oomkens and Terwindt, 1960, Fig. 8a) where the terms 'Flaser-' and 'Linsenschichten' (Reineck, 1960) are used, depending on whether sand or mud is the predominant component. The very clear differentiation of sand and clay, sometimes noted in tidal flat deposits (Van Straaten, 1959, Fig. 4; Oomkens and Terwindt, 1960, Fig. 8a (2))

is not, however, seen in the Kinderscout Grit or Grindslow Shales. Similar sediment is also found in many deltaic environments (Coleman and Gagliano, 1965, Figs. 2, 3 and 6 and Table 1.) and in river floodplain deposits. (Allen, 1965b).

Facies 6. Ripple-Laminated Fine Sandstone.

Description.

This facies is gradational with Facies 5, Siltstone with Sand Lamination and Ripples, and with Facies 7, Parallel Laminated Fine Sandstone. The sandstone is generally of fine to medium grain size and petrographically cleaner than any of the facies described above. It may, however, be micaceous and carbonaceous.

Table 3. Composition of Facies 6. Ripple Laminated Fine Sandstone.

Specimen No.	Quartz	Felspar	Mica	Carbonaceous Material	Matrix	Points Counted
K.5.	62.3	9.7	1.7	2.3	23.5	400

A grain size cumulative curve is presented in the Appendix. It shows that the sand is somewhat better sorted than the Facies 4, Silty Sandstone specimen analysed.

The platy grains define the lamination whose degree of

development is related to the mica and carbon content. The lamination is generally less than 1 mm. and is organised as small, cross-laminated sets of 1 to 4 cm.. The thickness of sets seems often to increase with a decrease in mica content. Units, normally up to 1 m., are made up of such cross-laminated sandstone.

Top surfaces often show 'rib and furrow' or 'micro-trough cross-lamination' (Hamblin, 1961) and this is used as an indicator of palaeocurrent direction (Photo 12). Sections perpendicular to the bedding and parallel to the direction of the trough axes, show cross-laminated sets with erosive, gently concave upwards or flat bases. Sections transverse to the axial direction have more strongly concave upward bases. In axial sections, the cross-laminae dip in a constant direction while in transverse section, they parallel the basal erosion surface and are symmetrically concave upwards. (Fig. 9 + Photo 13).

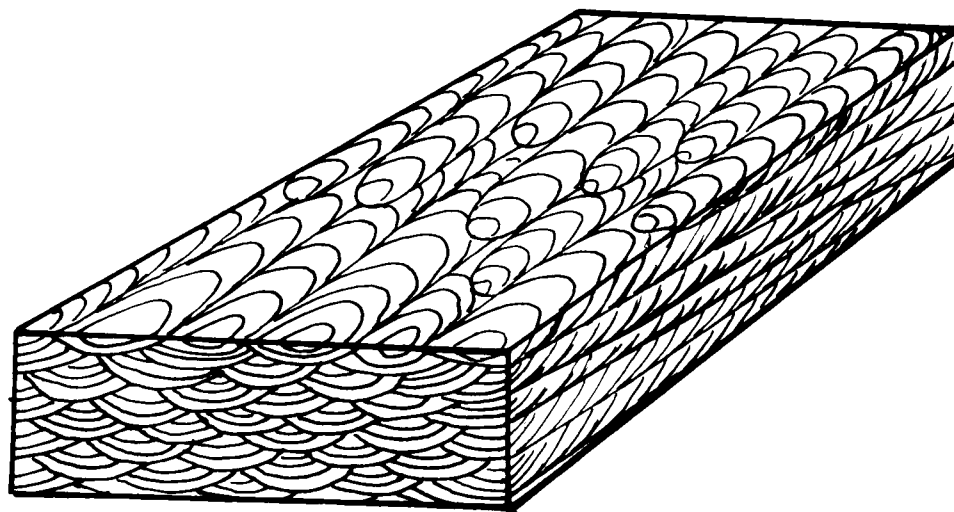


FIGURE 9.

Mica and carbonaceous material are often more abundant

in the bases of sets. (cf. Fig. 8) Occasionally, ripple forms occur on the top surfaces of cross-laminated units. (Photo 14).

Sometimes a simple cross-laminated geometry cannot be inferred and symmetrical ripple forms with laminae passing over the ripple crests are found, though erosion between sets often tends to obscure this relationship. (cf. Campbell, 1966). Thin silty drapes passing over ripple forms are sometimes associated with this case. (Photo 15).

Vertical burrows are sometimes found.

Interpretation.

Small-scale trough cross-lamination has been interpreted as being due to the migration of linguoid or lunate ripples under conditions of net sedimentation. Sets with planar bases may be due to straight crested ripples under similar conditions (Allen, 1963b). Such ripples result from flow, in the lower part of the lower flow regime, of unidirectional currents (Simons et al., 1965, p. 36), though it seems possible that similar results could be obtained by wave action (McKee, 1965, p. 72). Most of McKee's wave formed cosets, however, do not show erosion between sets as is invariably the case in this facies. Cosets showing laminae passing over the crests of symmetrical ripples may be wave generated or modified.

The concentration of mica and carbonaceous material in

the lower parts of the cross-laminae is due to grains of lower hydraulic radius being carried further in suspension over the crest of the ripple (Jopling, 1963; Allen, 1965a).

The occasional presence of silty drapes over ripples is similar to the situation in 'flaserschichten' found in tidal flat environments. When the facies is less regular and more erosive, it compares with the 'Sandy Streak' of de Raaf et al (1965, p. 27). Both 'Flaserschichten' and 'Sandy Streak' are thought to be related to intermittent current or wave activity and to uneven sediment supply.

Facies 7. Parallel Laminated Fine Sandstone.

Description.

This facies is gradational with Facies 6, Ripple Laminated Fine Sandstone and with Facies 9, Parallel Bedded Coarse Sandstone. It consists of fine to medium grained sandstone of variable mica content but otherwise rather clean.

Table 4. Composition of Parallel Laminated Fine Sandstone.

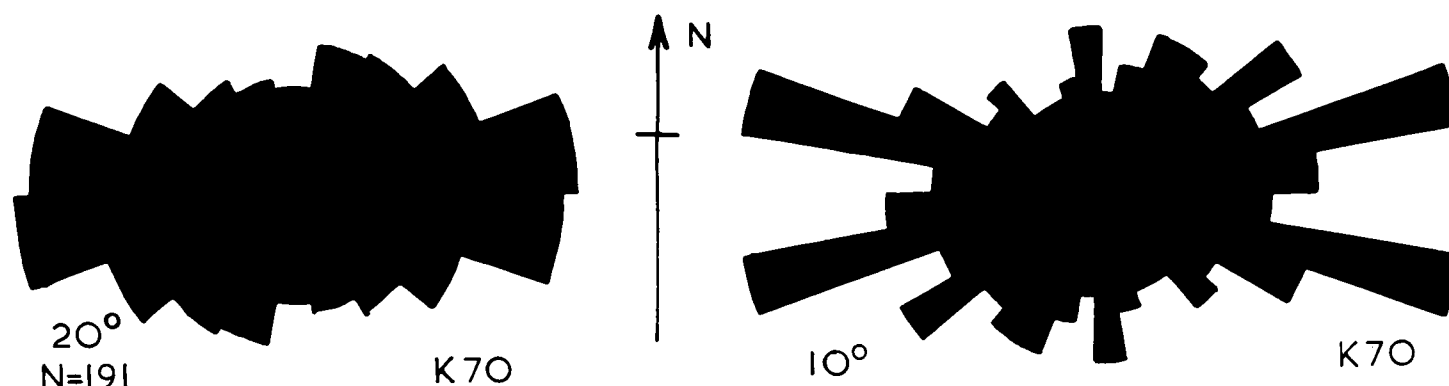
Specimen No.	Quartz	Felspar	Mica	Carbonaceous Material	Matrix	Points Counted
K.46	55.3	19.6	1.3	1.3	22.4	400
K.70	66.9	11.1	0.9	0.5	18.3	400

These two specimens were also analysed for grain size and the cumulative grain size curve presented in the Appendix.

The sandstone is bedded in thin parallel beds of up to 2 cm. though when mica content is high, the lamination is fine. (Photo 16). If the mica content is very high, the lamination is wavy and the facies grades in to the Facies 6, Ripple Laminated Fine Sandstone.

Bedding surfaces show primary current lineation (parting lineation) (Photo 12). Mudflakes are sometimes found lying on the bedding planes and large plant fragments are seen to lie with their lengths parallel to the primary current lineation when the two are seen together.

Analysis of grain long axis orientation in thin section shows a strongly preferred orientation when plotted in 20° classes. When the same data is plotted in 10° classes a bimodal pattern is seen, (Fig. 10) corresponding to the pattern noted by Allen (1964a). In the specimen analysed in this work, no primary current lineation was seen but comparison with Allen's results suggests that the lineation direction lies between the two modal directions of grain orientation.



Grain Long Axis Orientations in Facies 7, Parallel Laminated Sandstone.

FIGURE 10.

Interpretation.

Allen (1964a) has interpreted a similar facies from the Old Red Sandstone as being the deposit of flow in the lower part of the upper flow regime (Simons et al., 1965, p. 37) when the bed form is plane bed with sediment movement. He interpreted the bimodal histogram as due to opposed spiral vortices, operating close to the bed. The transverse directions, associated with the vortices, lead to the deviation from mean current direction, shown by the lineation.

Facies 8. Massive Bedded Coarse Sandstone.

Description.

Massive coarse sandstone is only allocated to this facies

when seen to be within a channel or when a channel can be inferred from field relationships. The reason for this is that other coarse sandstone facies (i.e. 9, 10 and 12) can weather in a massive way; for example, 200m. south of Fairbrook Naze (N.G.R. SK 096897), large scale cross-bedding (Facies 12) passes gradationally into massive weathering beds over a horizontal distance of about 100 m..

The facies is gradational with Facies 9, Parallel Bedded Coarse Sandstone. It consists of extremely coarse and pebbly, poorly sorted sandstone, with pebbles of up to 4 cm. and modal grain sizes of around 1 mm. Grain size cumulative curves are shown in the Appendix.

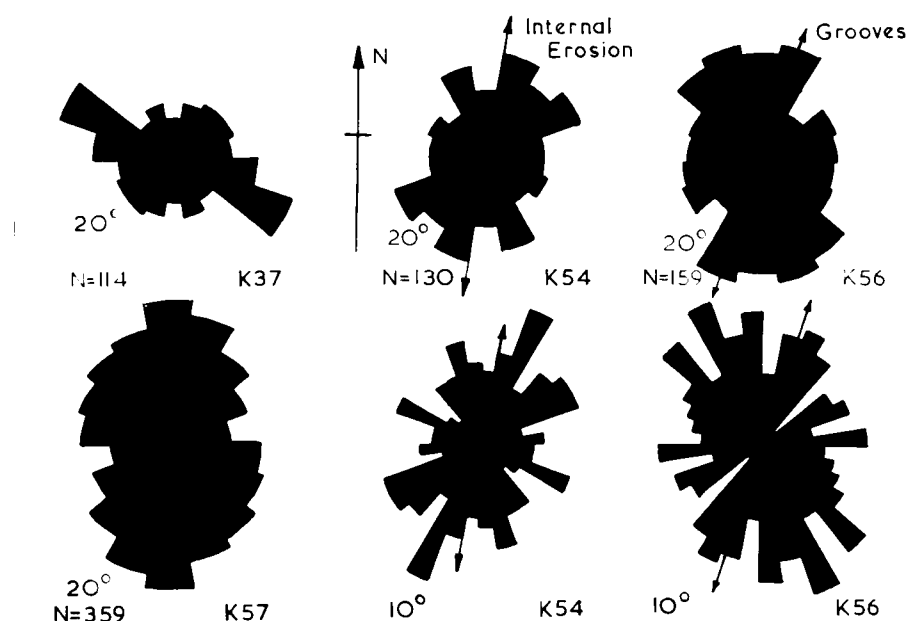
Table 5. Composition of Facies 8, Massive Bedded Coarse Sandstone.

Specimen No.	Quartz	Felspar	Mica	Carbonaceous Material	Matrix	Points Counted.
K.48	63	13.1	0	0	21.4	400
K.49	57.2	20.0	0.2	0.2	22.2	450
K.56	63.7	23.2	0.2	0.4	12.3	400

Mudflakes and siltstone blocks are common, particularly near erosion surfaces and may be randomly scattered through the beds or concentrated on bedding planes. Blocks of siltstone, up to 1.5 m. x 40 cm. may have their bedding in any

orientation relative to the bedding of the sandstone (Photo 17), and often show plastic deformation of their internal lamination and bedding (Photo 18).

Bedding units are up to 3 m. thick though 1 m. is more usual (Photo 19). Individual units are lenticular and broadly horizontal with erosive bases. Near channel margins, beds may dip at up to 20° , generally parallel to the erosion surface. (Photo 20). Wright (1964) considered that this bedding pattern should be described as 'cross-bedding'. Except for occasional evidence of slight grading, the massive units appear structureless and only occasionally can a faint thin internal bedding be seen. This is of the order of 1 cm. thick and is slightly wavy and irregular. Field observation of pebbles and the measurement of grains in thin section and on polished surfaces show a pronounced tendency for elongate grains to lie with long axes horizontal in vertical sections and to show a preferred orientation in horizontal sections. (Fig. 11).



Grain Long Axis Orientations in Facies 8, Massive Bedded Sandstone.

FIGURE 11.

The difficulty of seeing internal fine structure is increased by the susceptibility to weathering of this facies. It is frequently deeply rotted and shows steeply dipping joints (Photo 21), interpreted by R. Brown (Pers. comm.) as tensional release features, and vertical surfaces with a strong and irregular relief (Photo 22), the 'corded' or 'ropy' textures of Wright (1964).

Interpretation.

The lack of any structures of diagnostic significance, makes interpretation of this facies difficult. It resembles, in some ways, Walker's Facies C Sandstones (1964 and 1966) but differs in being coarser, cleaner sandstone and in being free from muddy partings between beds. Wright (1964) states that 'The significance and origin of this type of bedding will remain obscure until our techniques for its examination have improved or until modern equivalents are described'. The coarseness of the sediment and the presence of large siltstone blocks (Photos 17 and 18), along with the associated channels, suggest powerful currents. A discussion of their nature will be held over until the discussion of the Major Channel Association in Chapter 4. The relationships of the preferred orientation of grains in horizontal sections to the direction of the depositing currents will also be discussed in that section.

Facies 9. Parallel Bedded Coarse Sandstone.

Description.

This facies is gradational with Facies 8, Massive Bedded Coarse Sandstone and with Facies 7, Parallel Laminated Fine Sandstone. The sandstone varies from medium to extremely coarse and pebbly. The coarsest extremes are never quite as coarse as the coarsest extremes of Facies 8. Mudflakes and plant fragments occur, though the former are much less common than in Facies 8 and are seldom greater than 5 cm. in length. Grain size analyses of specimens of this facies are presented in the Appendix and compositions are shown below.

Table 6. Composition of Facies 9, Parallel Bedded Coarse Sandstone.

Specimen No.	Quartz	Felspar	Mica	Carbonaceous Material	Matrix	Points Counted
K.47	53.5	16.6	0.5	0.2	29.2	400
K.55	69.6	13.6	0.8	1.5	14.6	400

The bedding of the facies is thin and parallel, with beds of about 1 cm. thickness being traceable laterally over many meters. The minimum bed thickness observed is about 5 mm. though most beds are between 1 and 4 cm. (Photos 23 and 24). The beds sometimes weather in massive units of up to 35 cm.

when the internal bedding can only be detected with difficulty. The bedding is always horizontal except when associated with small channels, where it parallels the erosion surface (Photo 25). The flat bedding planes show, rarely, a primary current lineation (Photo 26), though this is seldom as clear as in the Facies 7, Parallel Laminated Fine Sandstone. Measurement of grain long axes, in thin section and on polished surfaces, shows a variably developed preferred orientation in the horizontal plane when plotted in 20° classes. The modal direction may diverge from the direction of the primary current lineation by up to 50° though 20° is probably more representative. No clearly bimodal pattern emerges from plotting the data in 10° classes. (Fig. 12).

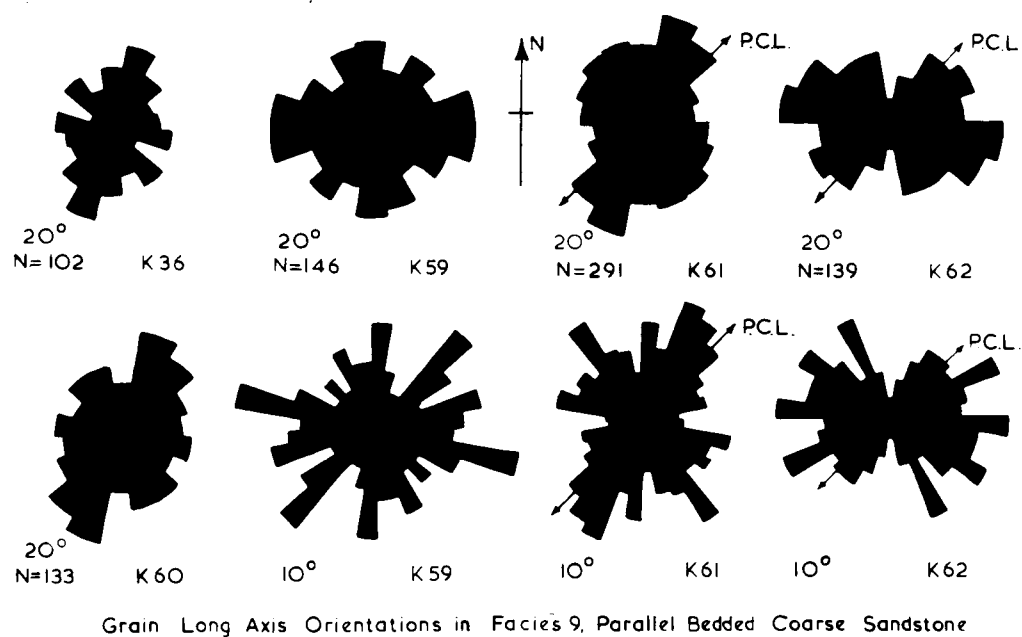


FIGURE 12.

Interpretation.

The grain size of the sediment and the clearly developed

bedding indicate that strong traction currents operated during deposition. The occasional presence of primary current lineation suggests that the flow was in the lower part of the upper flow regime when the bed form is plane bed with sediment movement. (Allen, 1964a, Simons et al., 1965). The presence of a preferred grain orientation tends to support this. Not enough data on grain orientation is available to show any significant differences between it and the fabric of Facies 7, Parallel Laminated Fine Sandstone.

Facies 10. Medium-Scale Cross-Bedded Coarse Sandstone.

Description.

This is the most common facies of the Kinderscout Grit. It is gradational with Facies 11, Cross-bedded Fine Sandstone, differing from it in grain size and size of bedding units.

Grain size varies between medium and extremely coarse and pebbly sandstone. Pebbles up to 3 cm., mudflakes and plant fragments are common, logs of up to 2 m. x 20 cm. occurring. Point counting gives the following compositions:-

Table 7. Composition of Facies 10. Cross-bedded Coarse

Sandstone.

Specimen No.	Quartz	Felspar	Mica	Carbonaceous Material	Matrix	Points Counted
K.29	67.2	11.8	0.2	0.9	19.8	450
K.33	69.3	12.5	0.5	0.5	17.5	400

The high matrix count may, as explained in Chapter 2, be due to the abundance of rotted feldspars. The apparent composition is that of a feldspathic greywacke (Pettijohn 1957, p. 291) though the rock was probably an arkose at the time of deposition.

The sandstone is cross-bedded throughout in sets of up to 3 m. in thickness. The sets may be tabular or trough shaped and either type can occur in cosets of up to at least 15 m.. Some cosets are formed of a mixture of the two set types, in which case tabular sets are found below the troughs. The two types are intergradational and have many features in common but will be described separately.

Tabular Sets: Sets are commonly between 50 cm. and 2 m. thick and up to 3 m.. They are parallel sided and can be traced laterally, quite often for distances upwards of 20 m.. Limits of exposure, rather than limits of sets, control the distance. The bases and tops of sets are commonly erosive. Sets are often graded, sometimes to the extent of having distinctly

pebbly layers at their bases.

The foresets which may have angular, (Photo 27) tangential or asymptotic bases (Fig. 13) (Crook, 1965) are up to 2 cm. thick and internally may be massive or inversely graded (Fig. 14).

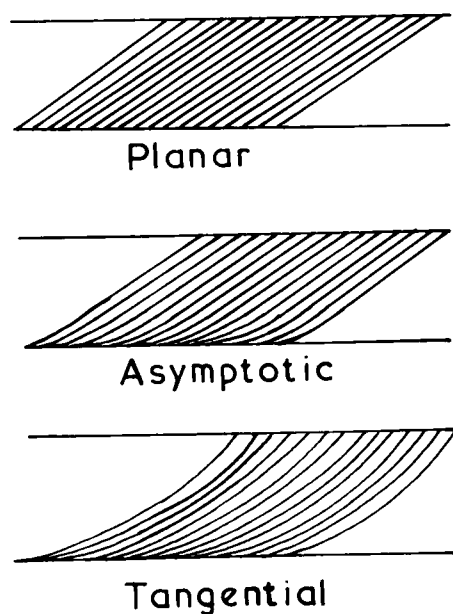


FIGURE 13.

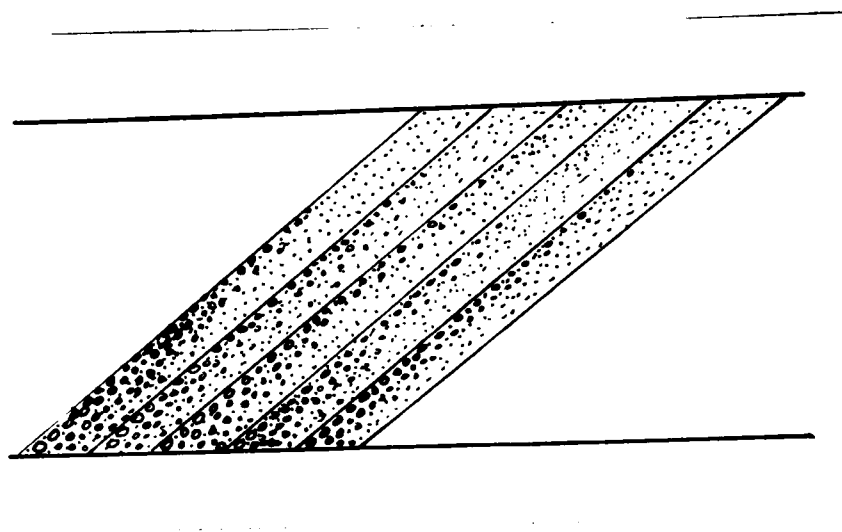


FIGURE 14.

They are rarely graded. When inversely graded, the foresets have pebbly top surfaces. Rarely, on the top surfaces of foresets, a lineation is seen, parallel to the dip. (Photo 28). Measurement of grain orientation, in thin sections cut parallel to the foresets, shows preferred long axis orientation roughly parallel to the dip in the top of the set but with a marked divergence from it in specimens taken from the base of the set. (Fig. 15).

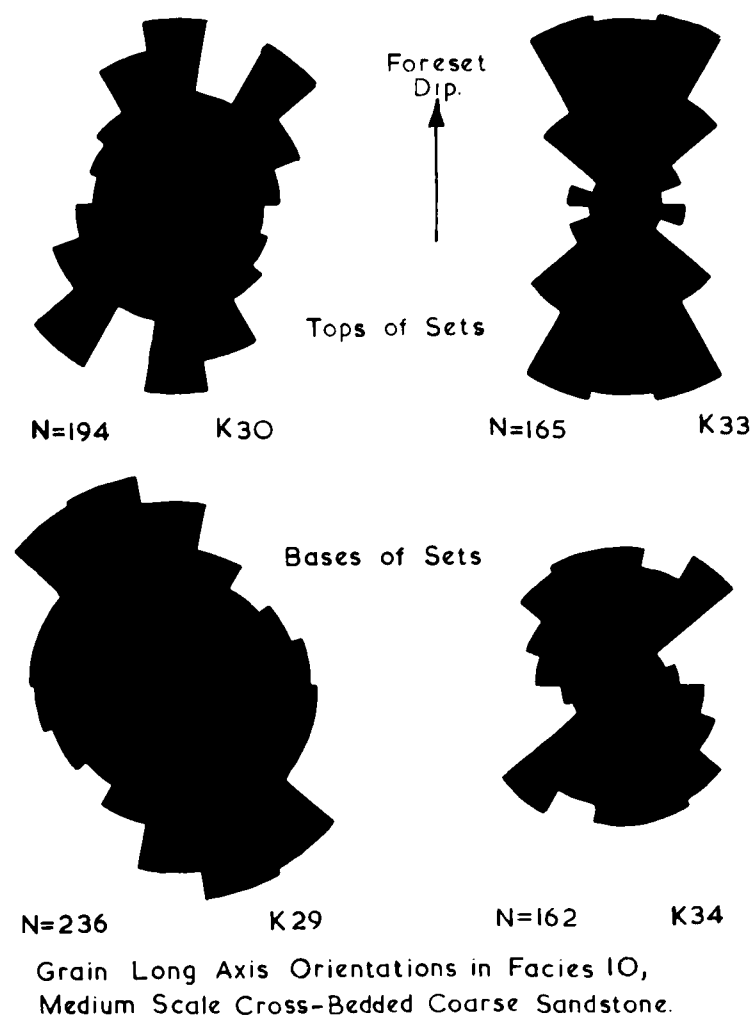


FIGURE 15.

Maximum dips of foresets are generally between 25° and 30° . The direction of dip is generally constant within the limits of exposure though in Crowden Little Brook, (N.G.R. SE 074021), the foresets of a 2.4 m. set change laterally, suggesting that in plan, the foresets are concave in the direction of dip. (Photo 29).

Three variations from uniformly dipping foresets have been recorded. In the first, where a small set overlies a larger one, two sets merge into one in the manner shown in Fig. 16.

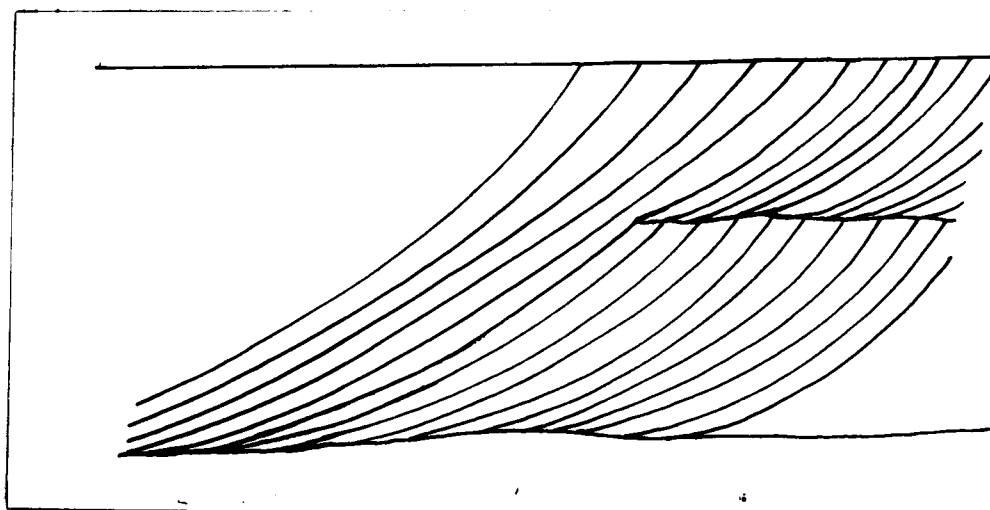


FIGURE 16.

The second, seen in Brogging Moss Dyke (N.G.R. SK 214913) shows angular based foresets becoming concave upwards and then being eroded by a planar erosion surface, above which further planar foresets parallel the erosion surface. (Fig. 17).

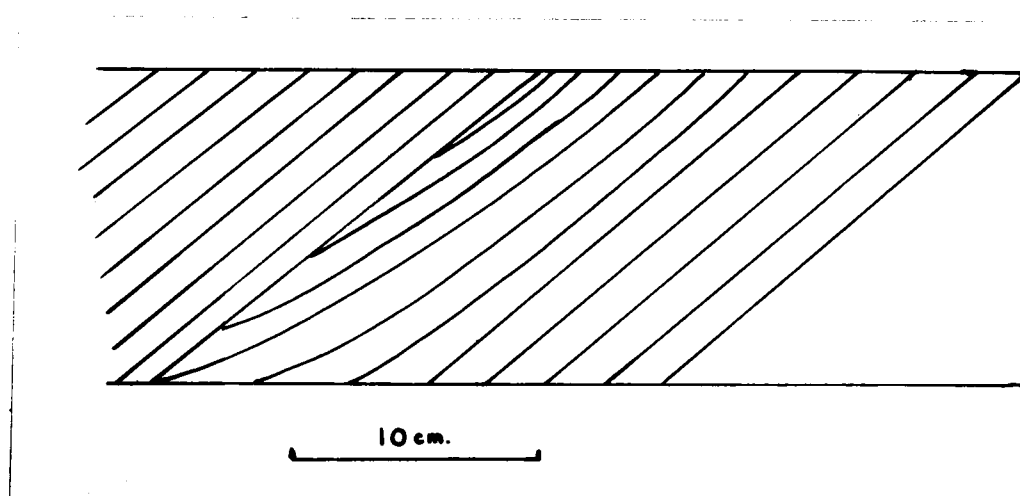


FIGURE 17.

At Glossop Low Quarries (N.G.R. SK 058961), the basal set of a cross-bedded coset is tabular and 1.7 m. thick. Overlying sets are all trough shaped, up to 70 cm. in thickness. The tabular set has sharply defined foresets with mica lying on the bedding surfaces, which are planar, making angular contact with the basal erosion surface. These features are not at all

unusual. The differences are that the direction of dip of the foresets of the tabular set is opposed to those of the overlying troughs and that, over a 3 m. wide zone, the dip of the planar foresets increases from 30° to 70° and then reverts to 30° with no sign of erosion or disturbance. (Photo 30 and Fig. 18).

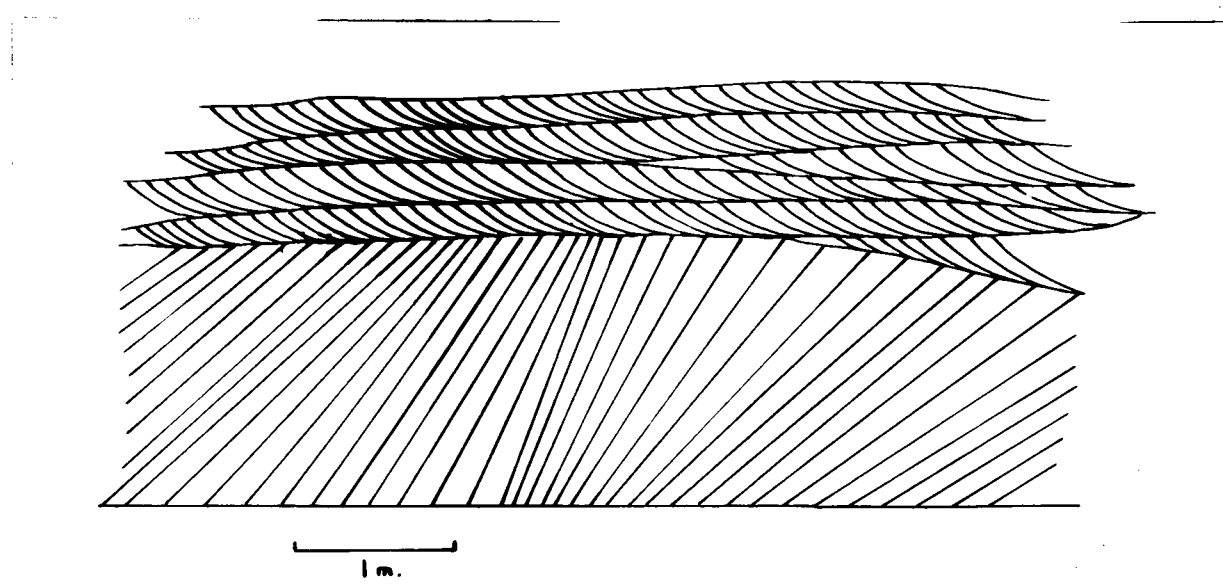


FIGURE 18.

The top surfaces of the foresets show a lineation pattern, which stands up as small steps, more like an incipient jointing than a current lineation. (Photo 31). The relationship of the lineation to the foreset dip is not known.

Trough Sets: The sets are seldom greater than 1 m. thick and are mostly between 15 and 40 cm.. There is often a rough correlation between set thickness and grain size. In vertical sections, parallel to the direction of foreset dip, the sets

have almost planar or gently concave upwards, erosive bases. In sections perpendicular to this direction, the bases are more sharply concave upwards, the curve tending to be symmetrical about a vertical axis (Photo 32). In plan view, the margins of the sets are rather parallel sided though with curved closures, concave in the direction of foreset dip (Photo 33). The term 'trough' is used here following McKee and Weir (1953), although, on the criteria proposed by Allen (1963a), the set shape is 'scoop-shaped', tending in some cases to 'trough-shaped'.

The troughs are commonly between 50 cm. and 2 m. wide and 10 to 15 m. long. Wider and narrower ones are longer and shorter. There is a rough correlation between set thickness and trough width.

The foresets are commonly between 2 mm. and 2 cm. thick and show a concave upwards shape, which, in sections parallel to the trough axis, is tangential to the base, (Photo 34), and, in transverse sections, is parallel to the erosional base, giving 'festoon' cross-bedding (Photo 32). In plan view the foresets are discordant to the sides of the troughs. The relationships are shown in an idealised way in Fig. 19.

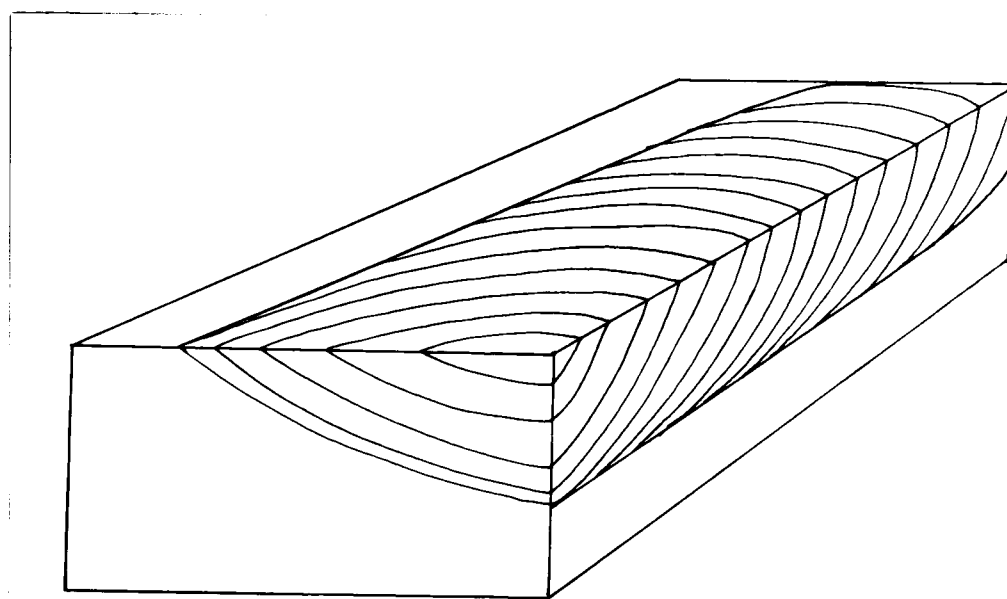


FIGURE 19.

Sets are sometimes graded with pebbly bases, though in sandstone of medium to coarse grade, there is a tendency for mica to accumulate in the toe of the set. Maximum foreset dips, measured at the tops of the sets, are generally between 15° and 25° . Plant fragments, which can often be associated with slight deformations of the bedding, generally lie with their long axes parallel to trough axes.

Trough cross-bedded sets are invariably found in cosets, when the form is equivalent to Allen's Pi Cross-Stratification (1963a, p. 110). Generally set bases are broadly horizontal in axial sections, though they may occasionally slope gently in a direction opposed to the direction of foreset dip (Photo 34). At a quarry at Woodhead, (N.G.R. SK 111999), however, a

coset, 3.2 m. thick, shows sets of 10 to 15 cm. superimposed so that the stoss-side erosion surfaces dip at between 14° and 20° , the dip increasing upwards and being opposed in direction to the dip of the foresets of the small sets. Each of the small sets is strongly graded, so that, when viewed from a distance, the coset looks like a tabular set with asymptotically based, graded foresets. (Photos 35 and 36). The coset compares with a large scale of ripple-drift bedding (Sorby, 1859b) and can be allocated to Walker's Type 1 (1963). Walker states that he has seen Type 1 Ripple Drift, in the Chatsworth Grit, in sets of up to 6" (15 cm.).

At Loftend Quarry (N.G.R. SK 075999), a similar coset is seen (Photo 37). This is 5 m. thick and, when observed from a distance, looks like a tabular set. The apparent foresets dip at 9° and are themselves internally cross-bedded in small sets. The foresets of the smaller sets dip at about 27° in the same direction as the 9° dip. (Fig. 20).

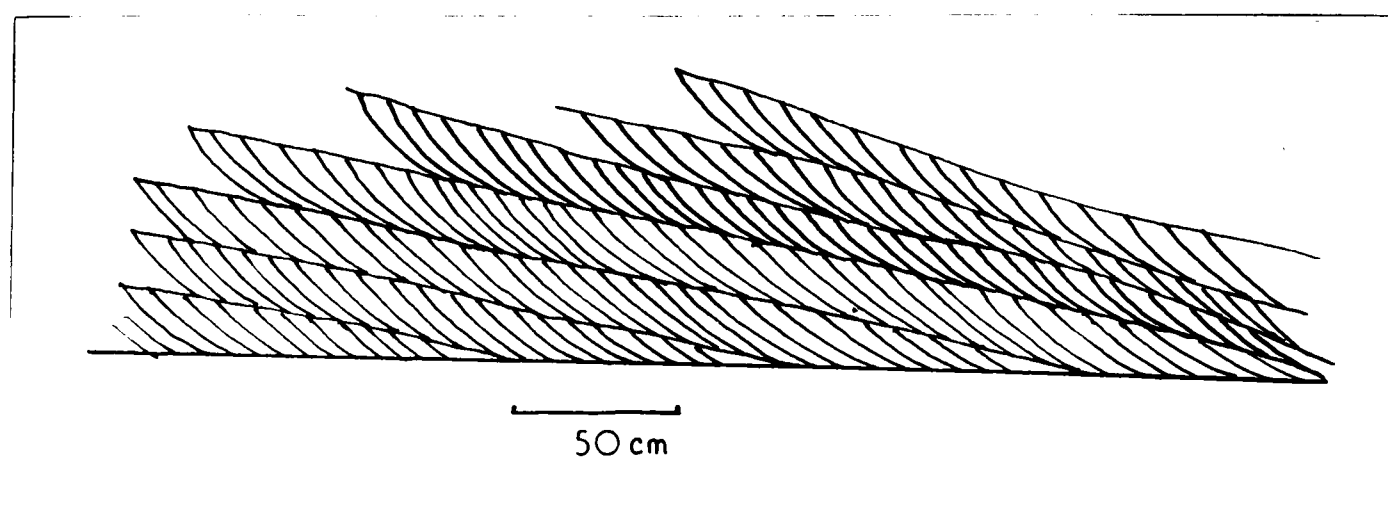


FIGURE 20.

This type of cross-bedding roughly resembled that figured by Potter and Pettijohn (1963, p. 76), said to resemble a type described by Reiche (1933). He writes of the 'doubly cross, not to say furious, character of the lamination'. In this case, however, the major foreset dip was 25° to 30° and the smaller internal lamination only slightly more steep.

The top surfaces of trough cross-bedded cosets sometimes have an asymmetrical dune form. At Loftend Quarry, a dune of 20 cm. height and 7 m. wavelength is found on the top of a coset of 10 cm. troughs. (Fig. 21).

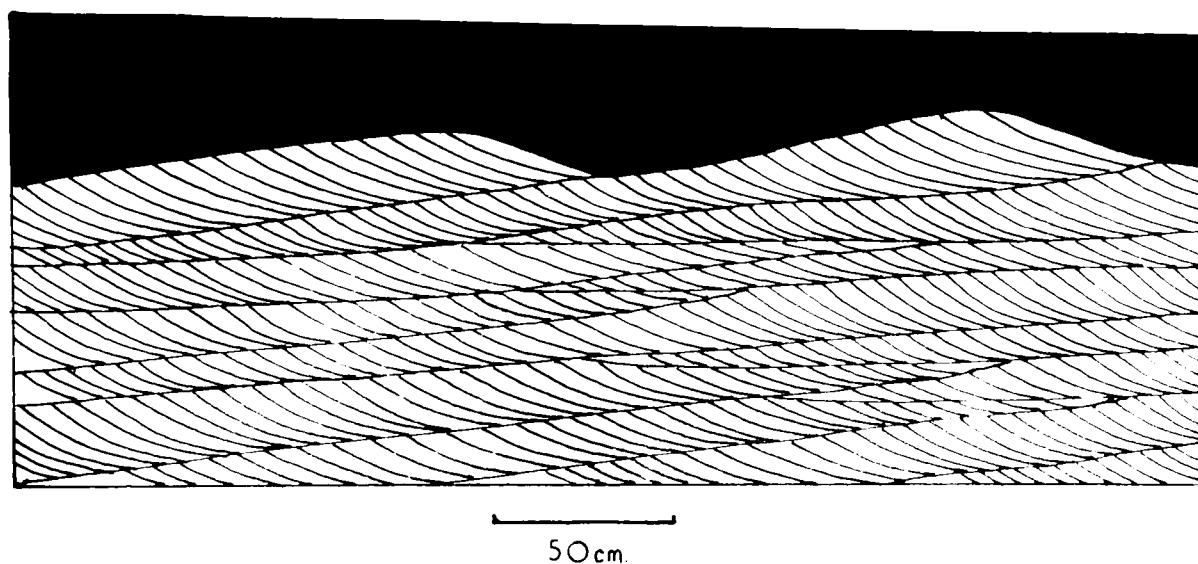


FIGURE 21.

Interpretation.

Earliest attempts at the interpretation of cross bedding were those of Sorby (1859a & b). He termed the structure 'drift bedding' as it was formed, he thought, by the drifting

of sediment by currents which, when they became weak, at a change in depth, deposited their load. In his paper on the Millstone Grit (1859a), Sorby noted and attempted to explain the occurrence of graded sets and the fact that observed angles of foreset dip were less than the angle of repose. Graded sets he explained by the tendency of pebbles to roll to the bottom of the foreset slope. The lower dip was explained as due to compaction of the sediment after deposition, aided by the diagenetic alteration of the feldspars. He showed that, by applying the percentage compaction to the tangent of the foreset dip angle, it was possible to reconstruct angles close to the angle of repose. In a later publication (1908), Sorby expanded this idea and suggested that with increase in the ratio $\frac{\text{structure height}}{\text{water depth}}$ (the 'depth ratio' of Jopling, 1963), the foresets changed in shape from planar to sigmoidal. He also showed a relationship between the formation of cross-bedding and the migration of ripples and observed that ripples formed when flow was between two flows associated with plane beds.

After Sorby's work, although cross-bedding was widely used as a palaeocurrent indicator, there was little progress in understanding the mechanisms controlling its formation until the last decade.

McKee (1957) dealt with tabular cross-bedded units in a

flume and showed that steepening of foresets could be achieved by using coarser and more angular sand with a lower clay mineral content. More significantly, he showed that lower velocities of flow gave steeper foresets.

Allen (1963b) showed that cosets of different types can be produced by the migration under conditions of net sedimentation, of trains of asymmetrical ripples. The type and size of the set depends on the geometry of the erosional and depositional areas of the migrating complex.

He showed that cosets of tabular sets are to be predicted from the migration of straight crested ripples and dunes. Trough shaped sets are the predicted product of the migration of linguoid and lunate bed forms. The erosional phase at the base of the set is precisely related to the activity of the separation zone in the lee of the advancing bed form.

Harms and his co-workers (1963, 1965) suggest a less rigid explanation of trough cross-bedding. On exposed river beds, they find spoon-shaped erosional hollows of the order of 1 ft. (30 cm.) deep, 5 ft. (1.5 m.) wide and 15 ft. (5 m.) long. The long axes parallel the current direction. The hollows are not, however, associated with the areas immediately downstream of dunes. They can occur on an otherwise flat area of sand. When excavated, partially filled scours show cross-

bedding with the same attitude to the scoured surface as the foresets of trough sets in the Kinderscout Grit. Harms attributes the spoon-shaped scours to turbulence elements, independent of the separation zones vortices of dunes. He cites macroturbulence elements such as those described by Matthes (1947). The dunes associated with spoon-shaped hollows seem very wide in relation to their lengths, tending, in fact, to being straight crested. Such dunes would not be expected to give trough cross-bedding by Allen's mechanism.

Tabular sets are also found by Harms and are thought to be associated with the commonly occurring straight crested dunes.

If Harms' explanation of the formation of trough cross-bedding is of general application, then the scouring of troughs is much more random both in space and time than is suggested by Allen's mechanism; a much lower rate of net sedimentation can then occur as most dunes will pass without leaving a record. Hemingway and Clarke (1963) have pointed out similar difficulties in Allen's hypothesis.

Allen shows an empirical relationship between dune height and flow depth; $H = 10 \text{ to } 20\% D$, which agrees broadly with Yalin's (1964) theoretically derived equations;

$$L = 5D \quad H/L = 1/30 \quad \text{i.e. } H = D/6.$$

For tabular sets the application of Yalin's equations,

using set thickness for H , should give a minimum value for depth of flow, though the equations themselves are open to some doubt.

The difficulty of applying such equations to trough cross-bedding is that the relationship between dune height and set thickness within a coset is not known. Using Allen's explanation it is possible to arrive at a reasonable minimum estimate (Allen, 1963d), but if Harms' mechanism is normal, there is no way of applying the criteria, as no relationship is known between the depths of spoon shaped scours and the heights of associated dunes. Should such a relationship be found, then accurate reconstruction of flow depth should be possible.

The only flow parameter which can confidently be deduced in the present state of knowledge is the flow regime, which in the case of migrating dunes, is in the upper part of the lower flow regime. (Simons et al., 1965).

Jopling has concentrated mainly on the internal organisation of tabular cross-bedded units. Many of his conclusions can, however, be applied to both tabular and trough sets. He showed (1963), by controlling different variables in flume experiments, that the association of sigmoidal foreset profile with high depth-ratio was correct and that dip could be reduced by increasing flow velocity over the topset. He suggested several

factors controlling the tendency of foresets to occur as discrete laminae or beds and not as an unbedded mass. Among these factors was the hydraulic sorting of grain sizes related to the particle trajectories, a phenomenon recorded by Allen (1965a) to the lee of dunes. This factor explains the mica concentration in the toes of some foresets. Heterogeneous discharge of sediment over the 'delta' lip, possibly related to movement of ripples on the topset surface, is another factor tending to increase foreset definition. Jopling also showed (1964) that increased flow initially improves definition but when upper flow regime is developed on the top surface, definition again deteriorates. Allen, (1965a), showed that at low flows, avalanching is in periodic, discrete, narrow tongues and this phenomenon may explain the lineation seen on the foreset surfaces of some tabular sets (Photo 28). With discrete avalanching, there is an associated sorting, dispersive pressures tending to bring the coarser grains to the top of the moving layer (Bagnold, 1941, p. 239). These grains also travel furthest giving graded sets and inversely graded foresets (Fig. 14).

The preferred orientation of grains in foresets is possibly due to the influence of the base of the expanding jet at the top of the set and to the activity of the counter-current vortex at the base of the set. (Fig. 22).

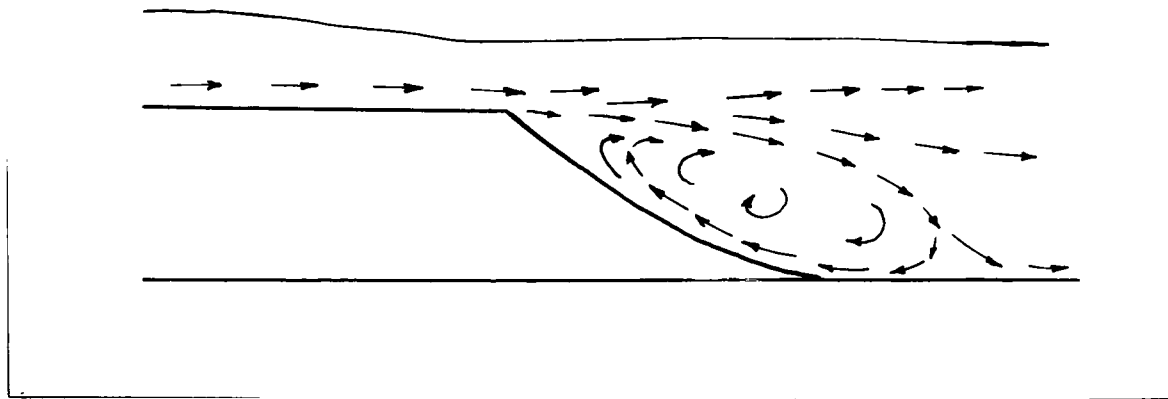


FIGURE 22.

Sengupta (1966) showed that the preferred orientation of pebble long axes was parallel to the dip direction in the middle part of a set, the orientations in the upper part and the toesets being less well ordered and transverse to the dip. The divergences from parallelism, noted in the present work may be due to a transverse component of the 3-dimensional flow pattern in the lee of the dune (Allen, 1966, Fig. 2).

The overtaking of one tabular set by an overlying, smaller one (Fig. 16) is similar to a situation figured by Harms et al. (1963, Pl. 3E) from the Red River Louisiana. The smaller dune, by virtue of the smaller volume of sediment involved, will migrate faster than the larger one and therefore tend to overtake it. That a higher one should be smaller is predictable from Yalin's equations (1964).

Internal truncation of cross-strata of a tabular set,

seen in Brogging Moss Dyke (Fig. 17), is similar to a feature seen by the author in a sandwave, excavated in the bed of the Tana River, Norway (Photo 38). This has been tentatively explained as modification of the foreset slope by a transverse current operating during the falling stage of the river.

No explanation can at present be given for the 70° reversed dip seen at Glossop Low. Potter and Pettijohn (1963, p. 79) state that 'angles of sands in excess of $34-36^{\circ}$ commonly appear to represent either soft sediment or tectonic deformation'. It must be questioned whether in fact the structure is depositional, though orientation of micas and very localised extent suggest that tectonic causes are rather unlikely.

The large-scale ripple drift, seen at Woodhead (Photos 35 and 36) suggests the migration of small dunes under extreme conditions of net sedimentation.

The 'doubly cross-bedded sandstone', Reiche states, 'should be diagnostic of conditions of origin were its significance understood'. Little can be added except to suggest that the implication is of dunes migrating with a component of movement down a depositional slope.

Deformational Structures.

The rare occurrences of penecontemporaneous deformation are associated with Facies 10. In Mickleden (N.G.R. SK 190984),

a 2 m. unit of deformed bedding lies between units of trough cross-bedding, all in extremely coarse and pebbly sandstone. Ball and pillow structures (Potter and Pettijohn, 1963, p. 148) of up to 70 cm. in diameter are present but the 3-dimensional shape of the structures cannot be seen (Photo 39).

In Foulstone Dyke (N.G.R. SK 218912), about 1 m. of medium to coarse, micaceous sandstone, underlain by trough cross-bedded sandstone and overlain by parallel bedded similar sandstone, with primary current lineation, is deformed into elongate folds. The section is exposed parallel to the axes of the folds which seem to be tight anticlines and broader synclines (Photo 40).

The restriction of these structures to discrete and relatively thin horizons suggests that the deformation took place soon after deposition. The structures observed seem mainly associated with vertical displacements of soft sediment though the elongation of folds suggests that the movement was controlled by a slope. Vertical movements are due to the adjustment of the metastable condition of denser sediment overlying less dense sediment. This may involve the escape of trapped pore water and the development of a thixotropic condition in the sediment, possibly triggered off by a shock wave.

Facies 11. Cross-Bedded Fine Sandstone.

Description.

This Facies is of minor importance and is gradational with Facies 10, medium scale cross-bedded coarse sandstone. The sandstone is medium to fine grained and often rather micaceous and carbonaceous. Plant fragments and mudflakes are occasionally found. When micaceous, the sandstone is thinly and clearly laminated, the clarity diminishing with decreasing mica content. Laminae are commonly 1 to 5 mm. thick and form cross-bedded sets of up to 30 cm., which may be tabular or trough-shaped, in cosets up to 3 m.. Occasionally isolated tabular sets are found, commonly in interbedded sequences of such sets and ripple laminated units (Photo 41). The ripple laminated units merge with the toesets of the overlying set but no example has been found of ripple cross-lamination opposed in direction to that of the overlying foresets. Foresets, which are tangentially based, have maximum dips of 15 to 25° and often show a concentration of mica in the toesets. Trough-shaped sets have similar geometry and internal organization to those of Facies 10, described above. Dune forms are seen on the tops of cosets and an example in Oaksike Clough, Longendale (N.G.R. SE 093004) shows a dune of 30 cm. height and 10 m. wavelength with ripples on the stoss-side surface (Photo 14).

Interpretation.

The cosets of cross-bedded sandstone differ only in grain size and set dimensions from those of Facies 10. Interpretation is therefore similar to that of the coarser facies. The tabular sets with interbedded ripple-laminated horizons are, however, unique to the finer sandstone. The tangential foresets of the sets suggest a relatively high flow velocity over the crest of the dune or delta body and a high 'depth ratio' (Jopling, 1965a). Because of the limited exposure, it is not possible to be sure of the nature of the advancing cross-bedded unit, though in an interbedded sequence, dunes seem the more likely. The ripple laminated horizons often seem intimately related to the toset of the overlying set but show no evidence of being worked by a counter-current as described by Jopling (1962) and Allen, (1965a). A similar phenomenon has been observed by the author in the excavation of the foreset slope of a sandwave in the Tana River, Norway. (Photo 38). One possible explanation of this cross-lamination direction is shown in Figure 23, where the separation zone impinges on the foreset slope. It seems rather doubtful whether this could occur in a normal dune regime.

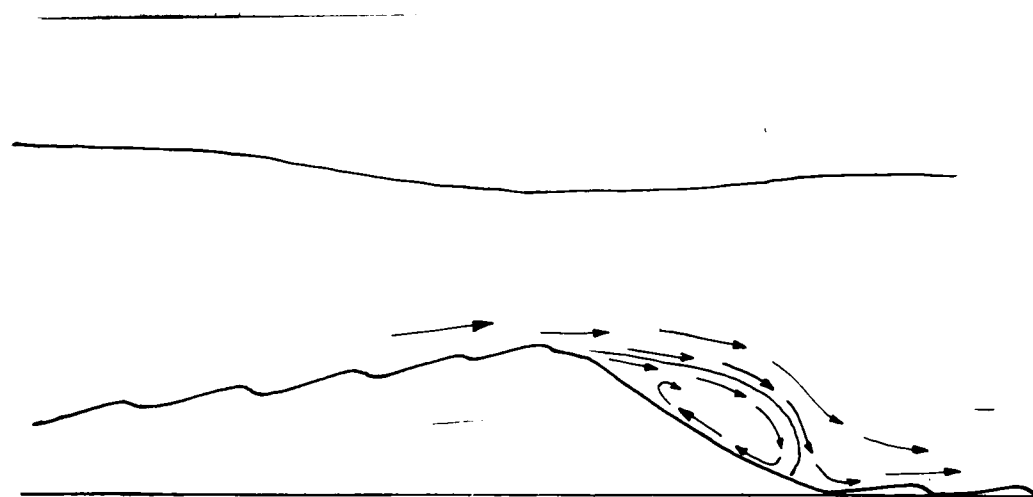


FIGURE 23.

The boundary between the top of a set and the overlying ripple laminated horizon is a planar erosion surface which could be due to the erosional activity of the separation zone vortices of ripples migrating on the stoss-sides of the dunes. That such ripples were present is shown by the exposure in Oaksike Clough (Photo 14). The interbedded sequence can best be ascribed to a migrating continuum of dunes, with ripples related to the stoss-sides and the toesets of the dunes. Preservation of such an interbedded sequence demands a high rate of net sedimentation though it is possible that erosion surfaces represent longer periods of time than that between the deposition of a dune and the passage of its stoss-side ripples. An alternative explanation of the sequence is that a ripple flow regime occasionally developed conditions suited to dune formation either by an increase in velocity or flow depth.

Facies 12. Large-Scale Cross-Bedding.

Description.

This facies is distinctive and not gradational with any other. It is formed mainly of extremely coarse and pebbly sandstone, though thin horizons of siltstone and fine sandstone are of minor volumetric importance.

Table 8. Composition of Facies 12. Large-scale Cross-Bedded Sandstone.

Specimen No.	Quartz	Felspar	Mica	Carbonaceous Material	Matrix	Points Counted
K.12	67.5	15.75	0.75	0.75	15.5	400
K.13	65.6	18.2	0.0	6.0	18.8	500
K.25	66.5	23.2	0.0	0.0	11.1	400
K.39	70.0	15.5	0.7	0.0	13.8	400
K.50	72.5	20.1	0.7	0.0	6.7	400

The coarse sandstones are normally poor in mica and carbonaceous material, and have a rather lower amount of matrix than other coarse sandstone facies. The grain size of the facies has been measured and the results are presented in the Appendix.

The coarse sandstone is bedded in units of 1 to 10 cm., which dip as the foresets of large cross-bedded sets. The

sets, which are tabular in shape, can be between 4 and 40 m. thick and are of great lateral extent. Distances of up to 2 km. in the direction of dip are found on the north edge of Kinderscout. Because of the size of the structures, large exposures are needed before rock can be confidently ascribed to this facies. Such exposures are most frequent in scarp slope edges (Photos 1, 42, 44 and 52), though dip slope stream sections (Photo 43) and isolated tors (Photo 2) also show the structure. Only single isolated sets occur and these can be divided into two types, mainly on grounds of size, and, to some extent, on internal organisation. Discussion of the relationships of the two types will be undertaken in the discussion of the Large-Scale Cross-Bedding Association.

The largest sets range in thickness from about 12 m. to 40 m. and are also of greatest lateral extent. The foresets are concave upwards, with dips of up to 27° in the tops of the sets. The location of the bases of these sets is often very difficult as the foresets pass downwards into horizontally lying sandstones of similar grain size. Only in the very largest exposures can the base be located precisely. The upward increase in foreset dip is very gradual (Photo 44). The tops of sets, when seen, are always truncated by broadly horizontal erosion surfaces.

The smaller sets range in thickness from 4 m. to about

15 m.. They generally have much more angularly based foresets with a distinct divergence often being seen, even in narrow stream sections (Photo 45). When the bases of the foresets are angular, the foresets are planar throughout the set with dips between 15° and 25° . Erosion surfaces truncate the tops of sets. Lateral extents of the smaller sets are less than those of the large ones, being measurable in hundreds of meters rather than kilometers. Evidence is found of smaller units dying out laterally both parallel and transverse to the foreset dip direction.

In plan, the foresets of the larger units curve round in broad arcs of about 1 km. radius. The arcs are convex in the direction of foreset dip and from the limited evidence, appear to interfere with one another. (Fig. 24).

The foresets themselves, when of extremely coarse and pebbly sandstone, are generally rather parallel sided and up to 10 cm. thick (Photo 46). Internally they may be massive, graded or inversely graded. Photograph 47 shows graded foresets. Such parallel sided foresets can occur in any size of set. In the larger sets only, medium-scale cross-bedded sets, up to 30 cm. thick, occur within the large-scale foresets (Photo 48). These are termed 'Intraset'. In isolation, they appear no different from the medium-scale cross-bedding of Facies 10. Only when the large-scale structure is obvious is their true

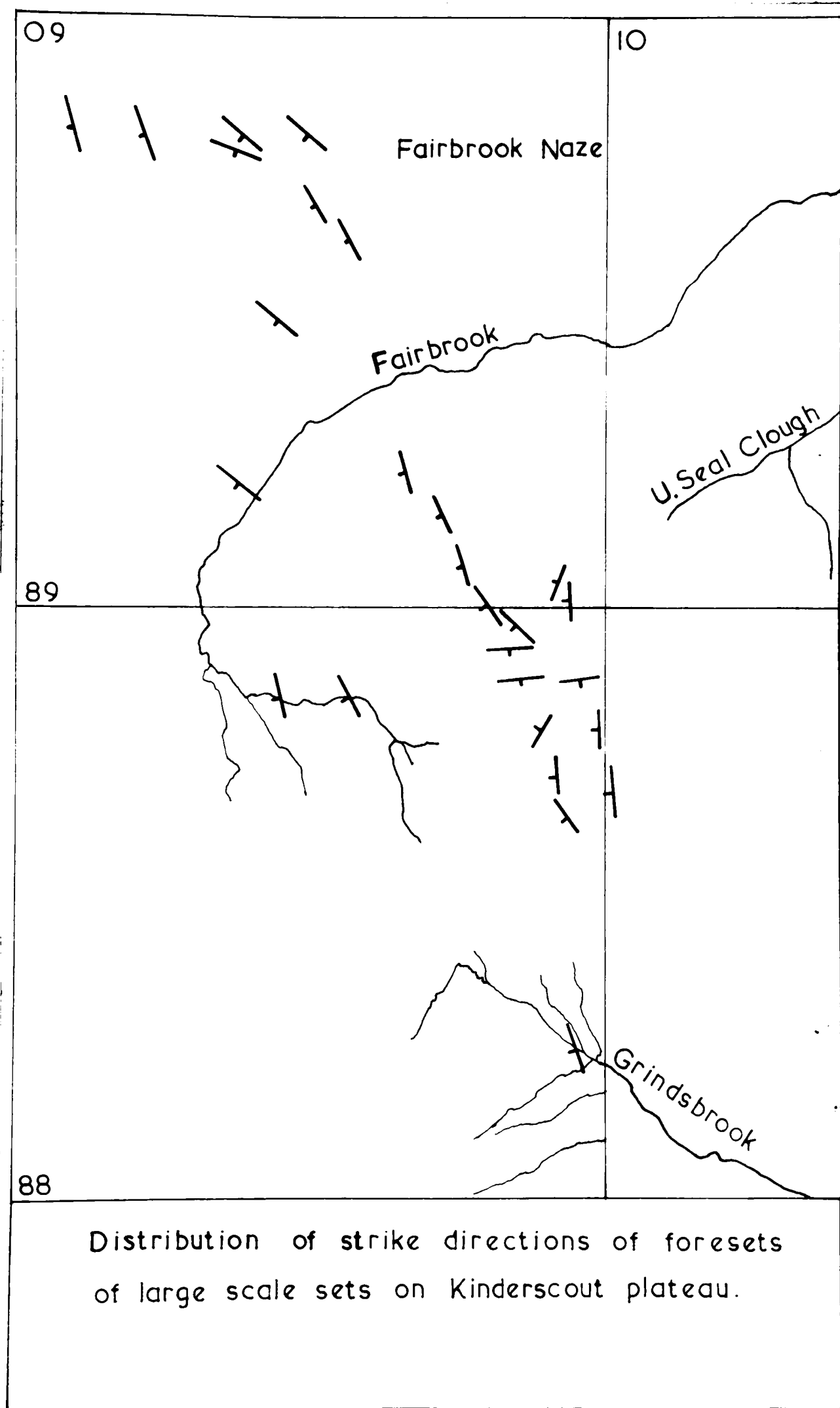


FIGURE 24.

nature recognised. Measurement of directions of intraset cross-bedding is difficult, but enough data have been collected to show their relationship to the large-scale foreset dips (Fig. 25). These data are also presented as true directions (Fig. 26).

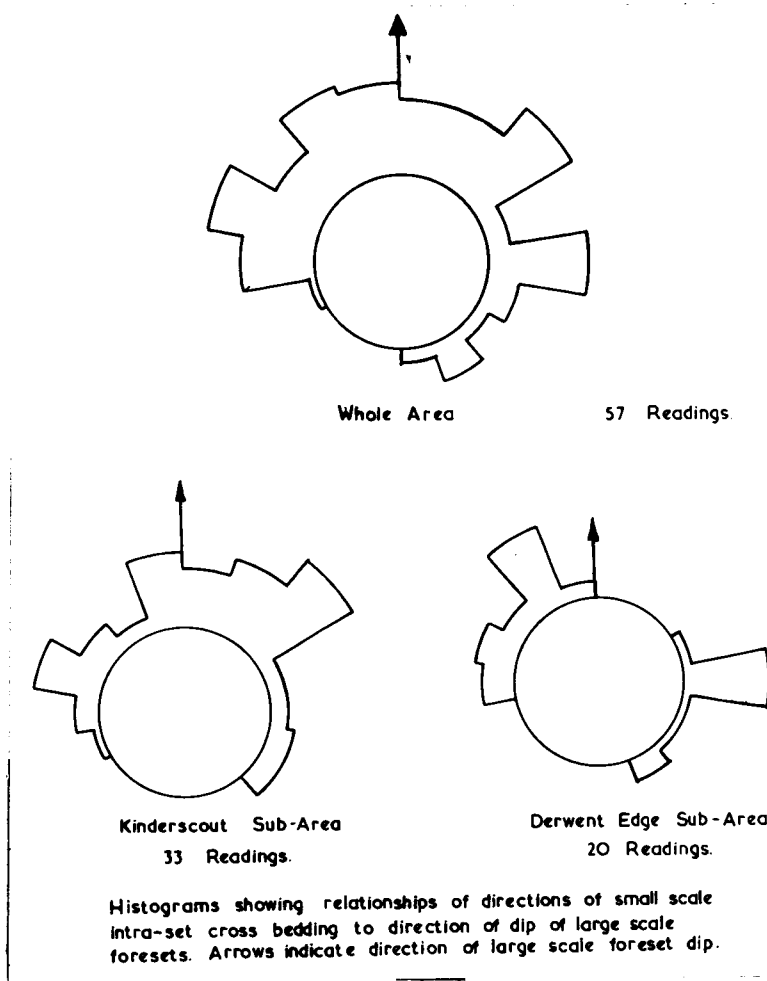


FIGURE 25.

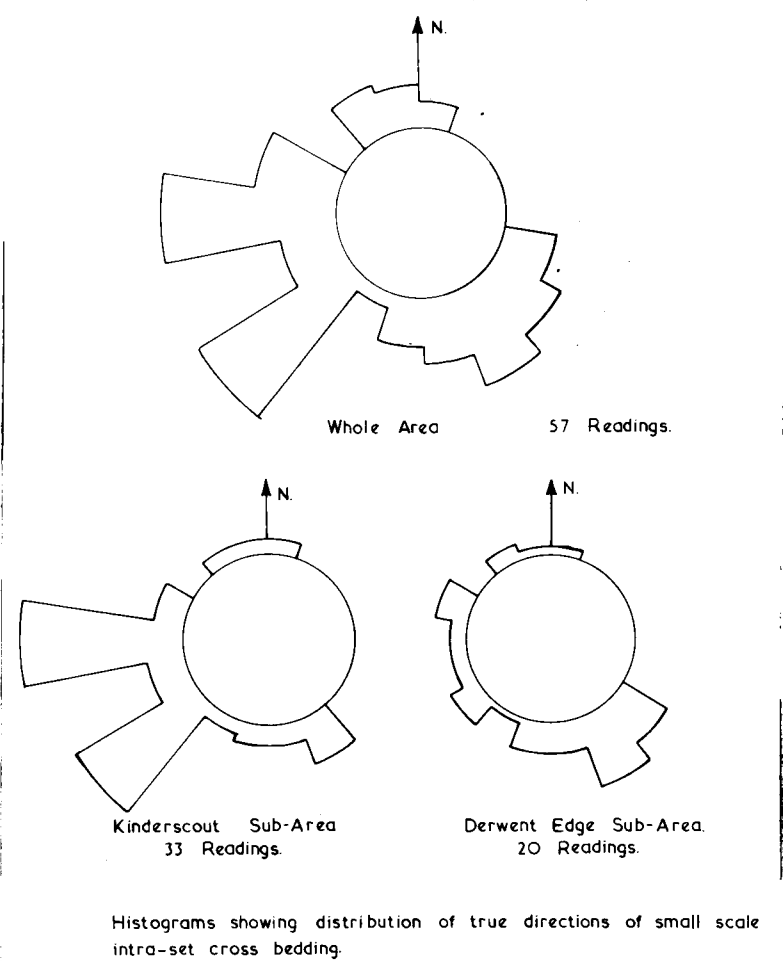


FIGURE 26.

There seems to be a preferred intraset direction towards the direction of large-scale dip. At only two localities are intrasets found in the base of tangential foresets, with directions opposed to the large scale dip (Photo 49).

There are, within the large sets, erosion surfaces, separating groups of foresets. The erosion surfaces are

rather planar and truncate underlying foresets. The overlying foresets parallel the erosion surface (Photo 50). Often the erosion surface cannot be traced far, but at Mousleden Quarry, (N.G.R. SK 208868), two erosion surfaces cut through the whole thickness of a set (Photo 51). It is possible that these erosion surfaces, seen in vertical sections, are related to the lines separating interfering arcs, seen in plan (Fig. 24).

While most of the sandstone forming this facies is extremely coarse and pebbly, in some stream sections, on the north edge of Kinderscout, fine grained, often silty sandstone and coarse silts are found in units of up to at least 4 m., dipping parallel to the coarser foresets. The sandstones can show ripple cross-lamination and the siltier sandstones and coarser siltstones are sometimes burrowed. These fine grained units seem to be associated with prominent slack features dipping across the main features, parallel to the large-scale dip. These features are particularly clear on oblique aerial photographs (Photos 1 and 52). The slack features are generally without exposure but the association noted above and the abundance of slack features, noted from aerial photographs, suggest that fine grained material may be present within the large-scale foresets more frequently than its exposure suggests.

Interpretation.

Tabular, isolated sets of cross-bedding of this scale have not, to the author's knowledge, been recorded in ancient or recent sediment. The formation of cross-bedding is either related to the advance of delta-like sedimentation units into bodies of standing water (Nevin and Trainer, 1927; McKee, 1957; Jopling, 1963) or to the advance of dunes. If each tabular set of cross-bedding is the deposit of a single dune, the dune would have to have been a hundred or more meters high, as shown in Fig. 27.

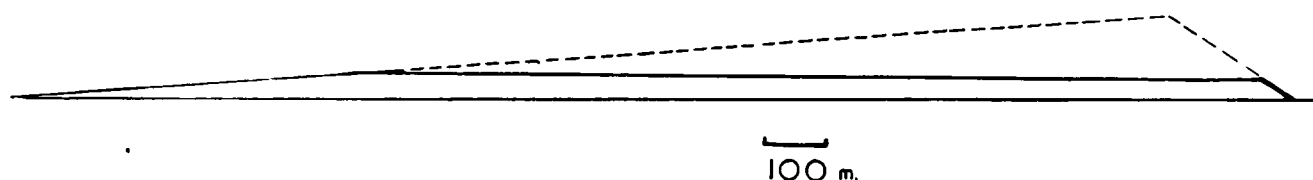


FIGURE 27.

On the other hand, if each apparently tabular set is due to a system of migrating dunes, stoss-side erosion surfaces should be present, as shown in Fig. 28.

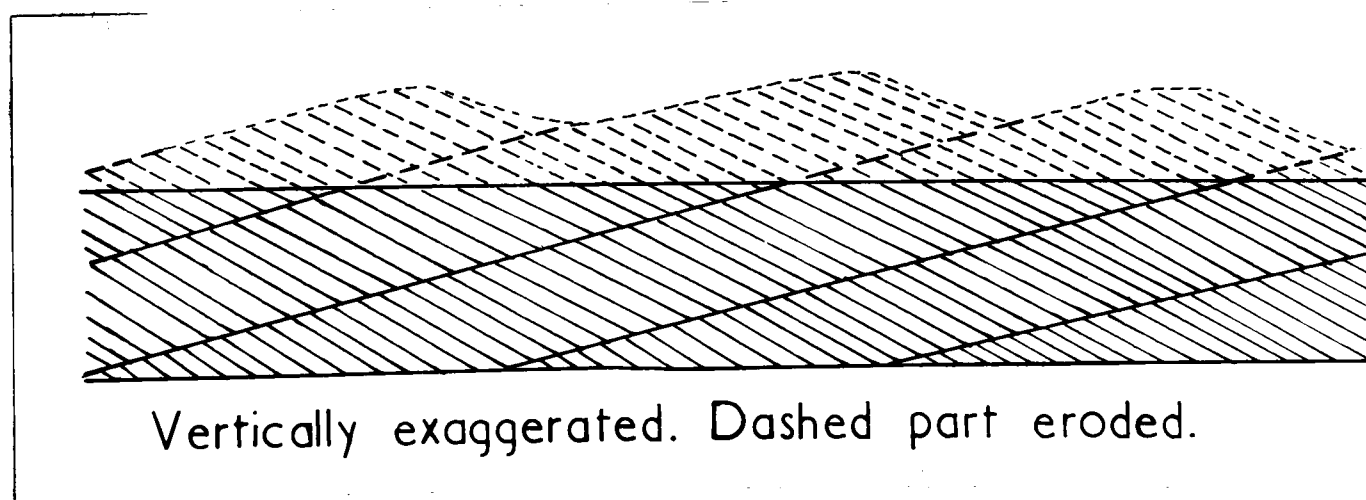


FIGURE 28.

As such surfaces are not seen, it seems more likely that the sets are the result of the advance of delta-like sedimentation units, whose initiation needs a relatively sudden rise in basin level and a high rate of sediment supply. (Nevin and Trainer, 1927; McKee, 1957).

The internal erosional lines, sub-parallel to the foresets, and the fine grained units both suggest that supply was locally intermittent, while the erosion lines and intrasetts suggest that currents operated in the basin. The nature of the currents will be discussed in the account of the large-scale cross-bedding association in Chapter 4.

Facies 13. Sharp Based Clean Sandstone Beds.

Description.

This facies is uniquely defined. It consists of coarse to medium sandstone, clean looking though often micaceous and carbonaceous. Point counting of two specimens gave the following results:-

Table 9. Composition of Facies 13. Sharp Based Clean Sandstone Beds.

Specimen No.	Quartz	Felspar	Mica	Carbonaceous Material	Matrix	Points Counted
K.17	57.8	18.5	2.3	0.5	20.3	400
K.45	61	15.2	1.7	0.2	22.1	400

These compositions plot close to Facies 6 and 7 sandstones on a ternary diagram (See Appendix). Grain size analyses are presented in the Appendix, and these plot close to Facies 5.

The sandstone is bedded in sharp based units of up to 1.5 m. but normally between 1 and 25 cm. in thickness. The beds are isolated in finer material, generally siltstone (Photo 53), and are broadly parallel-sided though relief on the bases, in the form of flutes and grooves, sometimes accentuated by loading, may be up to 10 cm. (Photo 54). The beds, in their lower part, are massive and sometimes graded. Polished surfaces show a weak internal lamination (Photo 55). In the upper parts of some beds, parallel lamination is developed, showing primary current lineation (Photo 12) and above may be a ripple cross-laminated division, showing 'rib and furrow' (Photo 12) or a ripple morphology. Top surfaces sometimes show trails (Photo 56) and top and bottom surfaces may show vertical burrows.

Interpretation.

Apart from the clean petrography and the presence of trace fossils, this facies is similar to Walker's Facies A Sandstones. These he interpreted as due to deposition from turbidity currents, implying deep water. The internal evidence, however, only indicates a sudden incursion of sand into a

quiet environment, collecting sediment from suspension. The massive or graded base, the parallel-laminated division and the ripple-laminated division correspond to the lowest three intervals ('divisions' of Walker, 1965) of Bouma's ideal turbidite (1962). This sequence has been interpreted by Walker (1965) in hydrodynamic terms for turbidites and a similar interpretation would seem to apply to this facies without implying deep water.

Of Walker's three proposed mechanisms for the deposition of the massive or graded division, a current with a traction carpet at its base seems most reasonable in this case. Such a mechanism produces a relatively mud-free bed irrespective of source. The other two mechanisms require a clean source to give a clean bed. Muddy sediment was eroded by the currents and therefore carried in suspension. A mechanism maintaining mud in suspension while depositing clean sand is therefore to be favoured and a traction carpet operates in this way. Increases in shear stress increase the thickness of the carpet (Bagnold, 1955), while a sudden fall in shear could produce a massive or graded bed.

The parallel laminated division with primary current lineation is due to flow in the lower part of the upper flow regime and the ripple-laminated division to the migration of ripples in the lower flow regime.

The parallel laminated and ripple-laminated divisions represent the waning tail of the current.

Walker's mechanisms were postulated for turbidity currents flowing under a body of deep water. There seems no reason, however, why similar beds might not be formed under shallow water or even subaerially, provided that slope and thickness of flow are large enough to provide high bed-shears.

Facies 14. Seat Earths and Coal.

Description.

These two facies are described together because of their small volumetric importance and their close association. Seat Earths are recognised by the presence of rootlets in their growth position. The sediment in which they occur varies between ripple-laminated sandstone and fine siltstone and is often rich in detrital carbonaceous material. The siltstones are often limonitic. Most seat earths are between 30 and 60 cm. thick, though one, in Laund Clough, is 3.3 m.. In most cases the seat earth siltstone is homogeneous in grain size but in three examples, rootlets are found in the tops of sandstone units, which pass up rapidly into siltstones, also full of rootlets, below thin coal seams. Other siltstone seat earths become richer upwards in detrital carbon.

Coal is poorly developed, the thickest seam being 8 cm.

and including a silty parting. The coal is often gradational with carbonaceous siltstones and may itself be muddy or silty in appearance. Large plant fragments lie parallel to the bedding, with the exception of one 35 cm. diameter trunk, preserved in the position of growth, in siltstone, just above a seat earth and coal in Crowden Little Brook (N.G.R. SE 077024). A length of 50 cm. is seen. The trunk is hollow with 1 cm. thick walls and is filled with siltstone identical to that outside the trunk. (Photo 57).

Interpretation.

The presence of rootlets indicates that plants were growing in situ and that the associated coal is probably therefore autochthonous. The fining upwards, noted within some of the seat earths, suggests that the siltstone was still being deposited after the onset of plant colonisation but that the rate of sedimentation was reduced by the inhibiting effect of the plants on current strength. The rather sudden decrease in grain size of some seat earths near their base suggests that the onset of colonisation had a sudden effect on the competence of currents. The upward increase in the content of detrital carbon, through some seat earths, supports the above theory. The presence of silty bands and the frequently silty nature of some of the coal seams suggests that there was

never a good establishment of growing peat in the area.

The preservation of a trunk, in the position of growth, implies that sedimentation around it took place quickly before the plant had time to rot after its death. Even if the plant continued to grow after the onset of sedimentation, its life span was probably not large. Broadhurst and Magraw (1959), describing a much larger trunk (12 m.) in the Coal Measures near Wigan, suggested a rate of sedimentation of about 11 cm. per year, assuming that the tree had a life span or survival time of 100 years. This estimate is, if anything, conservative.

The environment of deposition of this facies must have been in very shallow water, such as might be found in lagoons on delta top interdistributary areas, coastal plains and fluvial overbank areas.

Facies 15. Mudstone Melange.

Description.

This facies is of minor importance and is gradational with Facies 8, Massive Bedded Coarse Sandstone and Facies 17, Turbidite-like Sandstones. It is found exclusively as a channel filling deposit. It consists of medium to very coarse sandstone containing a very high proportion of mudflakes and siltstone fragments. These are generally small, up to 5 cm., and are frequently contorted. The whole melange forms an

unbedded, badly sorted mass.

Interpretation.

The coarse nature of the sediment, its unbedded nature and the presence of many mudflakes and siltstone fragments suggest high transport rate though not associated with any recognised bedform. Dispersive pressures may have operated to maintain suspension. Such flow rates could be developed in both turbidity and traction current environments.

Facies 16. Orthoconglomerates.

Description.

This facies is of small volumetric importance but of great interpretative significance. It consists of concentrations of quartz pebbles up to 3 cm. in length which occur in thin beds and lenses, up to a few pebbles thick. The pebbles may form grain-supported networks with coarse sand filling the interstices (Photo 58).

Interpretation.

The formation of grain-supported conglomerate is associated with winnowing activity of a current strong enough to carry all but pebbles in suspension. The pebbles themselves move as bed-load by rolling or possibly saltation. The currents may

be unidirectional or wave generated.

Facies 17. Turbidite-like Sandstones.

Description.

This facies is identical with Walker's Facies A and C Sandstones (1964 and 1966a and b). It consists of medium to extremely coarse and pebbly sandstone, which looks much more silty and poorly sorted in the field than any of the coarse sandstone facies described previously.

It occurs as horizontal massive beds, up to 70 cm. thick, occasionally showing parallel and ripple-lamination in their upper parts. Mudflakes and siltstone fragments are found in the lower parts. Some of the beds, particularly the thinner ones, show grading and a full Bouma sequence is very occasionally developed. The sandstones are usually interbedded with siltstones with which they have sharp lower contacts, showing grooves and flutes. If siltstones are absent, the beds may show mutually erosive contacts, multiple grading and amalgamation (cf. Walker, 1966a, p. 100), (Photo 59).

Interpretation.

Walker interprets both the thinner Facies A and the thicker Facies C Sandstones as the deposits of turbidity currents. No differences can be recognised between Walker's

sandstone facies and those described above and it is suggested that similar processes of deposition operated. It is superfluous to give an extended discussion of the individual features of the facies. Walker implied that turbidite deposition is synonymous with a deep water environment but such a relationship cannot be shown from the internal evidence alone. Discussion of any depth connotation implied by the facies can only be undertaken within the framework of facies relationships.

Trace Fossils.

Introduction.

Trace fossils are sedimentary structures resulting from the activity of animals, moving on or in the sediment at the time of its accumulation (Simpson, 1957).

Lithology.

With the exception of Facies 1, Mudstone with Marine Fossils, and Facies 7, Parallel-laminated Fine Sandstone, trace fossils are found in all the fine grained facies (i.e. 2, 3, 4, 5, 6, 13 and the finer parts of Facies 12). They are particularly abundant in Facies 3, 4, 5 and 13.

Classification.

Trace fossils have been classified by Seilacher (1953)

on the basis of the functional character of the trace, irrespective of the nature of the organism thought to be responsible. Three types of trace fossil are recognised in the Grindslow Shales and Kinderscout Grit, corresponding to three of Seilacher's classes.

Vertical Burrows. (*Domicnia*, Seilacher).

These are found mainly in the sandier facies, particularly 4, 5 and 13. They can occur in great density (Photo 60) and may often have sharply demarcated boundaries of distribution, apparently independent of any lithological boundary (Photo 61). Vertical burrows present different appearances on lower and upper bedding surfaces and in vertical sections.

Lower bedding surfaces are best seen where a sandier unit overlies a siltstone or mudstone. The burrows occur as ellipsoidal protrusions of about 1 cm. x 0.5 cm. and up to 0.5 cm. relief, sometimes showing a slight preferred orientation and being related to vertical disturbances in the overlying sediment. (Photo 60). In silty sandstone, the burrows often show a slightly cleaner fill than the bulk of the rock.

On upper bedding surfaces, two manifestations of vertical burrowing are seen. The most common is ellipsoidal depressions of up to 1.3 cm. x 0.8 cm. and 0.5 cm. deep. These are generally rather poorly and irregularly developed. The second bedding

plane feature, associated with vertical burrowing, has been found at only one exposure, Heyden Brook, (N.G.R. SE 097013). The sandstone bedding plane, on the top surface of a unit of Facies 5, Siltstone with Sandstone Lamination and Ripples, is sharply overlain by fine mudstones. On the bedding plane are many small radiating clusters of lobate depressions, now filled with the overlying mudstone. The lobes are up to 2 cm. long and 4 mm. wide. Most of the clusters have an asymmetry, though no attempt has been made to detect any preferred direction to this. (Photos 2 and 63, and Fig. 29).

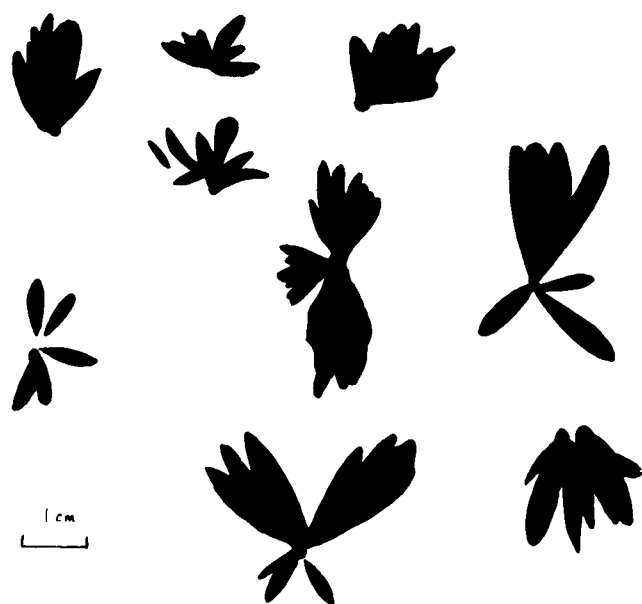


FIGURE 29.

This pattern appears only to have formed on the top surface and not within the sediment as in the form figured by Lessertisseur (1955, Fig. 31,C and D) after Weyland and Budde (1932) from the Devonian of Elberfeld. In vertical

sections, bedding and lamination are dislocated in vertical zones up to at least 1.5 cm. wide and up to 10 cm. deep (Photo 64 and Fig. 30).

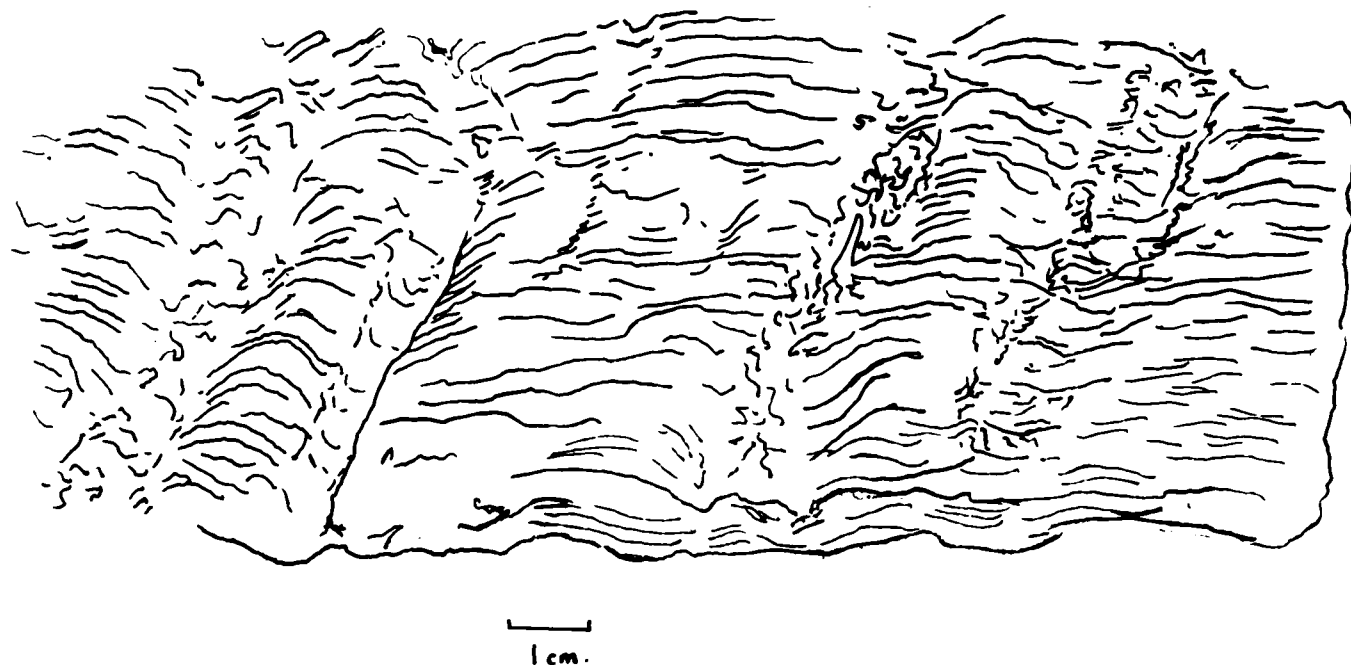


FIGURE 30.

When intensively developed, the burrowing virtually obliterates the bedding (Photo 6) but the burrows never show the sharply demarcated boundaries seen in forms like Diplocraterion (cf. Goldring, 1962, pl. 22). In Crowden Brook, Edale, (N.G.R. SK 096872), an isolated burrow penetrates the stoss side of a dune and is filled by overlying siltstone (Photo 10).

It is possible to make only tentative speculations as to the organisms responsible for the burrows. As no body fossils are found, it is most reasonable to assume that the organisms had no preservable hard parts, though the possibility of hard parts having been dissolved cannot be discounted, particularly as bivalves can form traces similar to those described. The

burrowing bivalves, Scrobicularia plana and Macra both collect food from the sediment surface by means of their siphons and give stellate clusters of depressions around the tops of their burrows. (Evans, 1965, Fig. 5j; Schäfer, 1962, Fig. 52; Lessertisseur, 1955, Fig. 1Cc.). Some Annelid worms are known to have vertical burrows with stellate patterns on the sediment surface (Lessertisseur, 1955, Fig. 1Ca). Stellate patterns are also found at the tops of the burrows of the amphipod, Corophium (Lessertisseur, 1955, Fig. 15g) and an unnamed amphipod, also figured by Lessertisseur (1955, Fig. 1Ce).

Horizontal Burrows. (Fodinichnia, Seilacher).

These are found mainly in the siltier facies, particularly Facies 3, Striped Siltstones. This is the type recognised by Walker in the Grindslow Shales and is therefore diagnostic of his Facies G, Mudstone (1966a, Fig. 13). On horizontal surfaces, the burrows occur as ridges of relatively clean fine sandstone within a silty matrix. They are 2 to 3 mm. and rarely up to 5 mm. wide and are seldom traceable for more than 3 cm. along their length. They are of irregular orientation both within an individual and relative to one another in an assemblage. They can achieve a high distribution density. In vertical sections, the burrows have a roughly circular cross-section, though this is often slightly flattened parallel to

the bedding. Within many burrows, there is no organisation to the sediment, though in some, a weakly developed, concave upwards lamination suggests upward migration. (Fig. 31).



FIGURE 31.

1 cm.

This trace fossil has affinities with both Phycodes and Teichichnus, both of which are interpreted as feeding burrows. (Hantzchel, in Moore, ed., 1962, Vol. W, Figs. 128, 1a and 1b. 136, 7b; Goldring, 1962, Fig. 5).

The organism most likely to be responsible for this burrow is thought to be some species of worm.

Horizontal Trails. (Hepichnia, Seilacher).

This type of trace fossil is found at only one locality, at the north-west corner of Kinderscout, (N.G.R. SK 067898). It occurs on the upper surface of a Facies 13, Sharp-based Clean Sandstone. The trails are sharply defined grooves up to 5 mm. wide and 2 to 3 mm. deep. In plan, they are up to 10 cm. long, with a wavy, roughly sinusoidal trace (Photo 56). The trails appear to have affinities with Cochlichinus.

" (Hantzchel, 1962, Fig. 116, 1) and Gordia (Hantzchel, 1962, Fig. 121, 1). Both are the crawling trails of worms. (cf. Lessertisseur, 1955, Fig. 6A).

Environmental Significance.

Little environmental significance can be attached to the occurrence of the trace fossils described above. Their presence and abundance are probably related to the grain size of the sediment, its nutrient content and rate of accumulation and to the physical and chemical characteristics of the water. How exactly these parameters affect the trace fossils is not clear from the assemblage in this succession.

CHAPTER 4. FACIES ASSOCIATIONS.

Introduction.

A facies association is a group of facies, genetically related to one another, in such a way as to have environmental significance. The environment is diagnosed by the organisation, both in space and time, of the processes deduced from the individual facies constituting the association. Five major facies associations are recognised here:-

1. Major Channel Association.
2. Large Scale Cross-Bedding Association.
3. Fluvatile Channel Association.
4. Slope Association.
5. Interdistributary Complex Association.

The first three involve mainly coarse, pebbly sandstone facies and are more ordered and predictable. The other two involve finer grained facies and are less predictable, particularly the Interdistributary Complex Association.

1. Major Channel Association.

Introduction.

This association involves Facies 8, Massive Bedded Coarse Sandstone, Facies 9, Parallel Bedded Coarse Sandstone and Facies 10, Medium Scale Cross-Bedded Coarse Sandstone, lying

within channels which are either visible or can be inferred from field relationships. The authenticity of Facies 8, as noted in Chapter 3, is only claimed when a channel can be seen or inferred.

Channels occur in complexes of up to four channels. A complex is defined as the recognisable channels encountered in a single vertical section or in lateral relationship in a large exposure. The number of erosion surfaces recognised in a complex is always a minimum value because of the narrow extent of most stream sections. For example, at Nether Tor, where good lateral exposure shows the presence of at least three channels, vertical sections at either side would indicate only two channels (Fig. 32).

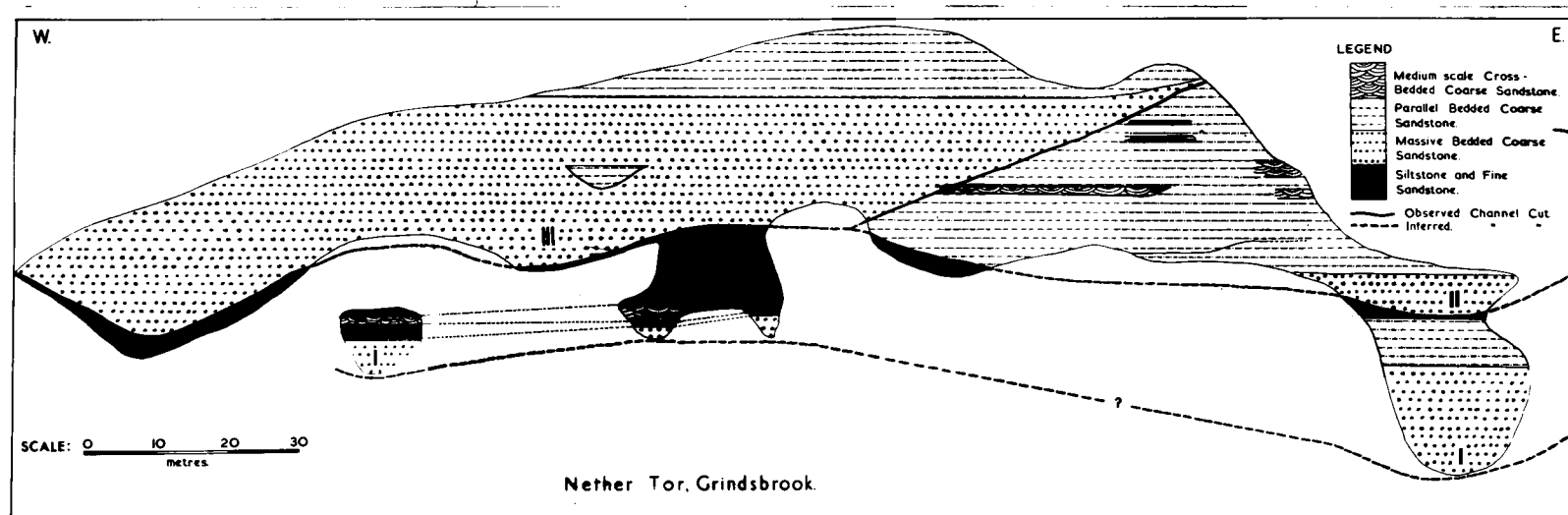


FIGURE 32.

With this qualification, therefore, the number and natures of recognised channel complexes are shown in Table 10.

Table 10. Numbers of Channels in Channel Complexes.

Single Channel Complexes			13 giving 13 Channels.		
Double	"	"	7	"	14
Treble	"	"	4	"	12
Quadruple	"	"	1	"	4
Total	"	"	25	"	43

Of these channels, thirty have their basal erosion surfaces exposed. Their locations are shown on the map (Fig. 37)

Dimensions.

Most exposures of this association are such that only minimum values of dimensions can be obtained. Tops of channels are frequently truncated by an overlying channel in a complex or the top of the exposure corresponds with the top of the topographic feature. Lateral extents are similarly limited and seldom are both sides of a channel seen. Even where the lateral limits are known, the problem of knowing the orientation of the channel in relation to the orientation of the exposure, makes an estimate of true channel width rather tenuous.

Thicknesses of channel deposits vary greatly, the smallest recognised thickness being that of the lowest channel of the complex in Crowden Great Brook, which is 4 m.. The maximum

thickness found is 60 m. for the higher channel of the Seal Edge Complex (N.G.R. SK 104888). Exposure here is poor and the top of the complex is uncertain. The thickest channel fill, which can be measured with certainty, is the highest channel of the Nether Tor Complex. This has a maximum observed thickness of 40 m.. 30 of the 43 channels have observed thicknesses between 10 and 30 m..

For only two channels can the width be estimated with accuracy. In Grindsbrook, measured sections and mapping evidence, combined with the direction of erosive lineation on the channel base, enable a width of 300 m. to be calculated. Similar evidence gives a width of 220 m. for the channel in Abbey Brook.

Other channels show only one or neither margin. In such cases, only a minimum width can be estimated and then only when some control of the channel's orientation is present. The greatest width which can be inferred is that of the Upper Tor Channel, Grindsbrook, (N.G.R. SK 113876) which is at least 530 m. The highest channel of the Seal Edge Complex has no associated palaeocurrent data and the lateral extent of some 850 m. along the edge cannot, therefore, be converted to a meaningful width. Other inferred minimum widths are between 100 and 400 m..

Erosion Surfaces.

Channels are normally cut into the Intertributary Complex Association but sometimes into the coarse sandstone fill of a lower channel in the complex or into the Slope Association. Relief on the erosion surface is divisible into two types, a large scale relief, associated with the geometry of the channel as a whole and a small scale relief, measured on the scale of tens of centimeters. Channel cross sections, where they can be reconstructed, are seen to have fairly flat bases with steeper sides. The bases may be locally irregular and have an overall dip, towards the deepest point, of up to 10° . The steeper walls generally slope at between 20 and 35° , though in the lower channel of the Seal Edge Complex, a local slope of 50° is needed to explain the field relationships. Channel cross sections show an asymmetry, with one side steeper than the other. (Fig. 33).

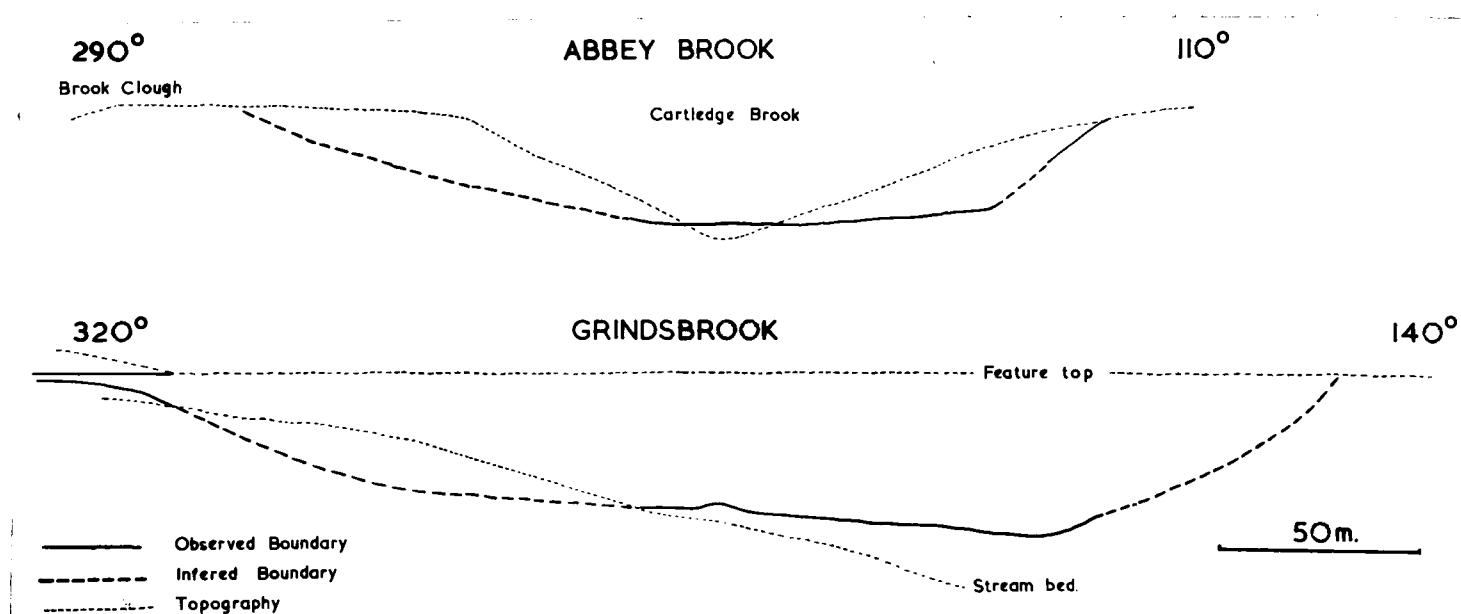


FIGURE 33.

The angles of slope of channel walls have no obvious relationships with either the depths of the channels or the lithology of the eroded sediment.

In Nether Tor, Channel 111, 34 m. of relief are seen (Fig. 32), while in Grindsbrook 41 m., in Abbey Brook 26 m. (Fig. 33) and in Middle Seal Clough, higher channel, 22 m. can be demonstrated from vertical sections and mapping evidence.

Minor relief on erosion surfaces varies from shallow grooves to more intense irregularity, giving local steepening of channel walls. Grooves are common, generally being seen as moulds or casts on the lower surfaces of sandstone channel fills (Photo 65). They are often the only evidence of channel orientation and most of the trends shown on the map (Fig. 37) are derived from them. Grooves are seldom deeper than 2 cm. but may reach 5 cm. in width with gently concave upwards bases.

More intense local irregularity may produce steep steps on erosion surfaces and, in extreme cases, may produce overhanging walls. A spectacular example of this is seen in Crowden Great Brook, (N.G.N. SE 062016), where two steep, overhanging steps are seen. (Fig. 34 and Photo 66).

The lower step has an overhang of about 30 cm., cut into siltstone with an extremely coarse and pebbly sandstone fill. There are grooves on the upper erosion surface of the fill.

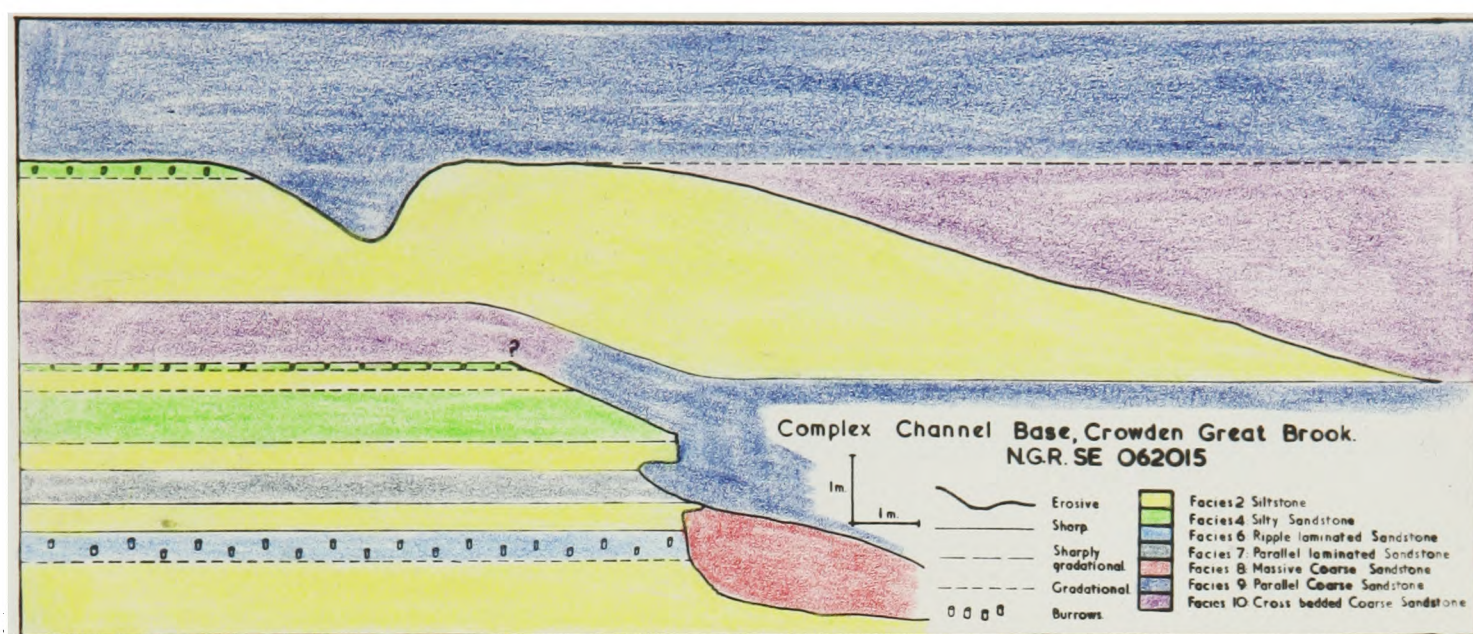


FIGURE 34.

The upper step overhangs 60 cm., again with hints of grooves on a horizontal top surface and with strong grooves on the wall just above. The sediments into which the channel is cut, are interbedded siltstones and fine sandstones of the Inter-distributary Complex Association. Siltstones are above both the overhanging steps with sandstones in the undercut regions.

Channel Fill Sequences and Facies Relationships.

Facies 8, Massive Bedded Coarse Sandstone, Facies 9, Parallel Bedded Coarse Sandstone and Facies 10, Cross-Bedded Coarse Sandstone are found within the channels in the following abundances:-

Table 11. Compositions of Channel Fills.

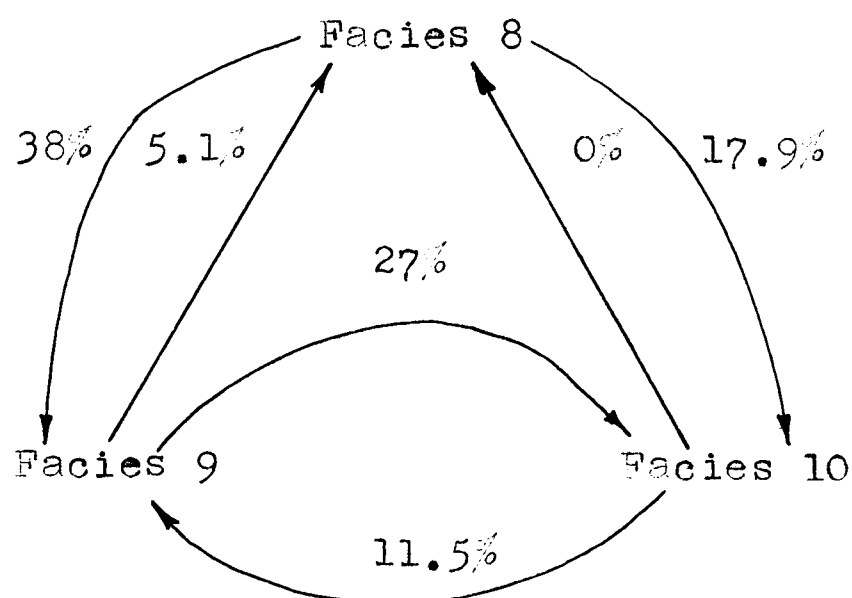
Facies 8.	68.1%
Facies 9.	16.7%
Facies 10.	15.5%

Based on 932.5 m. of measured section.

These proportions are calculated by measuring the vertical thicknesses of the different facies within all recognised channels. This includes those channels where the base was not seen and the top of the fill was not certainly exposed.

The sequences of facies found in channel fills have been analysed, an analysis of non-erosive facies changes giving the following results.

Table 12. Analysis of vertical, non-erosive facies changes in channel fills.



An analysis of channel fill sequences gave the following data:-

Table 13. Major Cha

Fill Sequence	8,9
Complete	8
Incomplete	5
Total	13

The information

Table 13. Major Channel Fill Facies Sequences.

Fill Sequence	8,9	8,9,10	8,9,10,9,10	8,10	8	10	9,10	9,10,9	9,10,9,10	8,10,9,10,9,10	9,8,10	Total.
Complete	8	5	3	5	1	1	0	1	1	1	1	27
Incomplete	5	1	0	4	4	1	1	0	0	0	0	16
Total	13	6	3	9	5	2	1	1	1	1	1	43

The information was subdivided into those channels where

the complete fill sequence is known and those where the limits of exposure or higher erosion surfaces truncate the sequence.

Following Duff and Walton (1962), it would seem that the modal sequence is 8,9 with minor modes of 8,10 and 8,9,10.

When this information is combined with the fact that in only 4 of the 30 channels with exposed erosion surfaces, is Facies 8 not the lowest facies of the fill, it becomes probable that the full modal sequence is, in fact:-

Erosion Surface → Facies 8 → Facies 9.

The composite sequence, from the above information, would seem to be:-

Erosion Surface → Facies 8 → Facies 9 → Facies 10.

As well as the vertical facies changes noted above, there is also evidence of lateral facies variation within channel fills. In the southern bank of Blackden Brook, (N.G.R. SK 118882), a channel, 17.5 m. deep and at least 140 m. wide (in the plane of the exposure) is cut into the Interdistributary Complex Association of the top of the Grindslow Shales. It is filled with Facies 8, Massive Bedded Sandstone. To the west, the unit thins as the erosion surface rests on progressively higher beds, until it is represented by 1.20 m. of ripple laminated sandstone. Between the ripple laminated unit and the massive beds of the thicker parts of the channel, the facies changes through medium scale cross-bedded sandstone

and parallel laminated sandstone and becomes coarser over about 20 m. horizontal distance. (Fig. 35).

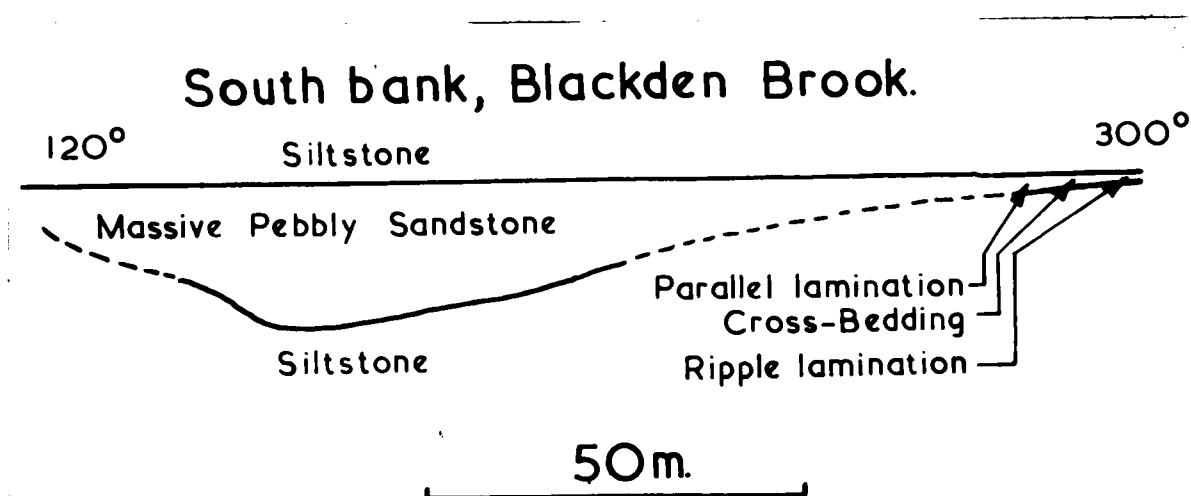


FIGURE 35.

The fill of the large channel in Abbey Brook, described by Walker (1966b) as being Facies 'C' Sandstone, has many similarities to Facies 8, Massive Bedded Coarse Sandstone and has been included as such in the above data. It appears to be an intermediate between the two facies.

Orientations and Palaeocurrents.

Directions of channel trends are obtained directly from mapping evidence and from the extrapolation of groove directions from the channel boundaries. This is considered to be the most reliable indication of channel trend being preferred to internal directions from the fill, following Allen (1966), who showed progressively greater current directional variability with decreasing size of bedform.

Palaeocurrents can, however, also be obtained from the primary current lineation of Facies 9, from the internal erosion lines of Facies 8 and from the cross-bedding of Facies 10. The relationships of these directions to the direction of basal grooves are shown in Figure 36.

Relationship between Internal
Palaeocurrents and the Major
Channel Trend inferred from
Grooves on Channel Boundary.

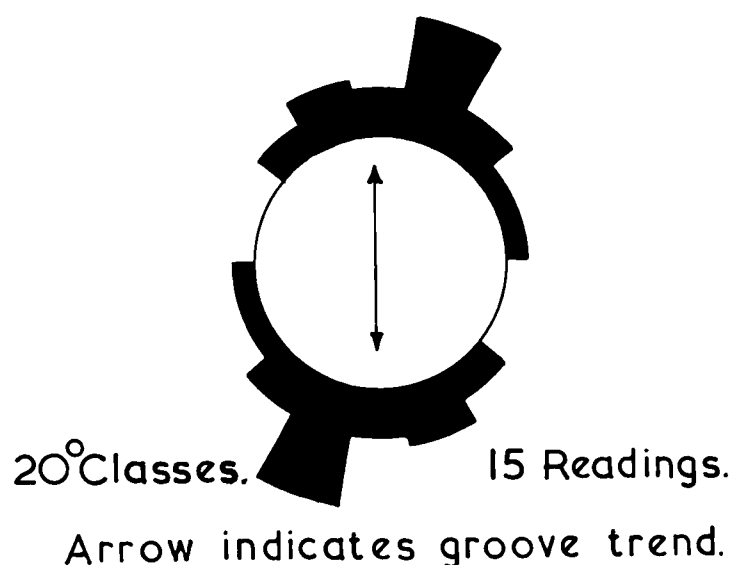


FIGURE 36.

From this it is seen that there is a considerable spread of internal palaeocurrents around the groove directions, the modal divergence being about 15° clockwise of the grooves. There is hardly sufficient data to give this great significance.

In the construction of the distribution map (Fig. 37), erosional grooves have been given precedence over internal erosion and primary current lineation, which in turn have been given precedence over cross-bedding directions, for reasons noted above. The data is also presented as a histogram (Fig. 38).

Current Data from Major Channel Complexes

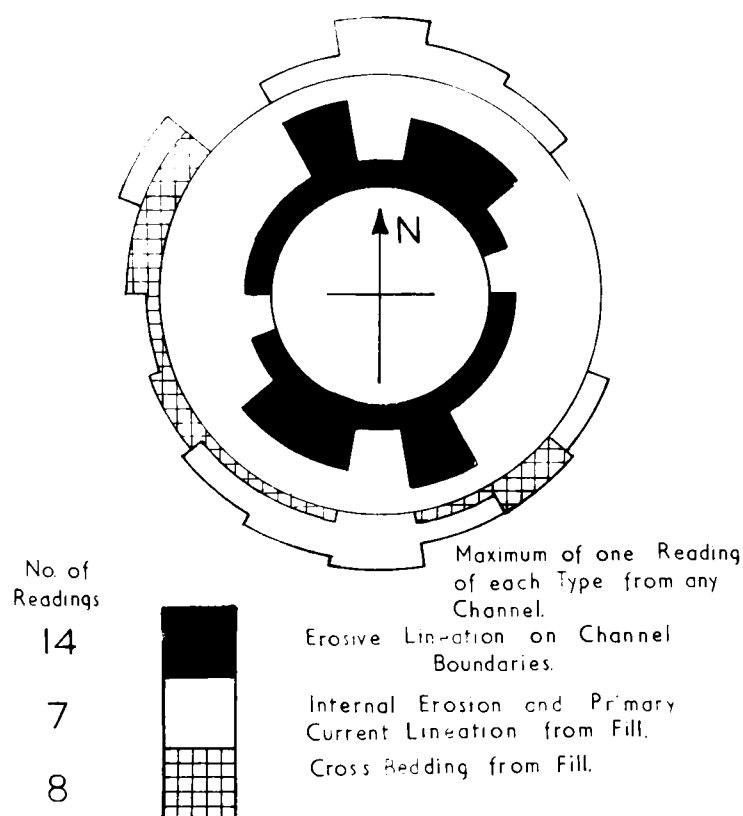


FIGURE 38.

Constancy of orientation of channels and their palaeo-currents, within a complex of more than one channel, varies from showing parallel to perpendicular trends for successive channels. At Crowden Great Brook, three channels in the complex have trends within 5° of one another, while in Stable Clough, cross-bedding and grooves of successive channels are perpendicular.

Minor Internal Channels.

Within some of the major channel fills are minor channels and scours. At Nether Tor (Fig. 32), three such channels are seen. Near the base of the Facies 9 part of the fill of

Channel II, a channel cuts down 1.20 m. and is filled with the same facies (Photo 25). In Channel III, a channel 3 m. deep and 10 m. wide is cut into Facies 8 and appears to be filled by Facies 9, Parallel Bedded Sandstone.

Interpretation.

The cutting of deep channels demands very powerful currents especially as, in many cases, the material eroded is of fine grain size and therefore more difficult to erode (Hjulström, 1935, Sundborg, 1956, p. 197). The coarse, pebbly nature of channel fills suggests that such material might have considerably added to the abrasive power of the stream. The fact that channel walls are rather steep and locally very steep or overhanging, suggests that the eroded sediments had achieved considerable strength, due, presumably, to compaction under a thick cover of sediment, equal in thickness to the channel depth. As fine sediment of the Interdistributary Complex Association accumulated relatively slowly, there was probably a considerable interval of time available for the compaction.

From the evidence of Crowden Great Brook, (Fig. 34 and Photo 66), it is possible to show that the finer sediments had a greater strength as it is siltstones which form the

overhanging parts of the walls, the sandstones being eroded away. On the larger scale, however, the grain size seems to have little control over the slope of erosion surfaces. The slope of the erosion surface of the topmost channel at Nether Tor (Fig. 32), which is cut into coarse, pebbly sandstone of the underlying channel fill, is as steep as erosion surfaces cut into siltstones.

The strength of the eroded sediment is further indicated by the presence of large blocks of siltstone in the lower parts of some channel fills (Photos 17 and 18), particularly associated with Facies 8.

The presence of siltstone blocks and mudflakes indicates the sediment's behaviour during erosion. It is certain that at least some of it was eroded as blocks and mudflakes and, because of the relative ease of doing this compared with grain by grain erosion, it is likely that most of the eroded material was removed in this way. Blocks would quickly be broken up in the stream and reduced to smaller particles.

From the palaeocurrent evidence of Figure 36, it is suggested that the cutting and filling of the channels were due to closely related currents. Of the three facies within the channel fills, two have already been interpreted in hydrodynamic terms. Facies 9, Parallel Bedded Sandstone has been interpreted as due to flow in the lower part of the upper flow

regime and Facies 10, Cross-Bedded Sandstone as due to flow in the upper part of the lower flow regime.

Fitting these interpretations into the composite sequence derived above of Erosion Surface → Facies 8 → Facies 9 → Facies 10, it would seem that the upper two members show deposition from a waning flow regime. If it is assumed that the maximum competency of the stream is now represented by the erosion surface, the position of Facies 8, between the erosion surface and Facies 9, suggests, therefore, that Facies 8 was deposited when the flow regime was higher than that giving Facies 9, that is, in the upper part of the upper flow regime (Collinson, 1966).

The lateral thinning and facies transition noted in the channel in Blackden Brook (Fig. 37), would seem to support this hydrodynamic interpretation of Facies 8. Weaker current transported finer sediment at lower flow regimes in the shallower parts of the channel.

Flow in the upper part of the upper flow regime involves the bed forms standing waves and antidunes (Gilbert, 1914, Simons et al., 1965). Recent examples of the deposits of this flow regime are poorly described. The only direct observations of antidune deposits are those of Middleton (1966). Using fine sand in a large flume, poorly developed, gently

lenticular, bedding was produced with faint, very faint or no internal lamination. The lenticular beds had mutually erosive bases sometimes with rather steep dips to the surfaces. The poorly developed lamination is attributed to the absence of any of the hydraulic processes noted in other migrating bed forms and to the large amount of sediment in suspension.

Other workers on antidunes have been more concerned with the surface configurations (Kennedy, 1961, Fahnstock, 1963, Harms et al., 1965). Kennedy showed photographs of antidune deposits, some of which show a poorly defined lenticular bedding while Harms and Fahnstock (1965) noted cross-strata dipping upstream at angles of less than 10° in sediments associated with violent antidune activity. They also state that stratification is commonly poorly defined in sediments deposited at this flow regime and predict that antidunes will give a pattern of complexly imbricating sets.

The erosive and gently lenticular nature of bedding produced at this flow regime correspond well with features noted from Facies 8. The poorly sorted nature of the sediment and the weak nature or absence of lamination also fit well, particularly if the horizontal preferred orientation of pebble long axes, noted from Facies 8 can be equated with the weak development of lamination. Low angle, up-current cross-bedding

has not been found in Facies 8.

In the present state of knowledge, the relationships between the massive beds of Facies 8 and the deposits of any one antidune must remain unanswered questions. Because of the poorly developed lamination, there is little reason for assuming that the massive units are related in any direct way to individual antidunes. If this were the case, however, for an antidune of 1 m. height, surface waves would have to be between 1.5 m. and 2 m. high (Simons et al., 1965, p. 40). Nordin reported waves 2 to 3 ft. in height from the Rio Grande and it seems possible that larger ones could exist to give beds of up to 1 m.

Until more detailed studies are made of both recent antidune deposits and of massive bedding, no further comparisons can be made. The limited fabric data from Facies 8 (Fig. 11) indicate preferred orientation of long axes of grains in the horizontal plane with modal directions somewhat divergent from the associated grooves and scours. However, not enough data are yet available to enable any general conclusions to be drawn.

While the overall interpretation of the composite channel fill sequence is of waning flow from high upper to lower flow regime, it is not meant to imply that this was necessarily one

continuous process. Rather it was the net result of the waning of the maximum flow regimes developed by the highest floods, when erosive scour would be at a maximum and would therefore remove much of the sediment deposited by earlier waning flows.

The presence of complex fill sequences and of small internal channels within the larger ones suggest that flows fluctuated considerably.

Several reasons for the initiation of channel downcutting followed by their filling by a waning flow can be suggested:-

1. Diversion of a large river, either suddenly or gradually, followed by a gradual cutting off of its own supply.
2. Climatic changes giving greatly increased run-off which subsequently waned.
3. Relative fall and subsequent rise in basin level, giving increased slope and therefore erosion followed by aggradation. This movement could be due to several factors.

These possible mechanisms will be discussed in Chapter 6 when the relationships of the Association to other sediments have been described in Chapter 5.

2. Large Scale Cross-Bedding Association.

Description.

This association involves Facies 10, Medium Scale Cross-

Bedded Coarse Sandstone and Facies 12, Large Scale Cross-Bedding with minor amounts of finer grained sediment. Wherever the top of a large scale set is seen, it is a horizontal erosion surface, overlain by medium scale cross-bedding. The erosion surface may be flat as on Bamford Edge (Photo 67) and Kinderscout N. Edge (Photo 67), or may have a relief of up to 1.5 m. as seen in Ewden Beck (Photo 43). Immediately above the erosion surface there may be a thin bed of Facies 16, Orthoconglomerate, though this is not always present.

The overlying, medium scale cross-bedding may be in tabular or trough sets. On the northern edge of Kinderscout, a 2 m. tabular set immediately overlies the erosion surface and is itself overlain by smaller trough sets (Photo 67). On Bamford Edge, trough sets are directly above the erosion surface (Photo 46).

The current directions, derived from the overlying medium scale cross-bedding, diverge by only small angles from the direction of dip of the foresets of the underlying large scale set. The divergence increases with increasing height above the erosion surface. Immediately above the erosion surface, 10° is the maximum divergence, but at 2.5 m. above the surface, this has increased to 30° .

When only one large scale set occurs in a vertical section,

as is generally the case, the association is confined to this simple relationship of two facies. When more than one large scale set is present, each has its own erosion surface and overlying unit of medium scale cross-bedding. There are never more than two large scale sets in any vertical section and the lower one is always thicker and of greater lateral extent. Upper sets can be seen to die out laterally at both Kinder Downfall and on Bamford Edge (Photos 44 and 68).

At Kinder Downfall, an upper set of 8.5 m. thickness dies out over a distance of some 60 m. in a direction roughly opposed to the direction of the foreset dip, the lateral equivalents being trough cross-bedded sandstone and possibly, to some extent, burrowed siltstone, though poor exposure obscures the exact relationships.

At the southern end of Bamford Edge, (N.G.R. SM 210846), the upper set thins from 7 m. to about 1 m. over a distance of 120 m., again in the direction opposed to the direction of foreset dip. The 1 m. set is itself within a coset of medium scale cross-bedding overlying the lower set which is at least 11.5 m. thick. This lower set itself thins to about 8.5 m. over the distance of 400 m. in the up-dip direction and becomes the upper of two sets seen at Great Tor. Here the lower set is at least 11 m. thick and possibly 20 m.. The overall pattern

is of a system of sets overlapping 'en echelon' (Fig. 39).

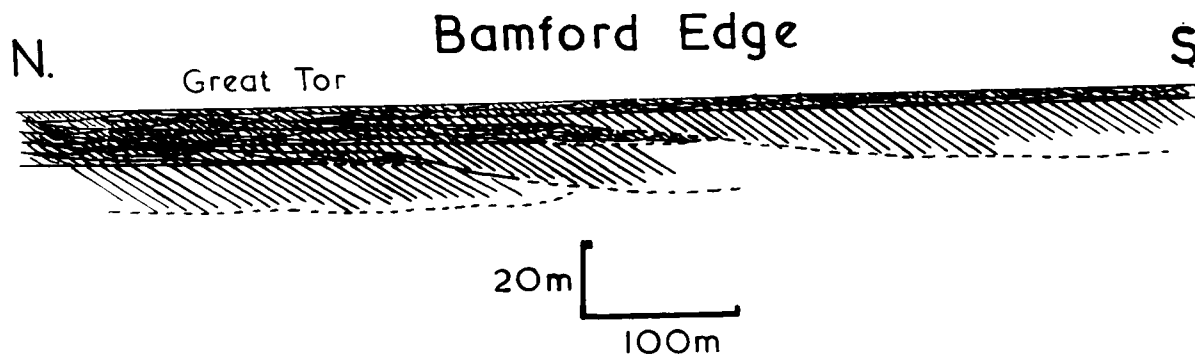


FIGURE 39.

This arrangement contrasts strongly with the northern edge of Kinderscout where one set is traceable over at least 2 km.. There is no evidence of the way in which sets die out in the down-dip and transverse directions though the occasional presence of fine grained sediment associated with the base of the upper set suggests that the sets may be flanked by such material, as is suggested in Fig. 40.

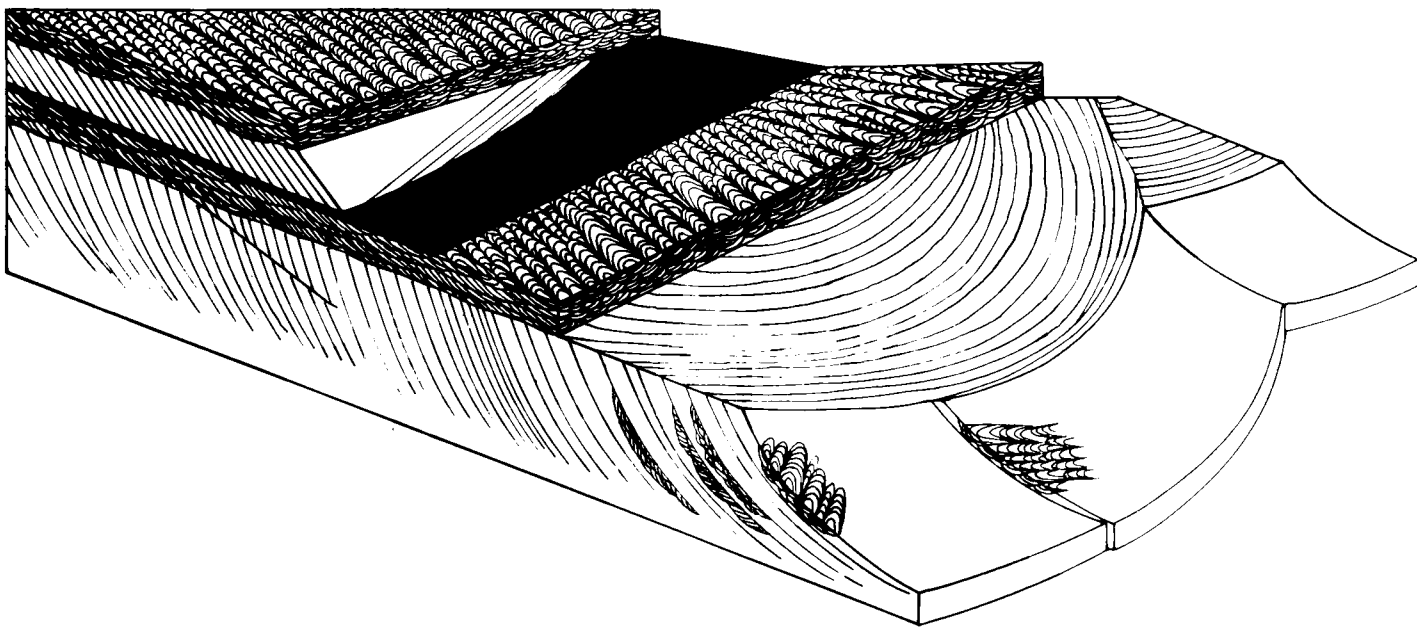


FIGURE 40.

The dip directions of the large scale foresets have been plotted on a map (Fig. 41) and histograms of these data are presented in Fig. 42.

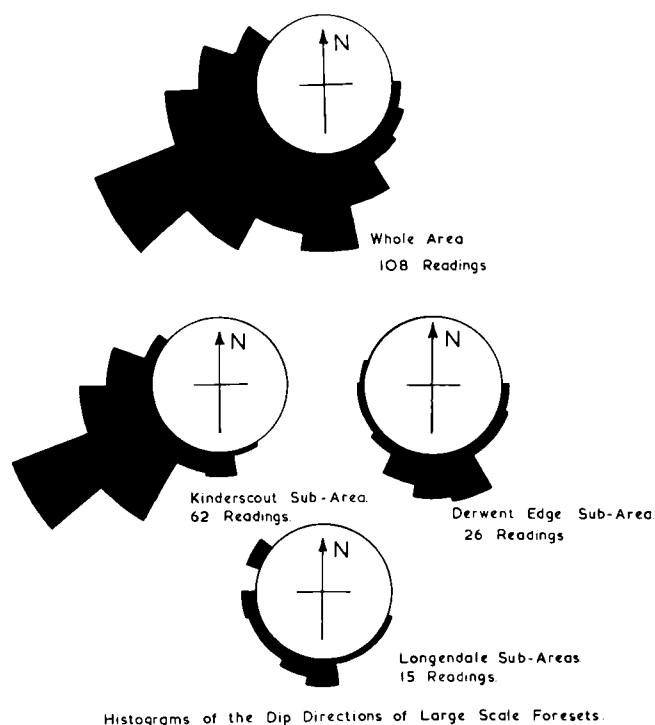


FIGURE 42.

As no sampling grid was used in the collection of these data, their statistical validity is questionable, though a qualitative impression of palaeocurrents is obtained, indicating a preferred direction of advance from the north and north-east.

Interpretation.

The large scale cross-bedded sets of Facies 12 have already been attributed to the advance of delta-like sedimentation units into bodies of standing water, probably subsequent to sudden rises in the level of the water and coupled with high

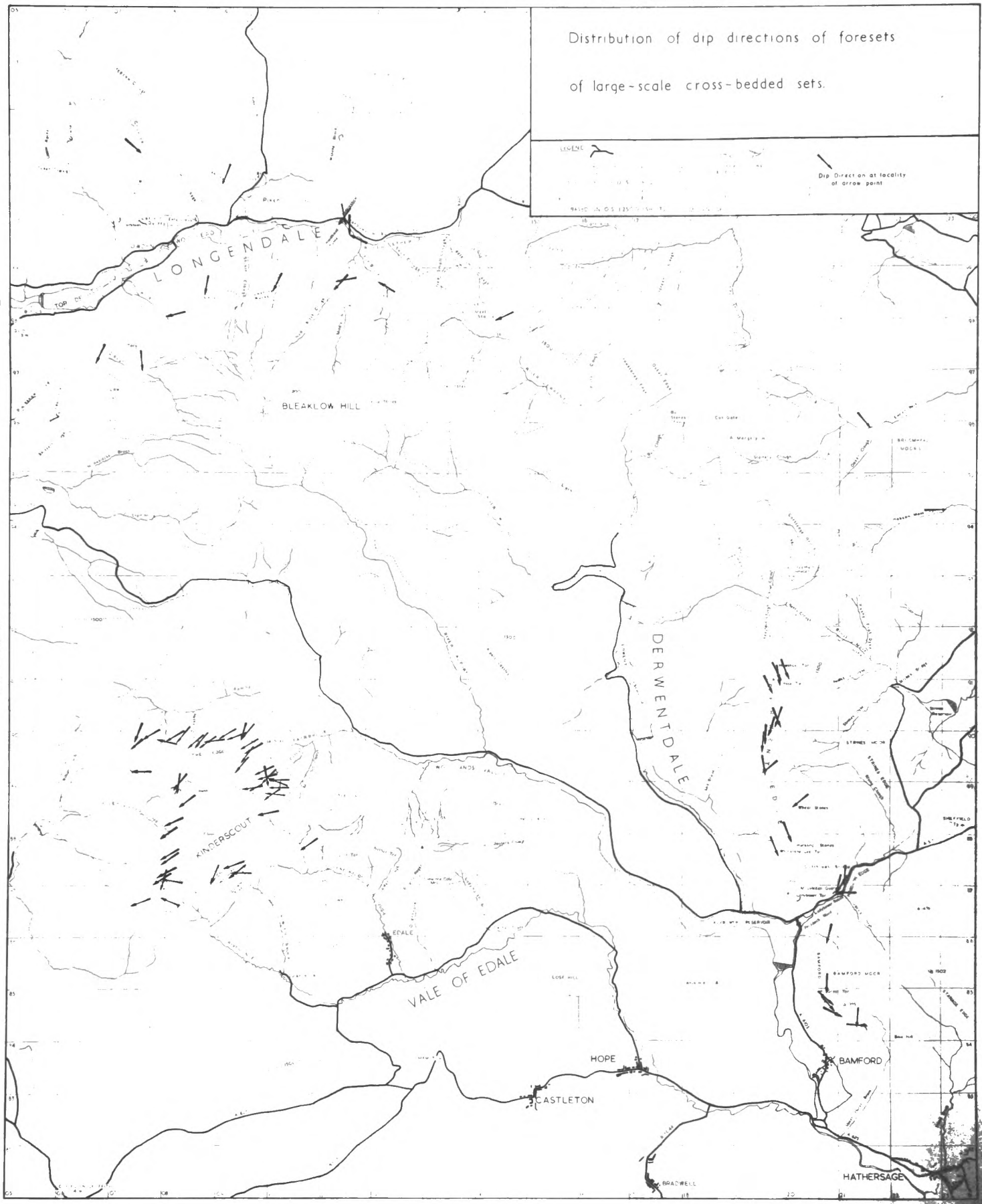


FIGURE 41.

rates of sediment inflow. Following Gilbert's (1885) tripartite subdivision of a delta, the large scale set represents the 'foreset' unit. The association described above points to the nature of the other two units, the bottom and topset beds. The poor exposure of the bases of most large scale sets makes the description of the bottomsets difficult, though the suggestion is that fine grained sediment sometimes occupies this position, indicating deposition from suspension in front of the delta. In other cases there seems to be a gradational passage from horizontally lying coarse sandstone.

The close similarity in current directions derived from the large scale sets and the overlying medium scale cross-bedding suggests that the latter represent the topsets of the delta units. Slow relative rise in basin level is needed for the aggradation of topset beds (McKee, 1957, p. 132; Jopling, 1963, 1966b) without the initiation of a new sedimentation unit. At the limit of backwater, the stream begins to lose its competency, and the deposition of coarser particles begins. Downstream, from the limit of backwater to the top of the foreset slope, there is a gradual decrease in competency. If the rise in base level is fast enough, topset aggradation will take place at the expense of major foreset advance. Rapid and sudden rise in the base level may initiate the development

of a new sedimentation unit, starting from the embryonic wedge, formed from a dune on the topset surface, at the limit of backwater.

Such a mechanism could well explain the formation of the 'en echelon' sets with upcurrent thinning, seen on Bamford Edge (Fig. 39 and Photo 68), though variable subsidence and/or irregular migration of distributary streams could give the same result.

Two types of erosion surface separate the two main facies of the association, those with and those without an overlying orthoconglomeratic layer. The significance of these layers is fully discussed in the Fluvatile Channel Association. It may just be said here that they represent the product of winnowing of the top of the large scale set or of earlier deposited coarse sandstone of the topset environment.

If the latter is the case, the erosion surface may represent the migration of a channel deeper than that which transported material to the lip of the delta cone. It is then a rather surprising coincidence that the current directions of the large scale set and the overlying medium troughs are so similar.

The nature of the currents transporting sediment over the topset environment is thought to be fluvatile. The unidirectional nature of the palaeocurrents, the coarseness of the

sediment and its freedom from silty laminations all support this. The close comparison between the topset beds and the sediments of the Fluvial Channel Association will become clear in the discussion of that association.

Migrations and diversions of the distributaries may have controlled the pattern of distribution of the delta lobes to form a sheet sandstone and also have given rise to the periods of depleted supply now indicated by fine grained units on the foresets, and by erosion surfaces between them.

Examples of recent deltaic sedimentation units are rare and are much smaller than those described here. Jopling (1966^a) described a tabular set from a glacial outwash deposit and the present author has seen a small delta cone built into Ladybower Reservoir by a tributary stream (Photo 69).

The nature of the currents which formed the intraset cross-bedding can now be discussed. The physical and chemical characteristics of the water into which the delta cones advanced are not known. Neither is the nature of any currents in the basin known, though, as will be suggested in the discussion of the Interdistributary Complex Association, both tidal and wave activity were probably rather weak. While weak tidal or wave activity could give rise to intrasets, it is tempting to look for other mechanisms.

The preferred orientation of intraset cross-bedding down the foreset slope (Fig. 25) suggests the possibility of currents, which flowed on the top surface of the delta cone, developing into density underflows down the foreset slope, the 'hyperpycnal flow' of Bates (1953). This could only happen if the basinal water was of lower density than the inflowing water for reasons of salinity, temperature or suspended sediment load. There are no criteria which can usefully be applied to differentiate between these possible reasons and the question must be left open.

In the large scale set exposed at Woodhead Tunnel (Photo 49), the intraset cross-bedding in the base of the set is directed up the foreset slope, suggesting that a counter-current was developed in front of the delta cone (Jopling, 1961, Allen, 1965^a). It seems therefore that no one simple explanation can at present be given for intra-set cross-bedding.

3. Fluvial Channel Association.

Introduction.

This is the most widespread coarse sandstone facies association in the Kinderscout Grit, occurring in both the upper and lower parts. It involves all facies except Facies 1,

Marine Mudstone, 15, Melange, and 17, Turbidite-like Sandstones. Facies 10, Medium Scale Cross-Bedded Coarse Sandstone is volumetrically the most important facies, though the others are often of great diagnostic importance. The association consists essentially of an erosion surface overlain by Facies 10 sandstone which passes upwards into ripple or parallel laminated fine sandstones and then into Interdistributary Complex Association. The idealised sequence is shown in Figure 43.

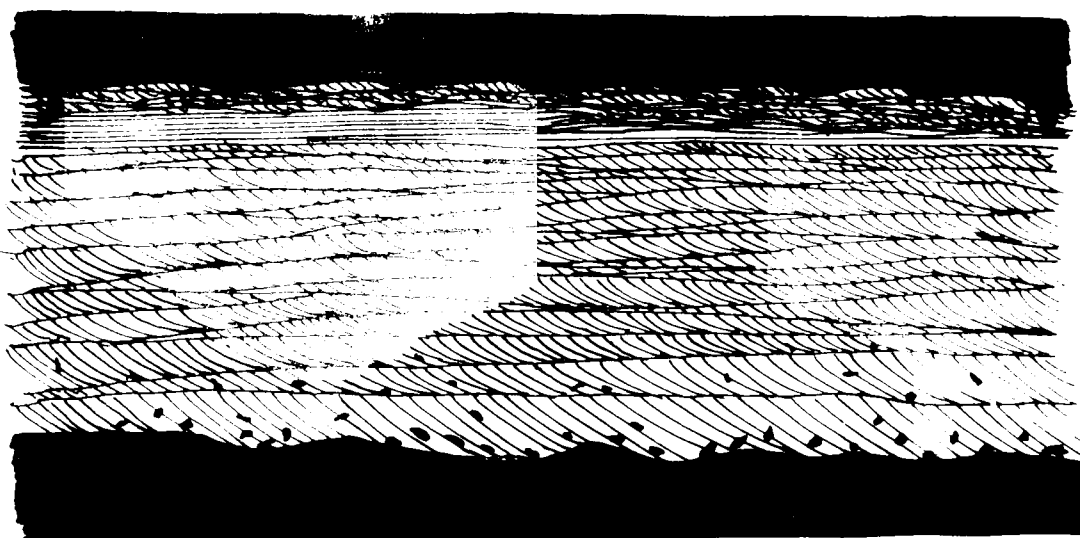


FIGURE 43.

Within this broad framework there is wide variety at all stages.

Basal Erosion Surfaces.

The erosion surfaces at the bases of examples of the association are broadly horizontal and laterally extensive, often traceable in outcrop over hundreds of meters (Photo 70).

It is thought, on mapping evidence, that some of the erosion surfaces may extend over several kilometers. The erosion surfaces may be underlain by any member of the Interdistributary Complex Association or by a member of another unit of the Fluvial Channel Association. Of these, Facies 2 Siltstone is the most common, being seen the same number of times as the rest of the fine grained facies together. Erosion surfaces underlain by Facies 10 sandstone are the second most common type, being about half as common as those underlain by Facies 2. The recognition of surfaces both underlain and overlain by Facies 10 sandstone is difficult and this type of erosion surface is possibly more common than is apparent.

In detail the erosion surface may be flat or may show relief of up to 2 m., though of 53 erosion surface localities examined, only 5 showed a relief of more than 50 cm. and 41 were less than 20 cm.. The most common form of relief is grooves of about 1 cm. depth, though these may be superimposed on larger features.

Basal Conglomerates.

Erosion surfaces are most commonly overlain directly by coarse and often pebbly sandstone. Occasionally, however, thin and discontinuous layers of Facies 16, Orthoconglomerate

overly the surface (Photo 58). These horizons are confined to those erosion surfaces which overly coarse sandstone. Where fine sandstone or siltstone is the sub-stratum, the lowest part of the coarse sandstone may be extremely coarse and pebbly and have abundant siltstone fragments. In only one example were siltstone fragments seen when the erosion surface overlaid a coarse sandstone. The sandstone immediately above an erosion surface may also be rich in carbonaceous material. An analysis of the occurrences and types of basal conglomerate is given in Table 14.

Table 14. Compositions of Basal Conglomerates of the Fluvial Channel Association.

Coarse Sandstone	26
Extremely Coarse and Pebbly Sandstone	6
Mudflakes and Siltstone Blocks	6
Orthoconglomerate	6
Mudflakes and Pebbles	2
Carbonaceous Material	3
Carbonaceous Material and Pebbles	1

Coarse Sandstone.

With the exception of small and sometimes rather doubtful occurrences of Facies 8, Massive Bedded Coarse Sandstone and Facies 9, Parallel Bedded Sandstone, the coarse sandstone

member of the association is always Facies 10, Medium Scale Cross-Bedded Coarse Sandstone. Only three examples are found of Facies 8 above the erosion surface. In each case, the unit is less than 1 m. thick, and poorly exposed. Of the four examples of Facies 9, three are less than 1 m. thick, the exception being a 5 m. unit in Near Black Clough (N.G.R. SK 114989). All the examples of Facies 8 and 9 pass up into Facies 10.

Thicknesses of the coarse sandstone members vary from 1.5 m. to 40 m. but in the latter case it is possible that one or more erosion surfaces may have gone undetected. Most units fall within the range 4 m. to 15 m.. The tendencies for the basal erosion surface not to be exposed and for the coarse sandstone to form the topographic feature mean that, in many cases, minimum thicknesses only are recorded. This is also the case where the upper part of a unit has been removed by a later erosive phase.

Within the cross-bedded unit, several trends can be detected. The first, which has already been hinted at in Chapter 3, is the tendency for sets to change upwards from tabular to trough shape. This is associated with the tendency for sets to decrease upwards in thickness. In an 8 m. unit, it would be common to find trough sets of 30-40 cm. in the base, passing up into 10-20 cm. sets in the top. The reduction

is not usually uniform, as is shown by the thicknesses of successive sets seen in Stainery Clough (N.G.R. SK 207965). These have thicknesses 10, 30, 10, 15, 10, 13, 11, 16, 8, 10, 12, 9, 10 cm.. Plotted as moving averages, in groups of three, a more uniform reduction becomes apparent as shown in Figure 44.

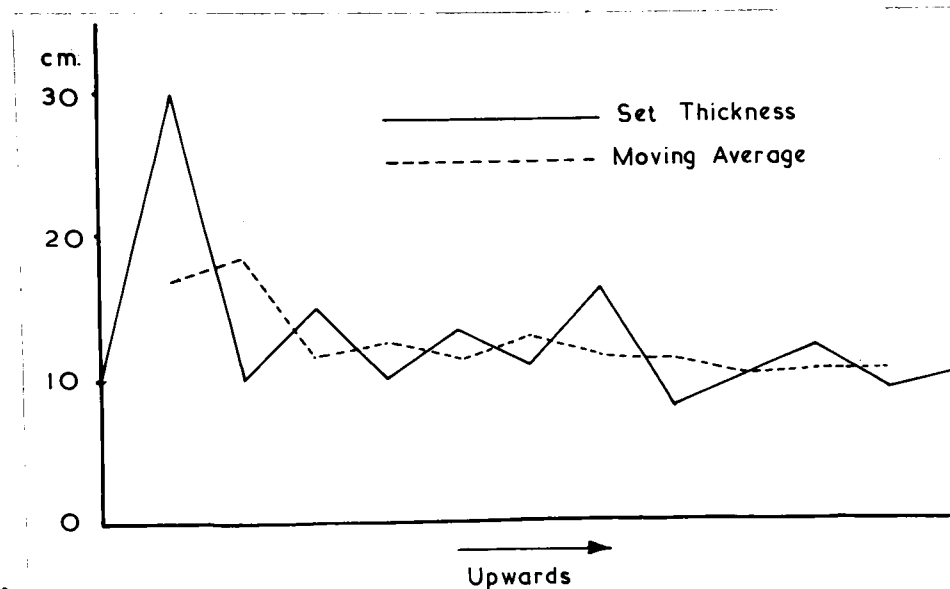


FIGURE 44.

Another common tendency is for the grain size of the sandstone to decrease upwards through the unit. This is not as common as the two tendencies described above and is never seen without a corresponding reduction in set thickness. Associated with the grain size reduction is a reduction in the abundances of siltstone fragments and carbonaceous material.

Occasionally, within the coarse sandstone member, internal erosion surfaces are seen with a greater relief than that associated with the base of a trough cross-bedded set. In Mickleden (N. G.R. SK 189986), a steep-walled channel, 60 cm. deep, is cut into coarse cross-bedded sandstone, in 20 cm. troughs (Fig. 45).

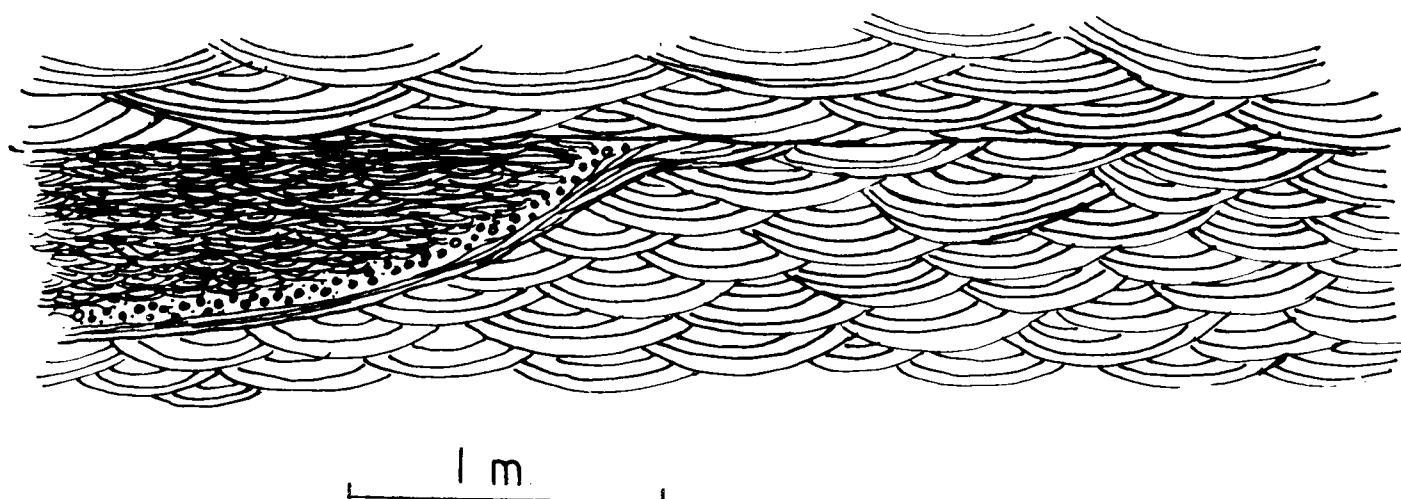


FIGURE 45.

The trend of the channel is roughly parallel to that of the trough axes. The erosion surface is draped by a 10 cm. layer of thinly bedded, fine to medium sandstone which is, in turn, draped by a thin pebble layer. The remainder of the channel is filled with horizontally lying, ripple cross-laminated, fine sandstone. The whole is then overlain by more trough cross-bedded sandstone.

In Crowden Great Brook (A.G.R. SE 063021), an erosion surface of 50 cm. relief is cut into extremely coarse and pebbly sandstone, cross-bedded in 20 cm. sets, near the top of a coarse sandstone unit. The surface is draped by a 5 cm. layer of thinly laminated medium siltstone which is then overlain by up to 1.5 m. of very coarse sandstone, cross-bedded in 10 cm. sets. There is some 65° divergence between the directions of trough axes above and below the erosion surface.

There is also a certain amount of lateral variation within the cross-bedded units. Trough cross-bedded horizons may pass laterally into tabular sets or into parallel bedded or laminated sandstone. Such transitions are particularly common towards the top of the coarse sandstone unit.

Directions of cross bedding from examples of the association are plotted on a map (Fig. 46). The Upper and Lower Kinderscout Grits have been plotted separately and the information is also plotted as histograms in Figure 47.

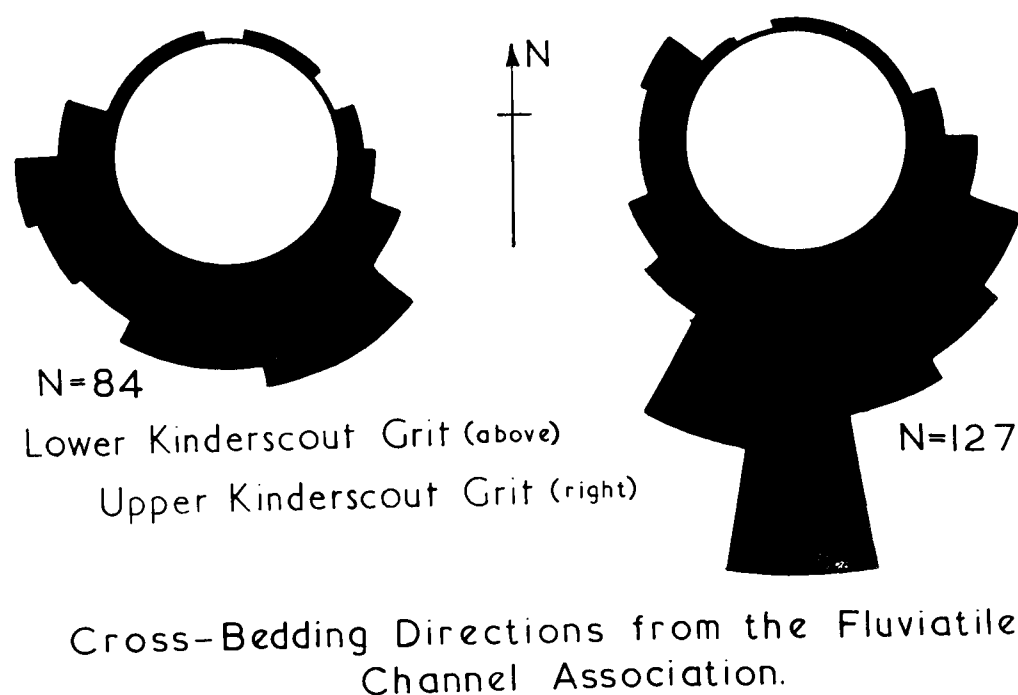


FIGURE 47.

These show a general trend to the south with more variation in the Lower Kinderscout Grit.

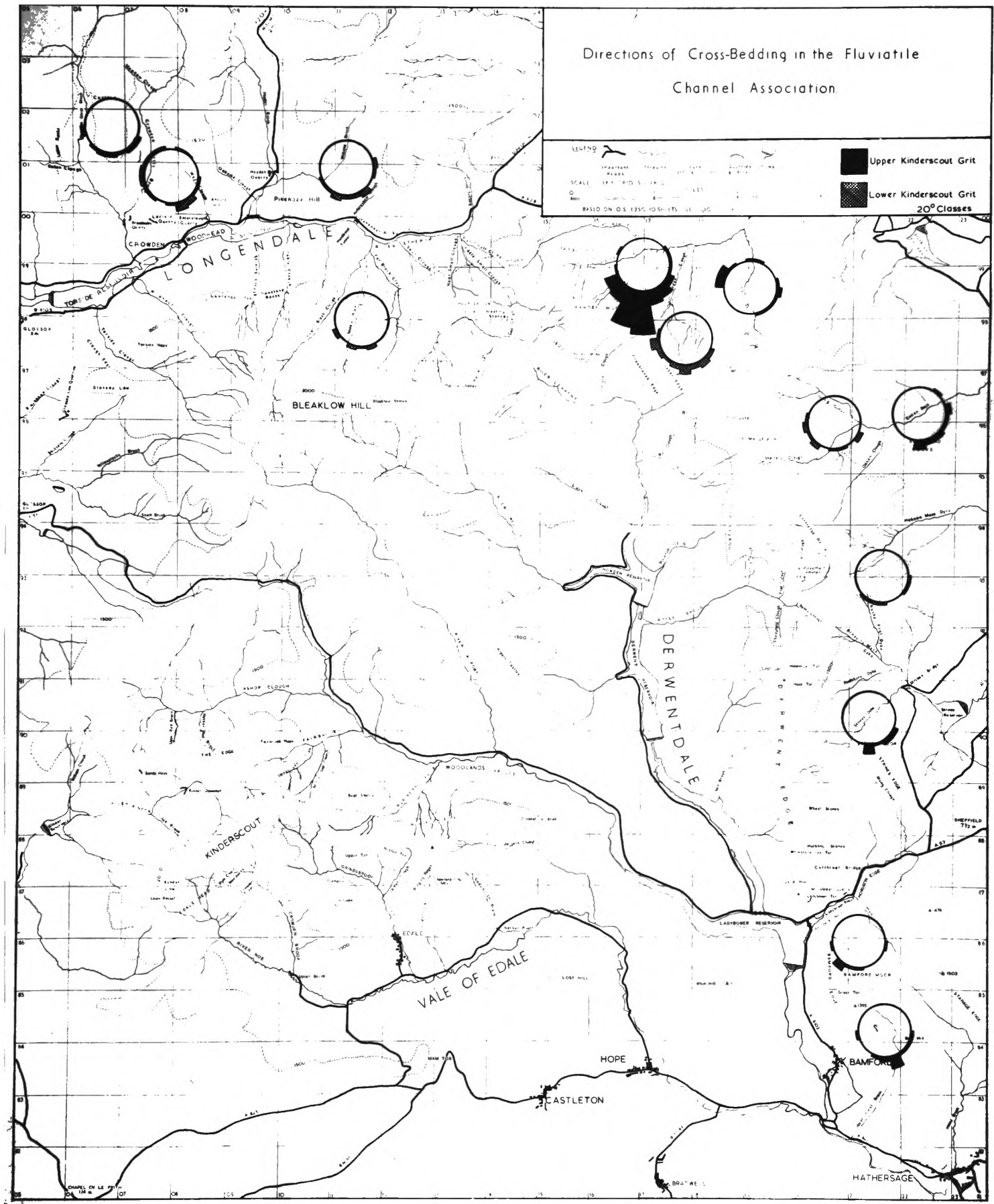


FIGURE 46.

Fine Sandstone.

Overlying the coarse sandstone unit is a variably developed, fine sandstone unit, seldom greater than 1 m. thick. This is not always present and the coarse sandstone may pass sharply into siltstones of the Interdistributary Complex Association. When the unit is present, however, it consists of either Facies 6 or 7, Ripple or Parallel Laminated Fine Sandstone or a mixture of the two, sometimes associated with thin cross-bedded horizons. The types of transition from the coarse to the fine sandstone unit are four in number, noted in Table 15 along with their frequency of occurrence.

Table 15. Transitions from Coarse to Fine Sandstone in the Fluvial Channel Association.

10 → Siltstone.	10 → 6	10 → 7	10 → 7 → 6
6	24	6	3

The fine sandstone units may show sharp lateral changes and minor horizons of siltstone with sandy lamination may be interbedded with the sandstone. Very occasionally, the top of the unit may be disturbed by rootlets. Within the top of the unit, it is often possible to detect a low angle cross-bedding composed of the laminated sandstone. The directions of primary current lineation or rib and furrow often diverge markedly from the direction of the low angle dip. In Laund

Clough (N.G.R. SK 163991), a low angle set dips (100/18).

Rib and furrow on the 'foresets' is directed towards 190° .

The directions of primary current lineation and rib and furrow are generally in fairly close agreement with the cross-bedding directions of the underlying coarse sandstone unit.

The fine sandstone units pass upwards into the Inter-distributary Complex Association, which may sometimes be in the form of a seat earth and coal horizon.

Fine Grained Channel Fills.

In the western tributary of Crowden Brook, Edale, (N. G.R. SK 095872), a 9 m. thick sequence of siltstones and fine sandstones sharply overlies a coarse, cross-bedded sandstone unit. The sequence consists mainly of finely laminated siltstones in the basal 5 m., with Facies 4, Silty Sandstone, Facies 5, Siltstone with Sandy Lamination and Ripples, and Facies 13, Sharp Based Sandstone Beds, in the upper part. The unit is sharply overlain by extremely coarse and pebbly sandstone. In the eastern tributary, 200 m. away, at the same stratigraphical level as the fine grained unit, is up to 9 m. of medium to coarse, cross-bedded sandstone. This is sharply overlain by an erosion surface, dipping to 330° and overlain by fine siltstones with some silty sandstone horizons. The siltstones

are erosively overlain by extremely coarse and pebbly sandstone which, even further east, rests on the medium to coarse sandstone. The apparent relationships are shown in Figure 48.

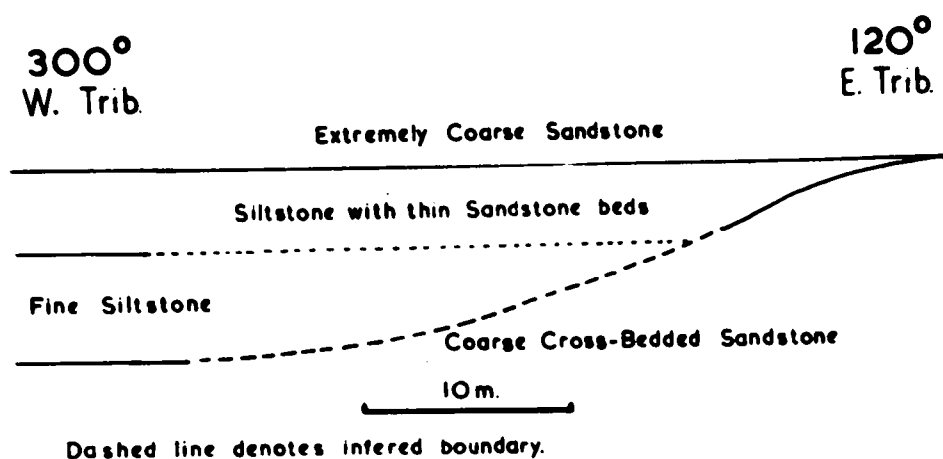


FIGURE 48.

From these relationships, it seems that the fine grained unit fills a channel within the medium cross-bedded sandstone unit. The erosion surface at the base of the upper coarse sandstone probably represents the base of another example of the association.

Low Angle Cross-Bedded Units.

At Loftend Quarry (N.G.R. SK 075998) and at the roadside quarry at Woodhead (N.G.R. SK 111999) are found the only two examples of low angle cross-bedding on a large scale. At Loftend (Photo 71), a unit, 6 m. thick, halfway up the quarry face, extends for the length of the quarry, a distance of some 150 m., without noticeably changing in thickness. The base of the unit is sharp with irregular erosive relief cut into the underlying siltstone unit. The bedding is in the form of a

single low angle cross-bedded set, the 'foresets' of which dip (070/04). The sediment is mainly medium to coarse sandstone, often cross-bedded in sets of up to 15 cm. These are directed towards 190° , that is, slightly up the low angle slope, in a direction 30° from the strike direction of the low angle 'foresets'. Interbedded with the sandstone are units of up to 50 cm., of siltstone and fine silty sandstone, dipping with the 'foresets'. Some finer sandstone beds show ripple cross-lamination with rib and furrow to 225° being recorded from one such bed. The siltstones may be burrowed.

At Woodhead, a similar situation is seen, though there the unit is only 2.5 m. thick. An overlying erosion surface may have considerably reduced the thickness. The low angle set dips to the west at about 5° . The lithology is predominantly fine to medium sandstone but this changes laterally into siltstones with sandy ripples before reverting to sandstone.

Interpretation.

The association described above fits readily the general model of fluvial sedimentation proposed by Allen (1964b) and Visher (1965a and b). This shows how a laterally migrating channel cuts a horizontal erosion surface and by removal of one bank and lateral accretion of the other, lays down an

essentially tabular sandstone unit. The channel depth corresponds roughly to the thickness of the sandstone unit (Fig. 49).

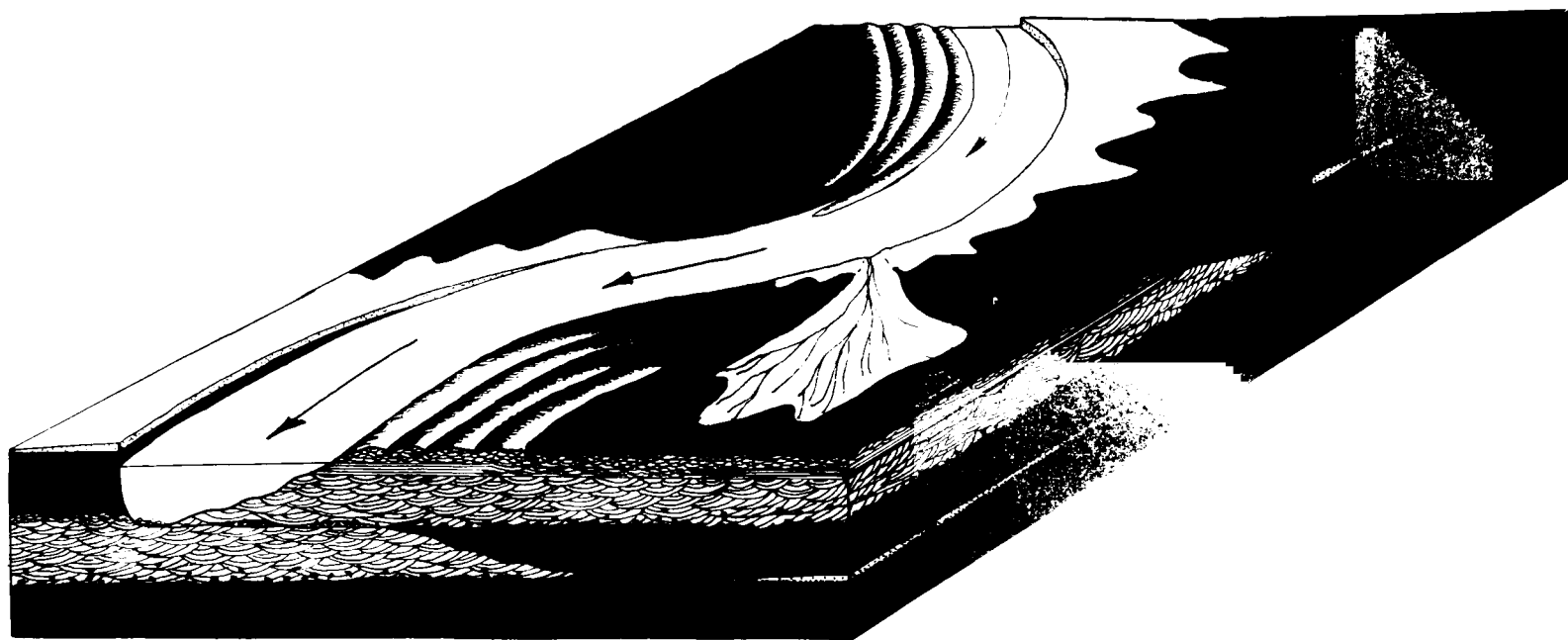


FIGURE 49.

The level of erosion into the pre-existing sediments corresponds to the deepest part of the stream. In a curved reach, such as a meander, this point tends to be nearer the outside bank of the curve, which is, in fact, the one undergoing erosion (Leopold et al., 1964, p. 300). Maximum scour is found to occur at times of flood when the coarsest sediment is entrained (Leopold et al., 1964, p. 228). At the lower stages, the coarsest sediment undergoes winnowing and this can well result in the formation of an orthoconglomerate, provided that pebbles are available. Facies 16, Orthoconglomerates, noted above some erosion surfaces (Photo 58), fit this model

and the facies is therefore interpreted as a channel lag deposit. The presence of siltstone and mudstone fragments in the lower parts of the coarse sandstone unit, corresponds to a feature noted by Allen from the Old Red Sandstone (1962). They show that the substratum was being eroded, at least in part, as blocks due to the cohesion of the fine sediment. The presence of carbonaceous material in the lower parts of the coarse sandstone unit may indicate either that the eroded sediment was rich in carbonaceous material or that growing or recently rotted plants were present near the top of the eroded bank.

The sandstone overlying the erosion surface or lag conglomerate represents the result of the lateral accretion on one side of the stream. Allen's and Visser's model is based largely on comparison with meandering rivers when the accreting surface is the point bar surface on the inside of the meander. Such surfaces are known in modern rivers to have dunes of considerable size migrating over them (Sundborg, 1956, Lane et al., 1940, Harms et al., 1963). Deposits of point bars show cross-bedding of a scale comparable with that of the coarse sandstone unit of this association (Frazier et al., 1962, Harms et al., 1963).

The upwards decrease in size of cross-bedded set (Fig. 43)

is to be expected from Yalin's equations if the size of the set has a direct relationship with the height of associated dunes. The upwards decrease in grain size, frequently seen in the coarse sandstone unit, has several analogies in modern rivers (Allen, 1965b).

The tabular sets (Photo 27) found in the base of some examples of the association are probably referable to large straight-crested dunes and 'transverse bars' (Sundborg, 1956). The rare occurrences of massive and parallel bedded sandstone in the base of the association may be due to the development of the upper flow regime conditions at periods of flood.

All the above noted features fit the model of a laterally migrating point bar in a meandering river. Several features, however, suggest that this might not always have been the case; the first of these is the relatively thick development of parallel bedded sandstone in the base of the unit seen in Near Black Clough. This suggests that upper flow regime conditions were dominant for considerable periods of time and this is probably an uncommon feature in the lower parts of meandering channels. Allen (1964b) attributed a similar feature, in the Old Red Sandstone cyclothem at Mitcheldean, to deposition by a braided river, where upper flow regimes are more commonly developed. The presence within the coarse

sandstone unit of small channels such as those in Mickleden (Fig. 45) and Crowden Great Brook, also suggest that the river might have had a more braided pattern. Small channels, capable of being temporarily cut off from the main flow were filled with finer material, in the case of the siltstone by deposition from suspension and in the case of the rippled sandstone, by relatively weak currents. Such small channels of temporary duration would seem more likely in a braided stream (Doeglas, 1962) though the one in Crowden Great Brook, being near the top of the coarse sandstone unit, could represent a position high on a point bar surface, possibly associated with the swale and ridge topography sometimes found in this position (Sundborg, 1956).

The parallel or ripple laminated horizons of finer sandstone, found overlying the coarse sandstone, are also features of Allen's and Visher's model, though neither seems to be able to attach a very precise significance to these units. One possibility is that they represent 'in-channel' deposits, formed on the highest parts of the point bar by the thin edge of the river flow. Harms and his co-workers (1963) found parallel lamination overlain by ripple lamination on the upper parts of the Beene Point Bar in the Red River. Flow regime is controlled by both the depth and velocity of flow and the

development of a particular flow regime will be governed, in a case like this, by local details of channel morphology. Sharp lateral, as well as vertical variations in facies in the fine sandstone unit tend to support this. It is possible that wave activity, acting on the point bar surface, may also be partly responsible for the ripple and parallel lamination of the fine sandstone.

Allen (1964b) suggests that the ripple laminated horizons above the main channel sandstone are the result of overbank flooding close to the channel and may therefore be levees or swale fill deposits, between the point bar ridges. The occasional presence of rootlets in the rippled sandstone units suggests that the sediment surface was probably close to water level and in many cases the overbank environment is therefore the most likely.

The low angle divergences in the ripple laminated sandstone horizons, with their transverse current directions, support the idea of the fine sandstone's being an 'in-channel' deposit. The dipping surfaces represent the surfaces of lateral accretion. The bedding corresponds to the 'epsilon' cross-stratification of Allen (1963a) which has been interpreted in a similar way for examples from the Old Red Sandstone of Anglesey (1965d), though in that case, the whole of the sandstone

unit showed low angle cross-bedding.

Channels filled with fine grained sediment in a fluvial environment are generally associated with the sudden or gradual abandonment of the channel by the river and its subsequent filling by material deposited from suspension during floods. In the higher part of the fill, flood currents will operate and the sediment may be worked into ripples to give Facies 5, Siltstone with Sandy Lamination and Ripples. Facies 13, Sharp-based Clean Sandstone Beds, are thought to correspond to the deposits of crevasse splays (Allen, 1965b), which introduce bed load material from the main channel when the stream bursts its banks at time of flood.

The sharp base to the fine grained channel fill, seen in Crowden Brook (Fig. 48), suggests that, in this case, the abandonment of the channel was sudden. The very existence of this type of fine grained unit raises the question of how many of the units of Intertributary Complex Association throughout the succession are lying in channels, unrecognised as such because of the limits of exposure. Extensive sub-surface data would be needed to answer this question.

The thick units of low angle cross-bedding, as noted above for thinner units in the fine grained unit of the association, compare with Allen's (1963a) 'epsilon' cross-stratification.

This has been interpreted as showing the successive positions of surfaces of lateral accretion during the lateral migration of the channel (Wright, 1959, Allen, 1965d). Such bedding is not normally seen for a variety of reasons, such as the size and orientation of the exposures and the size of the sets of trough cross-bedding making up the unit. At Loftend (Photo 71) and Woodhead, however, the surfaces are seen, by virtue of extensive exposure and relatively fine and alternating grain size. The variation in grain size, within a unit, suggests that the channels were rather variably operative. This type of cross-bedding has only been described in modern environments from tidal flats (Hantzschel, 1939, Evans, 1965), though there is no reason why it could not be formed in more normal fluvial environments. That smaller structures should indicate an up-slope component of palaeocurrent is predictable from the helical nature of the flow around the meander, (Allen, 1966). Similar types of bedding have been recorded from the Torridonian (Williams, 1966) and from the Devonian of Spitzbergen (Moody-Stuart, 1966) as well as from Anglesey. Moody-Stuart took the presence of 'epsilon' cross-bedding to be an indication of a high sinuosity stream and implied that its absence indicated low sinuosity. While generally agreeing with the first opinion, the present author sees no reason why high sinuosity stream

should be incapable of giving deposits devoid of 'epsilon' cross-bedding. The sediments of modern, large, high sinuosity rivers have not been shown to have 'epsilon' cross-bedding (Harms et al., 1963, Frazier et al., 1962).

4. Slope Association.

Description.

This association is confined to the lower part of the Grindslow Shales and to the fine grained horizon, sometimes associated with the Butterley Marine Band. It also occurs in the lowest fine grained unit in Hey Clough, Longendale, whose stratigraphical significance will be discussed in Chapter 5. The association has a gradational relationship with the Intertributary Complex Association, the boundary between them, in the Grindslow Shales, being taken arbitrarily at the base of the lowest horizon showing evidence of traction currents. The association consists of up to four facies, namely Facies 1, Marine Mudstone, 2, Siltstone, 3, Striped Siltstone, and 4, Silty Sandstone, forming units of up to 65 m. thick. Normally, however, the thickness in the Grindslow Shales is about 50 m. and in the upper unit about 10 m.

The base of the association, in the Grindslow Shales, is taken at the top of the highest Facies 'C' Sandstone of the

Shale Grit and in the higher unit at the top of the underlying coarse sandstone. The lowest sediments are frequently fine grained, laminated and often sulphurous mudstones which generally coarsen upwards within 5 m. into medium to coarse siltstone. This may show the striped appearance which distinguishes Facies 3. Within the lowest 10 m. of the Grindslow Shales, thin turbidite sandstones, corresponding to Walker's Facies 'A' occur. These are seldom over 20 cm. thick and die out in frequency upwards. Turbidite sandstones are absent in the higher unit of the association. The succession above consists of striped and homogeneous siltstones, bedded in thick units of up to 5 m.. Higher in the sequence, Facies 4, Silty Sandstone is found in increasing amounts, frequently bedded in units of less than 50 cm. with sharply gradational bases and tops more gently gradational back into siltstone.

The general coarsening upwards of the sequence is associated with an increase in the abundance of burrows. These are present in the striped siltstone facies and in the silty sandstone. They are usually the horizontal type, though vertical forms occur in the coarser units of silty sandstone. In the Grindslow Shales, the lowest trace fossils are found at between 25 and 35 m. above the base.

Major channels, within the lower part of the Grindslow

Shales, have been described by Walker (1966b) as being filled with Facies 'C' turbidite sandstones. No major channels have been recorded from the higher occurrences of the Slope Association.

Interpretation.

The present author sees no reason to dissent from the general conclusions arrived at by Walker (1966a) for the depositional environment of the lower part of the Grindslow Shales. He interpreted the broadly coarsening upwards sequence with turbidites in the base, as the deposits laid down on a prograding slope, below wave base. The prograding slope may be that of a delta or that in front of any other form of coastline with abundant sediment supply.

Evidence of traction currents in the upper part of the Grindslow Shales (Interdistributary Complex Association) tends to support the idea of the 'Slope' Association's representing the progressive shallowing of the environment.

The pattern of sedimentation corresponds to the deltaic and regressive-marine models of Visher (1965) and with the distal bar environment of Coleman and Gagliano (1965), with the difference that burrows are restricted to upper part of the Slope Association.

The lack of turbidite sandstones at the base of the smaller coarsening upwards unit, associated with the Butterley Marine Band, probably indicates that the marine band does not represent such deep water as that represented by the sediment at the base of the Grindslow Shales. The sequence of this higher unit is still, however, that of a prograding slope.

The channels in the lower part of the Grindslow Shales are interpreted by Walker as being both cut and filled by turbidity currents. While it is agreed that the channel fills in this part of the succession closely resemble the Facies 'C' sandstones of the Shale Grit, the nature of the currents must await discussion of the broader topic of turbidity current genesis in this basin, which will be undertaken in Chapter 6.

5. Interdistributary Complex Association.

Description.

This association, which characterises the upper part of the Grindslow Shales and all the finer grained horizons of the Kinderscout Grit, differs from the other associations in being generally haphazard. All the fine grained facies, with the exception of Facies 1, Marine Mudstone, occur within it. Volumetrically the most important are Facies 2, Siltstones and Facies 3, Striped Siltstones, but important thicknesses

of fine sandstone also occur.

Bedding is on a much finer scale than that of the Slope Association, generally being less than 1 m. and commonly of the order of 20-30 cm.. Units seem generally parallel-sided and are horizontally lying. Most boundaries are gradational and burrowing, both horizontal and vertical, is often intense, the lithology to some extent controlling the type of burrow. Facies 13, Sharp Based Clean Sandstone Beds can occur within any facies except Facies 7, 11 and 14.

As noted above, there is, in general, little order to the association, though several minor sub-associations can be recognised and interpreted.

The first of these is a sharp based unit of Facies 11, Cross-Bedded Fine Sandstone, up to 2 m. thick, which passes up into ripple-laminated sandstone. This sub-association is common in the finer horizons of the Kinderscout Grit and in the upper part of the Grindslow Shales where it is sometimes associated with a small coarsening upwards unit, up to 4 m. thick. These units pass up from Facies 2 or 3 Siltstone into Facies 4, Silty Sandstones which frequently is strongly burrowed (Photo 6). The erosion surface at the base of the cross-bedded sandstone is then cut into the silty sandstone. In Blackden Brook, three such 'cycles' are seen in the upper

part of the Grindslow Shales.

Other small channels can also be recognised in the association. These are seldom over 1 m. deep and may have a variety of fills. In Blackden Brook, a 90 cm. channel is cut into Facies 3, Striped Siltstones and filled by the same facies. Slightly coarser, silty sandstone occurs on the lip of the cut (Photo 5). Other channels have fills of Facies 7, Parallel Laminated Sandstone, 6, Ripple Laminated Sandstone or 4, Silty Sandstone. Those filled with parallel laminated sandstone sometimes show a low angle cross-bedding (Photo 72), a feature also noted by Walker (1964).

Occasionally, rather thicker units of up to 1.5 m. of ripple laminated sandstone occur within the association, sometimes with a gradationally basal transition from siltstone. An exceptional ripple laminated sandstone unit in Heyden Brook is 5 m. thick.

Seat earths and coals, the details of which have been discussed in Chapter 3, are found in this association.

Interpretation.

It is not possible to interpret such a complex and haphazard sequence in any but the most general terms. The presence of abundant, frequently rippled and cross-bedded

sandstone suggests a shallower environment than that of the Slope Association. The trend towards upwards increase in burrowing, seen in the lower part of the Grindslow Shales continues into the Interdistributary Complex Association of the upper part and therefore supports the suggestion.

The small thicknesses of most bedding units suggest that the environment was one in which sediment supply fluctuated greatly at any one point.

The presence of sharp based cross-bedded sandstone units can be attributed to the migration of small channels in a similar way to that suggested for the Fluvatile Channel Association. Such channels would hardly exist in any great depth of water and it is reasonable to suppose that their banks were at or near basinal water level.

The small coarsening upwards units may indicate the filling of a small body of quiet water by the approach of a stream, either by lateral migration or by prograding. The 'cyclicity' is probably best explained by internal controls of sedimentation such as irregular subsidence and/or the diversion of streams. The small channels filled with parallel laminated sandstone, sometimes showing low angle cross-bedding are also explained by the migration of streams, in this case flowing in the upper flow regime. The low angle cross-

stratification can be compared to the 'epsilon' cross-stratification of Allen (1963a) and interpreted as showing the successive positions of a laterally accreting surface (Allen, 1965d). Such cross-bedding is seen in modern environments on tidal flats (Hantzschel, 1939, Evans, 1965), though there seems no reason why it should not form in more normal fluvial environments.

The small channel in Blackden Brook, both cut into and filled by Facies 3, Striped Siltstones (Photo 5), may represent an abandoned channel filled with material which fell from suspension. The coarser sediment on the lip of the channel may represent levee deposits.

There is no evidence of subaerial exposure in the beds outside the channels and it is therefore probable that these were deposited under extremely shallow conditions, generally of the order of a few meters. The lack of evidence of a gradual upwards increase in wave activity throughout the whole of the Grindslow Shales, such as is frequently seen in regressive marine sequences (Coleman et al., 1965, Visher, 1965) suggests that the basin of deposition was cut off from waves of any great size. Thin beds of ripple laminated sandstone and of Facies 5, Siltstone with Sandy Ripples, may point to limited wave activity and some of the thicker, rippled units

possibly representing small beaches.

Evidence of tidal currents is also generally lacking and only the occasional occurrences of sediment, roughly ascribable to 'Flaser' or 'Linsenschichten' are recorded. The presence of seat earths and coals suggests that very shallow conditions could be maintained for considerable lengths of time, at a given place.

Facies 13, Sharp Based Clean Sandstone Beds can be interpreted in the same way as those found in the fine grained channel fill of the Fluvatile Channel Association, that is, as crevasse splays.

The environment of the Intertributary Complex Association can therefore be described as an area of shallow or very shallow water, subject to local fluctuations of sediment supply and with very limited wave and tidal influence. It was traversed by small migrating streams whose bank tops were close to the basinal water level. Flooding brought an increased load of suspended sediment into the area and crevassing of the banks of both small and large Fluvatile Channel Association streams gave coarser sandstone beds. In the Kinderscout Grit, this association can be roughly equated with the 'top-stratum' deposits of Allen's (1965b) fluvatile model when considered in conjunction with the Fluvatile Channel Association. In

the Kinderscout Grit, however, no convincing evidence of sub-aerial exposure has been found. The area was probably, therefore, a submerged interdistributary area rather than a floodplain.

Interdistributary areas of modern deltas display many of the features noted above (Coleman et al., 1965, Allen, 1964d), and such a broad environment is suggested for this association.

CHAPTER 5. STRATIGRAPHICAL RELATIONSHIPS.

Introduction.

In order to reconstruct a history of the sedimentation and the palaeogeography of the area during the deposition of the Grindslow Shales and Kinderscout Grit, it is necessary to build up a picture of the lateral and vertical relationships of the facies associations established in Chapter 4.

Nowhere in the area is there a clear and complete section through the whole sequence, different parts being exposed in separate areas. The whole area has been subdivided into five sub-areas, whose boundaries are shown on the locality map, presented in Volume 3, along with a correlation chart for each sub-area. Correlation within the sub-areas is generally fairly good and lateral and vertical facies variations can be established. Correlations between sub-areas are more difficult but can be attempted to some extent.

Each of the sub-areas will be discussed in turn, with reference to the appropriate correlation chart, presented in Volume 3, and this will be followed by a discussion of possible correlations between sub-areas and a synthesis of a general sedimentological history of the area.

Sub-Area I: South Kinderscout.

This sub-area extends for some 6 km., along the southern side of the Kinderscout Plateau from Edale Head in the west to Jagger's Clough in the east.

150 m. of the sequence is exposed, from the base of the Grindslow Shales into the lower part of the Kinderscout Grit, which forms the plateau top. Extensive exposure of the Shale Grit occurs in the lower parts of the streams and slopes. The thickest part of the Kinderscout Grit exposure is at the western end of the plateau and as the Butterley Marine Band has not been found, it is probably all within the Lower Kinderscout Grit. Comparison with the section found in the southern part of Sub-Area III, suggests that the Marine Band has only just been eroded.

The Grindslow Shales are not well exposed in this sub-area, the only extensive sections being those in Jagger's Clough and Grindsbrook. These were measured in detail by Walker (1964) and the lower part was shown to be predominantly mudstones and striped siltstones with some thin Facies 'A' turbidite sandstones at the base, therefore fitting well the Slope Association. The upper part of the Grindslow Shales are Intertributary Complex Association siltstones and sandstones, the transition between the two apparently taking place at

60-70 m. above the base of the Grindslow Shales.

The Interdistributary Complex Association of the top of the Grindslow Shales is extensively eroded by major channels. At Edale Head, Crowden Brook and Jagger's Clough, the lowest channels are cut into the Slope Association. The fills of the lowest two channels in Crowden Brook are very rich in mud-flakes along discrete horizons and appear intermediate in character between Facies 8, Massive Sandstone and the Facies 'C', turbidite sandstones of Walker (1966a).

Interdistributary Complex Association sediments are found between channels, as is particularly well shown at Nether Tor. It is clear that channelling was not confined to one discrete horizon but that large channels were cut and filled over a vertical range of about 70 m.. Between streams Ia and Ib, Interdistributary Complex Association sediments form the whole of the sequence to the level of the tops of the flanking channels. Isolated examples of the Fluvatile Channel Association are found, particularly in Jagger's Clough and in Crowden Brook, where the fine-grained channel fill described in Chapter 4 is seen at the 120 m. level.

At the western end of the sub-area, where the succession is thickest, Large Scale Cross-Bedding occurs above the major channel complexes. Exposure is poor and uniformly dipping

beds in isolated tors distinguish the facies, most of the foresets dipping to the west. The thin large scale set, seen at the 116 m. level of the Grindsbrook section, may represent the up-dip extreme of the thicker set seen further west. Lack of exposure makes confirmation of this impossible. Only in Edale Head and Grindsbrook is the horizontally lying trough cross-bedding present, above the large scale set.

Sub-Area II: North Kinderscout.

This sub-area covers the northern and north western parts of the Kinderscout Plateau. The chart, which is mainly E-W in orientation, changes direction to NW-SE at the western end. A total length is some 8 km. and up to 160 m. of the succession is exposed.

The succession covers the same range as that seen in Sub-Area I. Shale Grit is extensively exposed in the lower parts of the stream sections and the top of this member gives a prominent feature top with a feature base above. The higher feature has been used for correlation where no exposure is present. The top of the Shale Grit is well exposed in Blackden Brook and in Fairbrook. The feature base, well seen on Seal Edge, has been equated with the top of the Shale Grit in the construction of the chart. This correlation is, however,

somewhat questionable and it is probably not unreasonable to move the Seal Edge and Clough sections upwards by up to 30 m. from their positions on the charts. Similar latitude must also be allowed for the positions of the Red Brook sections relative to Fairbrook.

The Grindslow Shales are particularly well seen in this sub-area. In their lower part they show a Slope Association with thin turbidites in the base and with a large channel, filled with Facies 17, Turbidite-like Sandstones, similar to Walker's (1966a) Facies 'C' Sandstone, and Facies 15, Mudstone Melange, exposed in Blackden Brook. The poorly exposed but apparently rather thick Facies 17, Turbidite-like Sandstones, at level 30 m. in Nether Red Brook, may also possibly sit in a channel. This would explain their otherwise anomalous situation. The lowest evidence of traction currents in the Grindslow Shales seems to occur at about 60-70 m. above their base. This level appears quite constant, especially in the east where exposure is good. Interdistributary Complex Association sediments up to 50 m. thick are developed in the Blackden Brook area. Elsewhere, major channelling removes much of it. This channelling is spread over up to 60 m. of the succession and fine grained units are interbedded with the major channel units. Thin units of the Fluvatile Channel

Association sometimes occur within the relatively finer units between the major channels. The succession between Fairbrook and Stream IId seems relatively free of major channelling but the contrast between Streams IId and IIe is particularly striking, suggesting a steep channel margin between the two sections.

The channel complex within the fault block on the NW corner of the plateau has been positioned on the chart in its suggested true stratigraphical position, based on its height above a lower feature thought to represent the top of the Shale Grit.

Overlying the major channel complexes and Interdistributary Complex horizons at the western end of the plateau is a single set of Facies 12, Large Scale Cross-Bedding. The base of the set is never clearly exposed, though there seems often to be an upwards transition from horizontally lying beds of coarse sandstone. Normally the set is a simple single one, though in Fairbrook there appears to be more horizontally lying trough cross-bedding within the set. It is possible that two sets are present here, though no sign of this is found laterally. Fairbrook also corresponds to the maximum thickness of 40 m. of the large set. To the west it maintains a fairly constant thickness while eastwards, up-current, it

apparently thins. The top 20 m. of beds in Upper Seal Clough are extremely weathered and it is not impossible that they also represent the large scale set. Fine grained horizons on the foreset slopes, internal erosion surfaces and intrasetts are all found within the large scale set, which is overlain by horizontally lying trough cross-bedding. A higher unit of the Fluvial Channel Association occurs at Kinder Downfall.

Sub-Area III: Derwentdale.

This is the largest sub-area, stretching 20 km. from Hathersage in the south to the eastern end of Bleaklow at Derwent Head in the north. Exposure is not good, being mainly confined to edge exposures of small vertical and large lateral extents, on the scarp slopes and small sections in the banks of streams at the foot of the dip slopes. Exceptions to these are the stream sections on the scarp slopes at Abbey Brook, and around Derwent Head (Swains Greave, Barrow Clough and Hoar Clough) and the landslip backscar and quarry exposures of Ladybower Tor and Mouselden Quarry.

Although the full succession from Shale Grit to the 'Gracile' Marine Band occurs through most of the sub-area, at no place is it possible to draw up confidently a complete vertical section. This is largely due to the difficulties

of correlation between scarp slope edges and exposures in streams on the dip slope, sometimes 2-3 km. away. The critical relationships between the tectonic dip, the slope of the dip slope topography and the slope of the stream course control the level of exposure and it is seldom possible to judge these with sufficient accuracy.

A typical example of this problem is shown by the Margery Hill upper feature. It is impossible to be sure whether this represents the lower part of the lowest sandstone unit seen in Ewden Beck, a higher part of the same sandstone or a lower horizon altogether.

The Grindslow Shales are only exposed in Abbey Brook and at the eastern end of Bleaklow. At Bleaklow, the usual coarsening upwards Slope Association sequence is present with an apparent Fluvial Channel Association unit at the 60 m. level in Barrow Clough. In Abbey Brook, the position of the base of the Grindslow Shales is difficult to judge but thin turbidites, overlain by a coarsening upwards siltstone sequence are found below and as lateral equivalents of the large channel in the base of the Cartledge Brook tributary. The channel is filled with sandstone described by Walker (1966b) as Facies 'C' turbidite sandstone, though the present author regards it as intermediate in character between Walker's Facies 'C' and his own Facies 8, Massive Bedded Coarse Sandstone.

The stratigraphical position of the channel, relative to overlying beds, is difficult to judge. A larger gap than is shown on the chart could be accommodated above the level of the top of the channel fill. A persistent feature with no exposure extends from the position of the channel to the south and another channel, with the top of its fill at the same level as that of the large channel is cut into the north bank siltstone sequence of Abbey Brook. The features to the north on Robin Hood Moss are very confusing. Walker (1964) postulated a large E-W fault downthrowing to the north to explain them, but the present author favours a rapid thinning southwards of higher sandstone horizons, possibly passing into thick siltstone lateral equivalents. This transition could possibly be due to the lateral or down-dip limit of a complex of delta cones, such as are known to exist in Ewden Beck and are probably present at Crowstones Edge.

Exposures of the lower part of the coarse sandstones of the Kinderscout Grit are rare. Ladybower Tor and very poor exposures in Barrow and Hoar Cloughs suggest major channels, though the sandstone at 60 m. in Barrow Clough is possibly a Fluvial Channel Association Sandstone.

High dips in Hoar Clough and at Crowstones Edge point to the presence of Large Scale Cross-Bedding which is more clearly

exposed at Derwent Edge and Bamford Edge. The Derwent Edge exposure of Dovestone Tor is very rich in intrasets while Bamford Edge shows the 'en echelon' arrangement of sets described in Chapter 4. This horizon of Large Scale Cross-Bedding seems to die out in a down-current direction at Bole Hill.

In the north, the horizon of Large Scale Cross-Bedding is overlain first by a thick fine grained horizon shown by the extensive negative feature above Shepherd's Meeting Stones and Crowstones Edge. This is overlain by two units of the Fluvial Channel Association which form the Outer Edge-Dean Head Stones feature and the unnamed feature behind. These die out to the south until, at Strines, the Butterley Marine Band is only just above the top of the Large Scale Cross-Bedding Association unit. How these intermediate sandstone units die out is not clear because of the difficulty of tracing them across the Cut Gate Fault Zone.

At Agden and Strines, a well developed Slope Association unit at least 20 m. thick underlies the topmost sandstone which forms a mappable feature throughout the whole sub-area. The top of this Upper Kinderscout Grit Sandstone has a seat earth and coal where it is exposed and this passes into the 'Gracile' Marine Band within 2 m. at Laund Clough and within 25 cm. at Strines.

Sub-Area IV: South Longendale.

The sub-area extends E-W for about 8 km. from Glossop Low Quarries in the west to Far Black Clough in the east, along the northern 'edge' of the Bleaklow Plateau. At the eastern end, the sub-area is within the Bleaklow Fracture Zone and correlation is difficult. Because of this, sections J, K and L will be considered separately from the rest of the sub-area.

The main part of the sub-area, west of the bottom of the Black Cloughs, exposes the lower part of the sequence, the Grindslow Shales and the lower part of the Kinderscout Grit. Extensive exposures of Slope Association siltstones and silty sandstones are found in the lower parts of Torside and Shining Cloughs, though no certain base to the Grindslow Shales can be located. The turbidites in the base of the Torside Clough section are very poorly exposed and could belong to the Shale Grit or the lower part of the Grindslow Shales. At least 80 m. of Slope Association sediments appear to be present in the two cloughs. Interdistributary Complex Association sediments in the Bottom of Black Cloughs and the upper part of Smithy Clough appear, on mapping evidence, to be at the level of the upper part of the Grindslow Shales but complete certainty cannot be placed on this correlation, particularly in the case of the Black Cloughs section because of the incompletely understood

pattern of faulting. In the west of the sub-area, the Slope Association is eroded into by major channel complexes, again interbedded with Interdistributary Complex Association units. In the east, Interdistributary Complex Association sediments of the top of the Grindslow Shales appear to be eroded by a Fluvatile Channel Association unit.

Above the major channelling, which extends over a vertical range of some 70 m., the succession passes upwards into a Large Scale Cross-Bedded set which extends along the feature for some 4.5 km.. The set is between 15 and 21 m. thick and is overlain by horizontally lying, trough cross-bedded sandstone. The succession, therefore, resembles very closely that found in Sub-Areas I and II.

Above the trough cross-bedding, in West Torside section, there is a much thicker unit of Interdistributary Complex Association than that found in this stratigraphical position on the Kinderscout Plateau. The precise relationship between the top of the West Torside section and that found at Glossop Low Quarries is not known with any certainty, though a suggested correlation is given on the chart. There may well be room for a greater thickness between the top of the West Torside section and the base of the Glossop Low exposure.

The suggested correlation of the lower section in Smithy

Clough with the section at Glossop Low or in the top of West Torside is tentative and based largely on a knowledge of the succession in Sub-Area V, with which the Smithy Clough exposure is more naturally associated.

The small sections J, K and L in Near and Far Black Cloughs are separated from the rest of the sub-area by a fault, down-throwing south, in the bottom of Near Black Clough. The precise stratigraphical position of the beds involved is not known. The sediments are mainly Fluvial Channel Association, though the presence of a relatively thin example of a Large Scale Cross-Bedded set in Near Black Clough suggests a possible correlation with the upper parts of the sections in the western part of the sub-area. The position of these beds can, however, be best discussed after describing the succession from Sub-Area V, the section which relates the sequences of the sub-areas.

Sub-Area V: North Longendale.

The sub-area extends a distance of 9 km. from Crowden Great Brook in the west to Salter's Brook in the east. Long stream sections are augmented by several quarry exposures and correlation is helped by clearly developed topographic features. With the exception of Withens Brook, the area is free of important faults, though the Crowden Fault separates the sub-

area from Sub-Area IV.

The exposed rocks are referable almost entirely to the Kinderscout Grit. The 'Gracile' Marine Band is found at two localities and a prominent feature below it is traceable over the whole area. The Butterley Marine Band is present in Meadow Clough and is associated with a mappable fine grained horizon. Below these two well defined horizons, the succession is complex and open to some variety of interpretation.

In the bases of the sections in Crowden Great Brook, major channel complexes are found, cut into the Intertributary Complex Association sediments, tentatively ascribed to the top of the Grindslow Shales. Immediately below this is an 11 m. unit of Facies 17, Turbidite-like Sandstones, looking like Walker's (1966a) Facies 'C' Sandstones and including a large internal channel. The presence of such sediment within such a small distance of the Major Channel Association sediments is not readily explicable.

Above the channel fills in Crowden Great Brook is a confused horizon of Large Scale Cross-Bedding Association which appears to have several internal erosion surfaces. A similar Large Scale set is seen in Crowden Little Brook at a similar horizon. The poor exposure and the closeness of the tectonic dip to the slope of the stream bed make the determination of

set thickness rather difficult. Below the Large Scale Cross-Bedding in Crowden Little Brook, there is no evidence of Major Channelling on the scale of Crowden Great Brook. The succession in the lower part of Hey Clough contrasts strongly with that seen in the Crowden Brooks. A coarsening upwards sequence of siltstones occur, which, out of context, would be compared with the Grindslow Shales. The sequence would seem on the basis of correlation at the top of the unit to be the equivalent in its lower part to the Large-Scale set seen to the west. Indeed the direction of foreset dip, seen in the set in Crowden Little Brook, is directed exactly towards the lower part of Hey Clough, suggesting that the advance of the delta cone was halted between the two sections and that fine grained sediment then filled the body of standing water by falling largely from suspension. If this is the case, the feature mapped between the sections probably represents the top surface of the abandoned delta cone.

The succession at Brockholes Quarry does not, however, add to the clarity of the situation. The quarry itself appears to have sediments most readily referable to Major Channel fills, though no lower erosion surface is seen and the upper part of the exposure is very weathered. This upper part and the gap above, to the top of the feature, could well include a large

Scale Cross-Bedded set.

The turbidite-like sandstones in the base of Hey Clough and in Enterclough Quarry present a similar problem to those seen in the base of Crowden Great Brook. There is evidence in the sections of the Woodhead Reservoir Dam of an erosive contact between siltstones and overlying coarse sandstones, 60 m. below the top of the feature. This may be part of the same channel complex as that supposed to be present at Brockholes Quarry. The turbidite-like sandstones in the base of Hey Clough may then represent the final phase of filling of a major channel.

Above the Large Scale Cross-Bedding Association and the coarsening upwards siltstone sequence in the three main western stream sections is a thick sequence of the Intertributary Complex Association. This appears to be represented in Oaksike Clough by several units of the Fluvial Channel Association. There was probably a margin to a meander belt between Hey Clough and Oaksike Clough at this level.

The relatively thin unit of Large Scale Cross-Bedding at level 50 m. in Oaksike Clough seems to be at a different level to the units of this facies in the west and may be at the same level as the set seen at Woodhead Tunnel.

With the exceptions of these two sets and the major channel

in Heyden Brook, the succession between the top of the thick, fine grained unit and the Butterley Marine Band is one of interbedded Fluvial Channel and Interdistributary Complex Association units. Lateral variation is intense, no channel units being correlatable between adjacent sections with certainty. This points to a complex pattern of migrating streams possibly frequently changing course by a process of cut-off. Several of the thicker sandstone units contain several erosional surfaces.

The fine grained horizon, associated with the Butterley Marine Band is laterally extensive but does not coarsen upwards as in parts of Sub-Area III.

The sandstones of the Upper Kinderscout Grit appear to be of the Fluvial Channel Association. The 'Gracile' Marine Band is separated from the top of the highest sandstone unit by 13 m. of fine siltstones in Crowden Great Brook, though this is reduced to about 8 m. of coarser siltstone and rippled sandstones at Heyden Brook.

Relationships between Sub-Areas.

Sub-Areas I and II.

The relationships between the successions present in these two sub-areas is relatively simple as features and

limited exposure link them. The same stratigraphical sequence is found in each sub-area, involving very similar patterns of sedimentation. The coarsening upwards Slope Association and the overlying Interdistributary Complex Association of the Grindslow Shales are cut into by Major Channels over a similar range of beds. It is possible, from a comparison of the positions and palaeocurrents of the channel complexes, to suggest the equivalence of the Grindsbrook, Upper Tor and Nether Tor complexes with the complexes found around the head of Blackden Brook. Similarly, the channels in Crowden Brook may be related to those in Seal Edge. The Large Scale Cross-Bedding Association which occurs at the western ends of both sub-areas is undoubtedly the same horizon as it is mappable along the western end of the plateau. That is not to say that only one Large Scale set is present but rather that one tabular unit, built up of interfering delta cones, is found at the same level over the whole of the western end of the plateau, with foresets dipping to the west and south-west.

Sub-Areas I, II and III.

Sub-Areas I and II are separated from the nearest exposures of Sub-Area III by a gap of 5 km.. The suggested lower Major Channel unit at Ladybower Tor and the higher Large Scale Cross-Bedding of Mouselden Quarry and Derwent and Bamford Edges

suggest that a similar succession to that found on the Kinderscout Plateau may be present in the south of Sub-Area III. The apparent confinement of the Large Scale Cross-Bedding to one horizon and its position, just below the Butterley Marine Band in the south of Sub-Area III, suggests that the Butterley Marine Band is only just eroded from the top of the Kinderscout Plateau.

Sub-Areas IV and V.

These sub-areas are separated topographically by the Longendale Valley and geologically by the Crowden Fault. Essentially different parts of the succession are exposed in the two sub-areas, the lower part of the sequence in Sub-Area IV and the upper part in Sub-Area V. There would appear, however, to be a considerable overlap. The Major Channel horizons of Sub-Area IV and the overlying Large Scale Cross-Bedding can probably be equated with the similar though thinner sequence in the lower parts of the Crowden Brooks. To say that this part of the sequence is thinner in Sub-Area V may in fact be misleading, as the possibility of a lower channel must not be discounted, particularly in the light of the apparent channelling in the reservoir section. If this correlation is correct, the thick, fine grained horizon at the top of the West Torside section and at Glossop Low Quarries finds an

equivalent in the fine grained unit in the Crowden and Hey Cloughs.

At the eastern end of the two sub-areas, correlation is less certain. The Bleaklow Fault Zone makes correlation within Sub-Area IV difficult enough and the Crowden Fault adds to the problems of correlation outside the sub-area. However, the presence of a 12 m. thick Large Scale set in Near Black Clough and a 10 m. one at Woodhead Tunnel suggests a possible correlation. This would imply that the set in Near Black Clough is stratigraphically higher than the set to the west, in Torside and Shining Cloughs.

Sub-Areas III, IV and V.

The lower part of the sequence, in the north of Sub-Area III, as seen in Barrow Clough and Swains Greave, shows a similarity with the succession at the western end of Bleaklow in Sub-Area IV. There appears to be some channelling, though exposure is poor, and in Hoar Clough and possibly at Crowstones Edge, Large Scale Cross-Bedding is present above the channelling. This pattern fits well with that at the western end of Bleaklow. Above this horizon, a thick unit of fine grained sediment seen at the top of the West Torside section and at the western end of Sub-Area V, appears to be present in northern Derwentdale in the extensive negative feature behind Shepherds Meeting

stones and Crowstones Edge. The Fluvistile Channel Association sandstones, so well developed in the upper parts of the Lower Kinderscout Grit of Sub-Area V, appear to continue into the northern part of Derwentdale to give features such as Dean Head Stones and Outer Edge and the minor feature behind them.

The Upper Kinderscout Grit also continues from sub-areas V to III. The reduction in the thickness of sediment between the top of the topmost sandstone and the 'Gracile' Marine Band continues southwards until at Shrines, the marine band is only about 25 cm. above the coal horizon at the top of the sandstone, compared with the 13 m. found at Crowden Great Brook.

Regional History of Sedimentation.

From the sequences found in the various sub-areas and their mutual relationships, it is possible to attempt a reconstruction of the history of sedimentation of the area.

After the deposition of the proximal turbidites of the Shale Grit in fairly deep water, turbidity currents gradually ceased to be the main agents of sediment transport in the basin and the Slope Association of the lower part of the Grindslow Shales was deposited, mainly from suspension, on a prograding slope below wave base. The only exceptions to this method of deposition were the currents flowing in the large channels cut

into the slope, which, from the similarity of their deposits to Walker's Facies 'C' Sandstone, would appear to have many of the characteristics of turbidity currents. The Inter-distributary Complex Association at the top of the Grindslow Shales confirms the shallowing suggested by the coarsening upwards of the Slope Association. The presence of both major and smaller channels within this upper part of the Grindslow Shales suggests that the slope involved is in fact the main delta slope of the prograding coastline. The major channels, whose currents are thought to have frequently developed very high flow regimes, are not confined to a one discrete horizon but are dispersed over a some 60-70 m. of the succession. At the western end of Bleaklow channelling of this type extends down to the slope while in other areas, the fills of channels at this level appear to be intermediate in type between Facies 8, Massive Bedded Sandstones and Facies 'C' Sandstones (Walker, 1966a) found in lower channels and in the Shale Grit.

The irregularity of the development of the major channels contrasts strongly with the widespread nature of the overlying unit of delta cone development, which, with the thin exceptions at the eastern end of Longendale, appears to be everywhere at the same horizon. That delta cones should be so widespread at one horizon suggests an unusual event in the basin's history,

which is best explained by a sudden deepening of the basinal water. The underlying causes behind the deepening and the major channelling will be discussed in Chapter 6. When the delta cones had aggraded the depositional surface to relative equilibrium, meandering fluvial channels and interdistributary areas were developed to give a 70 m. succession in the north of the area. These units thin to the south and reduce to zero in the vicinity of Strines. This thinning is probably related to different rates of subsidence in the basin and possibly to the fact that the advance to the south of the delta cones enabled some fluvial channel and interdistributary sediments to accumulate as 'Topset' deposits to the north.

The Butterley Marine Band, which overlies these beds, is not well developed in the area, suggesting that any basinal control was not very important. The horizon certainly does not appear to represent a major transgression and the development of the marine band and its Slope Association was probably controlled by local details of palaeogeography combined with minor transgression.

The topmost sandstone, referable to the Upper Kinderscout Grit, is very widespread in its development, being mapped as a continuous feature over the whole area. It extends southwards, beyond the dying out of the Lower Kinderscout Grit at Bole Hill above Bamford.

CHAPTER 6. PALAEOGEOGRAPHY AND CONTROLS OF SEDIMENTATION.

Introduction.

In Chapters 4 and 5, environmental interpretations and relationships of facies associations have been discussed. In this chapter, it is hoped to discuss the factors which may have controlled sedimentation, to compare the succession studied with other parts of the Central Pennine Basin and to reconstruct the regional palaeogeography.

Grindslow Shales.

The Grindslow Shales have already been interpreted as the prograding slope of a delta or other type of coastline. As the coarser sandstones immediately above and at the top of the unit are confined to channels which are thought to be fluvial in nature, a delta is to be favoured (Visher, 1965a). Palaeocurrents within the Shale Grit and Grindslow Shales (Walker, 1966a), and within the overlying Kinderscout Grit, indicate that the dominant flow was from the north and north-east, suggesting that deltaic advance was also from that direction. The Interdistributary Complex Association, even from its lowest level within the Grindslow Shales, shows evidence in its small channels of very shallow conditions, probably of the order of

only a few meters depth, and possibly with subaerially exposed banks to the channels. If the base of the Interdistributary Complex Association in the Grindslow Shales was, therefore, deposited very close to basin level, then the highest turbidites of the Shale Grit could not have been deposited in water deeper than 60-70 m., the common thickness of the Slope Association. This depth can be increased somewhat by the application of a compaction factor. Jones (1942) estimated a compaction factor of 60% for the Edale Shales but, because of the coarser grain size and higher stratigraphical level of the Grindslow Shales, compared with the Edale Shales, it is probable that the compaction in the Grindslow Shales was less, possibly of the order of 25%, giving therefore a depth of 80-90 m..

For reasons which will become apparent, it is thought best to postpone discussion of the Major Channels until after a discussion of the Delta Cone horizon.

Delta Cones.

The advance of delta cones into a body of standing water to give the widespread development of an apparently single horizon of Large Scale Cross-Bedding represents a regression which contrasts strongly with that of the Grindslow Shales. The sediment is much coarser and was deposited by traction currents and avalanching, as opposed to the finer material's

falling from suspension. Only in those areas into which delta cones did not advance are coarsening upwards siltstone units found at their horizon (e.g. Hey Clough). Palaeocurrents indicate that the advance of the delta cones, though locally variable in direction, was also predominantly from the north and north-east.

The fact that the sediment below the delta cones shows evidence of extreme shallowness, whilst the cones themselves demand up to 40 m. deep water, suggests that a deepening took place. That this deepening was sudden is suggested by two facts. First, the absence, below the cones, of any sediment deposited during the deepening and second, the formation of a cross-bedded sedimentation unit in preference to some form of slower aggradation.

The controls behind the sudden deepening could be of two types:-

- 1) Cut-off and diversion of the major rivers feeding the delta at some point upstream, combined with normal basinal subsidence could give deepening. As the delta cones can be recognised as far north as Hebden Bridge, the diversion would have to have been on a very large scale, of the order, possibly, of hundreds of kilometers. One disadvantage of this mechanism is that, if cut-off on this scale did occur, it is highly

unlikely that supply would be resumed before the accumulation of at least some fine grained material below the delta cones.

2) An absolute rise in basin level, combined with the normal basin subsidence, would give a very rapid deepening, as the two factors operate in opposite directions and emphasise one another. Sedimentation, which might be expected to counterbalance the deepening, would, under conditions of rapid rise, be initially ponded up, at some point nearer the source, at the upstream limit of the delta cones. Continuation of the high rate of sediment input, which was clearly going on during the Major Channel phase, could then continue at a similar rate, as it was probably related to the climate, tectonics and topography of the source area. There would then be little time for the accumulation of a fine grained horizon below the delta cones. Such a rise in basin level is, therefore, to be tentatively favoured. Whether this rise was a eustatic rise in sea level, or something confined to the basin is more difficult to establish. In the light of the marine fossil in the Shale Grit and in the base of the equivalents of the Grināslow Shales to the north, it is difficult to see how, by the time of the formation of the delta cones, the basin could have become so isolated from the sea as to be able to undergo changes in level of the order of tens of meters, independently of marine control.

A eustatic rise in sea level would, therefore, seem best to fit the facts known about the formation of the delta cones. Before any definite commitment to this mechanism can be made, its implications for other parts of the sequence must be discussed and supporting evidence searched for in other parts of the basin.

Major Channels.

In the discussion of the Major Channel Association in Chapter 4, three possible controls underlying their development were suggested. These were:-

- 1) Diversions of a large scale river, either suddenly or gradually, followed by cutting off of its supply.
- 2) Climatic changes, giving greatly increased run-off, which subsequently waned.
- 3) Relative fall and subsequent rise in the basin level, giving an increased slope and therefore erosion, followed by aggradation.

These will be discussed in turn.

1) Cut-off and diversion explains quite well the occurrence of multiple major channels throughout a stratigraphical column, greater in thickness than the depth of individual channels. Most of the major channels are cut into Interdistributary

Complex Association sediment. Even though the lowest channel erosion surfaces in Sub-Area IV, South Longendale, are cut into Slope Association sediments, it is quite likely that Interdistributary Complex Association sediments were being deposited at the sediment surface, prior to the erosion, which cut down into the Slope Association.

As channels always have fills of coarse sediment, commonly showing evidence of a waning flow regime, it seems likely that diversions were rather gradual, or otherwise fine grained channel fills might be expected in cases where cut-off had been sudden and complete.

The factors most likely to have controlled the cut-off and diversion of rivers are subsidence and sedimentation. The scale of diversion envisaged for the multiple cutting and filling of channels is relatively local. Areas furthest from the distributary channels would receive less sediment by over-bank flooding and consequently undergo deepening. At some critical stage, probably during flood, a distributary would be diverted into this area, and, because of the higher energy gradient, would tend to remain there and develop at the expense of the original distributary. The process would then repeat itself when subsidence had had sufficient time to set up new conditions of disequilibrium.

2) It is clear that the rainfall in the source area must have been considerable throughout the whole of the zone, in order to maintain the high rate of sediment input into the basin. The rainfall need not have fluctuated greatly, except perhaps on a seasonal basis, giving floods, overbank sedimentation and possibly causing the striping of the Facies 3, Striped Siltstones. As the high rate of sediment input continues above the horizon of the Major Channels, with the formation of delta cones, it seems that climatic changes have little to recommend them as actual controlling factors for the cutting and filling of channels.

3) In the light of the control which may be exercised by the process of river cut-off and diversion, there seems, at first, little reason for invoking any changes in basin level to explain the Major Channels. The vertical extent of channel complexes and the shallow water nature of the sediments into which they are cut, dispense with Walker's (1966a) need for a eustatic fall of sea level to give the widespread erosion at the base of the Kinderscout Grit. The actual relationships of the channels can be adequately explained in terms of a simple regressive sequence, starting at the top of the Edle Shales, with distributary migration on the delta top. Other factors, however, suggest that some basin level changes may have taken

place. One of these is the sudden deepening, probably due to a eustatic rise of sea level, related to the formation of delta cones. If a eustatic rise did take place, particularly a glacially controlled one, it is not unreasonable that it should have been preceded by a eustatic lowering. This, if it was taking place at a rate similar to that of basinal subsidence, would help to maintain a high slope and thereby favour the development of the high flow regimes which are thought to have occurred in the Major Channels.

Subsequent eustatic rise may then have been responsible for the final filling of the uppermost channels as well as for the initiation of the overlying delta cones.

The pattern of sedimentation, therefore, during the phase of Major Channel development, was of large, non-migrating channels cutting across a delta top area of very shallow water and mainly fine grained sedimentation. The channels were frequently cut off and diverted and developed high flow regimes at times of flood. The phase was possibly also associated with a eustatically falling sea level, which was roughly keeping pace with the basinal subsidence.

Lower Kinderscout Grit above the Delta Cone Horizon.

Between the top of the delta cone horizon and the Butterley

Marine Band, there is the horizon of greatest lateral thickness variation in the area studied. The thick sequence of Fluvial Channel Association sandstones and Interdistributary Complex Association sediments of Sub-Area V, North Longendale, thin virtually to zero over a horizontal distance of some 16 km.. The thinning is roughly parallel to the depositional strike and so it seems that local inhomogeneity of basinal subsidence is a more likely control of sedimentation than a control related to proximity of the area to source.

Butterley Marine Band.

Though the Butterley Marine Band is only sporadically developed in the area studied, it has been recognised as far north as Wharfedale, where it is known as the Eccup Marine Band. The widespread development suggests that the transgression was extensive, perhaps related to a further eustatic rise of sea level. The sporadic nature of the development may be due to the rise being only of small amplitude, making it unable to overcome the aggradation due to sediment input, except in areas such as Strines, which must have been relatively isolated from sediment supply.

Upper Kinderscout Grit.

A coarsening upwards sequence overlies the Butterley Marine Band, when it occurs, and this is then overlain by fluviatile channel sandstones of widespread distribution, the overall pattern conforming to the 'normal paralic cycle' of Reading (1965). The fluviatile channel deposits appear to have been laid down in laterally migrating rivers, suggesting that there was no longer great irregularity in depth of deposition. The overlying 'Gracile' Marine Band is extremely widespread in distribution and if this was due to a eustatic rise, as seems likely, it is immediately tempting to look for manifestations of a preceding sea level lowering. In the Upper Kinderscout Grit, recognition of these is difficult. The only possible evidence is the apparent limitation and relative constancy of thickness of the Upper Kinderscout Grit, which possibly suggests that subsidence was being counteracted by some other factor, which was probably sedimentation but could have possibly been a falling sea level. However, if this was the case, no other evidence is seen. No high flow regime deposits are recognised, though long term climatic changes relative to the Lower Kinderscout Grit could have taken place, rendering high flow regime floods unlikely.

The Succession outside the Area Studied.

The chief aim in studying the succession in other parts of the Central Pennine Basin is to see if any more evidence can be found for possible controls of sedimentation, eustatic changes in particular, and to obtain a wider picture of the basinal palaeogeography and evolution. Correlation has, in the past, been somewhat confused, though recently a chart produced by Ramsbottom (1966) has provided a useful summary of the present state of knowledge. More detailed correlation within this broad framework is less certain. Figure 50 shows suggested correlations and facies relationships. This is based on Ramsbottom's chart and on maps and memoirs of the Geological Survey.

On the basis of the palaeontology and mapping, there seems good evidence for the time-equivalence of the Shale Grit, the Todmorden Grit, the Parsonage Sandstone and the Crley Crag Grit. Within this time interval, there appears to have been some facies variations. The Shale Grit and Todmorden Grit of the Todmorden area are thought to be turbidite sandstone units (Walker, 1964). The Todmorden Grit at Hebden Bridge is reported to be cross-bedded (Wright et al., 1930, p. 26). The Parsonage Sandstone is reported to look very much like the Shale Grit (Reading, pers. comm.) and is therefore thought to also be a

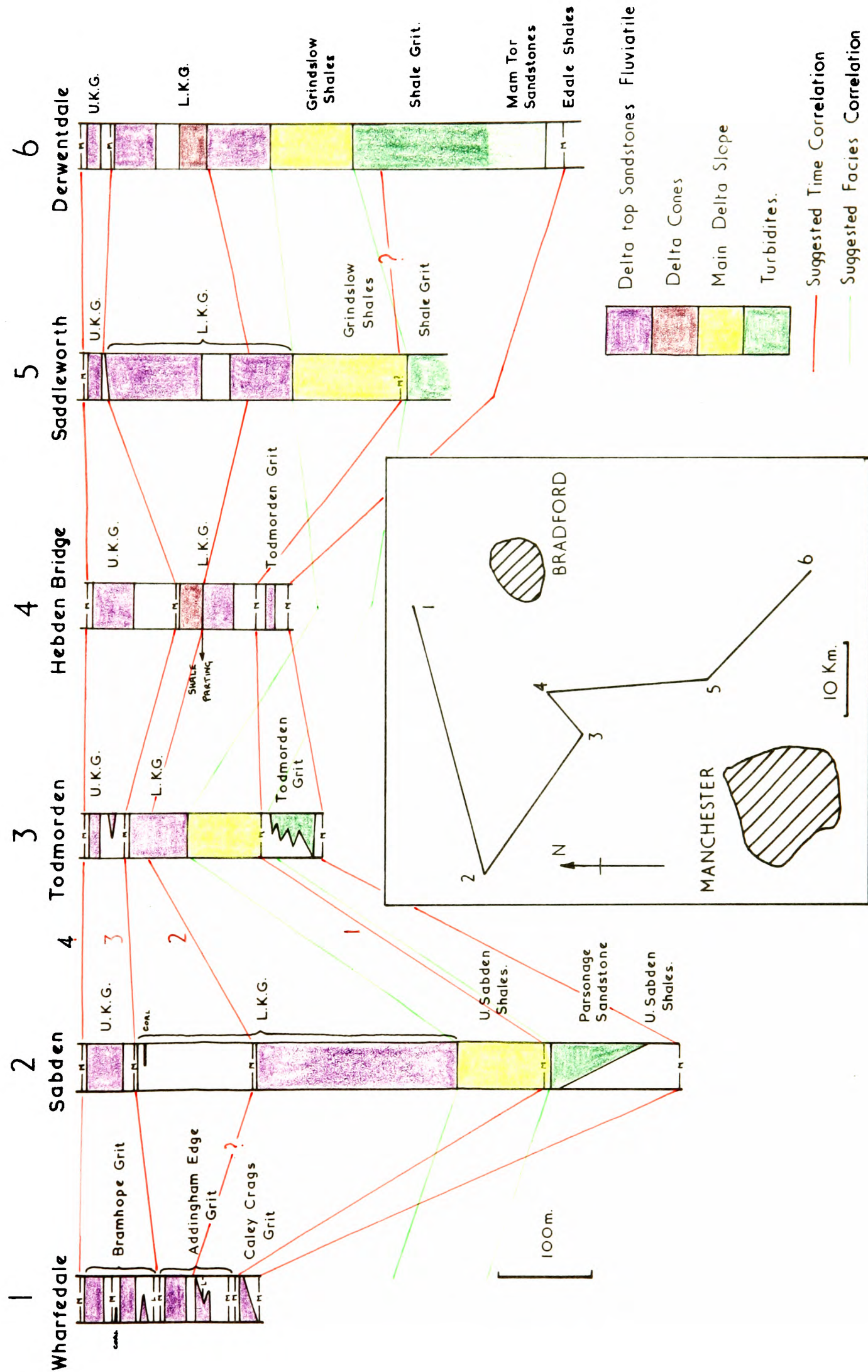


FIGURE 50.

turbidite formation. The Caley Crags Grit is cross-bedded (Walker, 1955) and is attributed to a fluviatile environment. If the time equivalence and facies interpretation of these beds are accepted, it then becomes possible to suggest the position of the main delta front at this time, (Fig. 51 A). In the central area the slope must have been between Hebden Bridge and Todmorden, while in the north-west, it was between Sabden, where the Parsonage Sandstone dies out, and Wharfedale. Between Hebden Bridge and Todmorden, there is no exposure for reasons of structure and erosive level. Between Sabden and Wharfedale, the Parsonage Sandstone appears to pass into a thick, fine grained unit in a north-easterly direction. It is tentatively suggested that this fine grained unit may represent a slope comparable with the Grindslow Shales.

The slope reached further south and west at a later time, to give the Grindslow Shales and the Upper Sabden Shales above the Shale Grit and the Parsonage Sandstone respectively, (Fig. 51 B & D).

The Lower Kinderscout Grit shows considerable variation. Its top is fairly clearly defined by the Butterley-Eccup Marine Band. It reaches its maximum thickness in the region of Sabden, where a marine band is found within it. This bed has been correlated with a mudstone bed with crushed bivalves, found in

the upper part of the Worth Valley (Earp et al., 1961, p. 110). At Hebden Bridge, the Lower Kinderscout Grit has a variably developed siltstone parting (Wray et al., 1930, p. 27) and the present author has observed Large Scale Cross-Bedding on a scale comparable with that found in the south. It is quite likely that the siltstone parting is at a level very close to the base of the Large Scale Cross-Bedded set. Large Scale Cross-Bedding has also been observed in the Lower Kinderscout Grit near Rishworth, some 9 km. to the south of Hebden Bridge, and it is suggested that the development of this structure can be correlated with the similar development seen in the main thesis area. Correlation of the base of the delta cones with the siltstone parting of Hebden Bridge and the marine band at Sabden is also suggested, fitting with the suggestion of a eustatic rise of sea level in mid-Lower Kinderscout Grit times (Fig. 51 C). The situation in Wharfedale is somewhat confused. The Addingham Edge Grit is shown on the column of the Geological Survey Map (Sheet 69) to have two sandstone members with finer grained sediments between them. These cannot be fitted easily with the map itself or with the sections shown in the Memoir (Stephens et al., 1953). There seems no reason why the fine grained parting between the two members of the Addingham Edge Grit should not be a manifestation of the eustatic rise in sea

level, suggested here to explain the succession to the south.

The correlation of the Upper Kinderscout Grit with the Bramhope Grits of Wharfedale seems well established both on the presence of the 'Gracile' Marine Band above and the Eccup-Butterley Marine Band below.

There is, therefore, no evidence in the northern part of the Central Pennine Basin to oppose the idea of a eustatic rise of sea level during the deposition of the Lower Kinderscout Grit and, in fact, considerable evidence to support it.

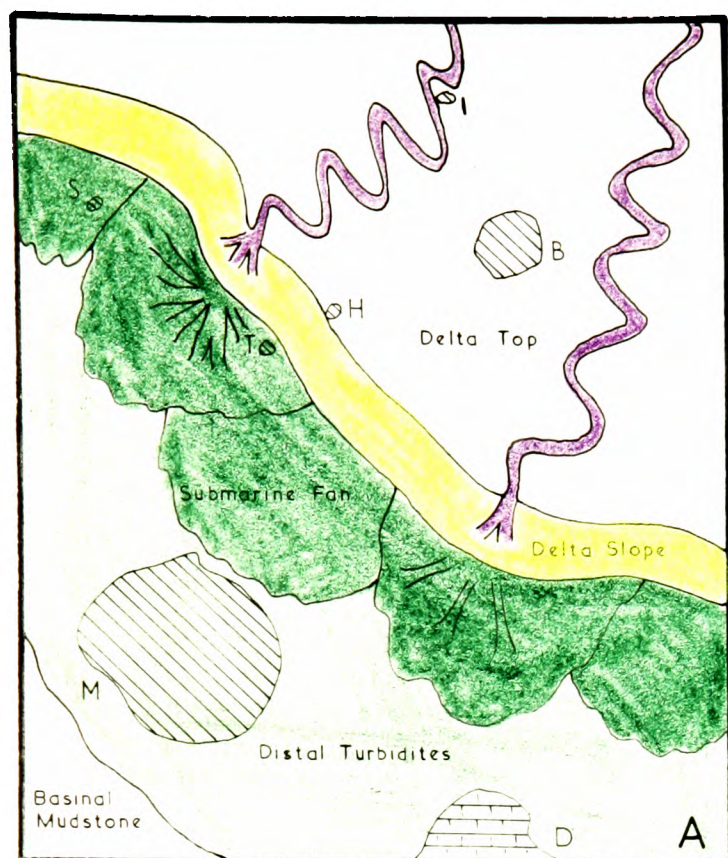
Eustatic rises are also suggested to explain the Eccup-Butterley and 'Gracile' Marine Bands and the occurrence of marine fossils above the Todmorden Grit, particularly as this is thought to be fluviatile at Hebden Bridge, suggests the possibility of yet another eustatic rise, probably of minor importance at this horizon.

The other implications of eustatic changes for the basinal history and for the problem of turbidity current genesis are discussed below.

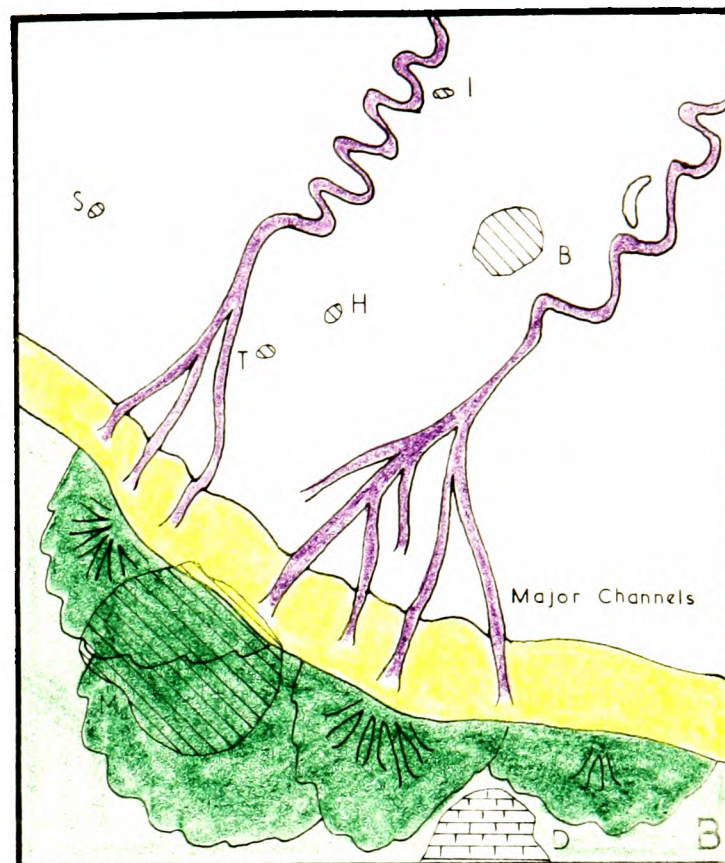
Implications of Eustatic Changes.

Four possible eustatic rises of sea level could have occurred between the beginning of the deposition of the Mam Tor Sandstones and the end of the deposition of the Kinderscout

Maps and Sections of Suggested Palaeogeographies.



End of Toadmore Grit Deposition
Pre-Eustatic Rise

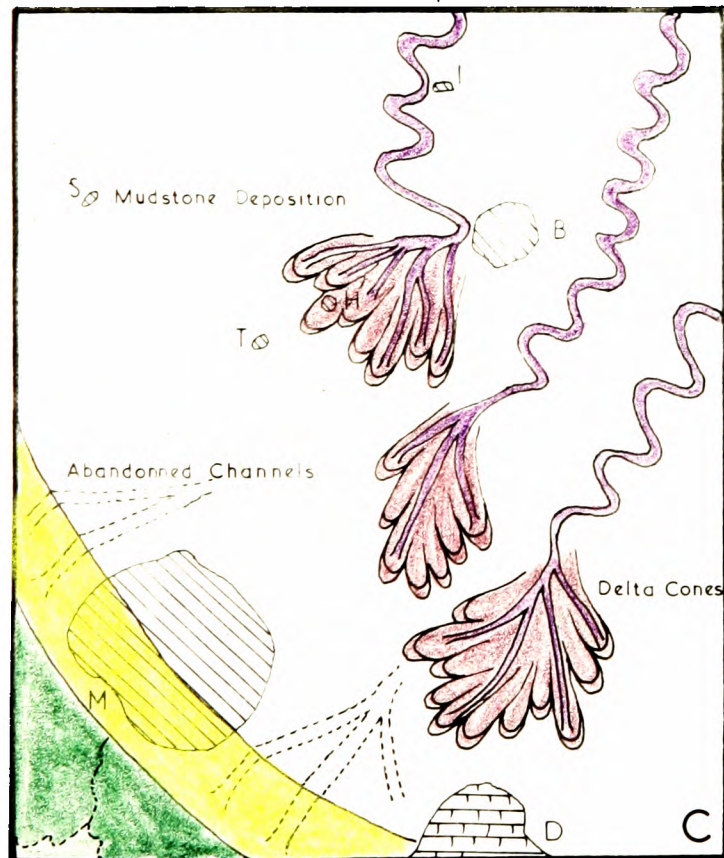


Grindslow Shales and Base of Kinderscout Grit
During Eustatic Lowering

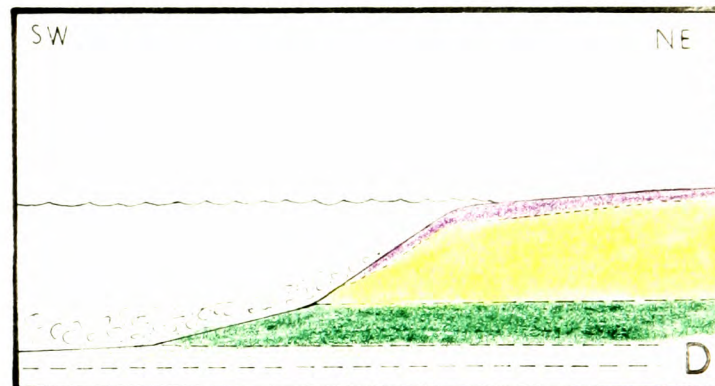
LOCALITY KEY: I, Ilkley, Wharfedale
S, Subden
B, Bradford
T, Todmorden



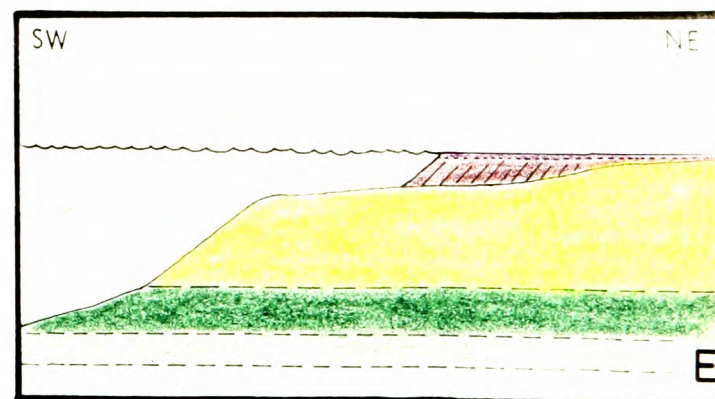
Towns



Upper Part of Lower Kinderscout Grit
During Eustatic Rise



Section of Map B



Section of Map C

Grit, with the possibility of eustatic lowerings between each one.

The rises are:-

- 4) 'Gracile' Marine Band.
- 3) Butterley-Eccup Marine Band.
- 2) Mid-Lower Minlonscout Grit Marine Band (at Salfen).
- 1) Post-Rodmorden Grit Marine Band.

Eustatic rises of sea level have two principle influences on the pattern of sedimentation at any point. The first is to deepen the water and the second is to pond up the incoming sediment at some point nearer the source area. If the second influence operated effectively, it would help in the accentuation of the first by inhibiting aggradation. Conversely, a lowering of sea level tends to shallow the basin and, by increasing the slope, to encourage a large influx of sediment and the forward building of the coastline. It is suggested that the succession described in this thesis illustrates these influences rather well.

The highest marine band, 'Gracile', only shows itself as a deepening, though how deep is not known. This process was probably accentuated by the ponding up of sediment nearer the source, possibly some hundreds of kilometers away. The Butterley Marine Band probably did not have as large an amplitude to its eustatic rise and therefore did not manage

everywhere to overcome aggradation by the incoming sediment.

The mid-Lower Kinderscout rise illustrates, in the thesis area, one of the ways in which sediment might be ponded up on the delta top, by the formation of delta cones (Fig. 51 C & E). This prevents sediment from reaching the edge of the main delta slope, further to the south and west. In the Babden area, the rise resulted in a marine mudstone, the difference between this succession and that of the thesis area being probably due to the sediment dispersal pattern at the time. A suggested palaeogeography is illustrated in Figure 51 C.

The preceding period of supposed eustatic lowering gave rise to the development of major channels and probably, to some extent, to the main southwards movement of the main delta slope of the Grindslow Shales (Figs. 51 B & D). How much of the Grindslow Shales was deposited during a falling stage of sea level, and how much during any preceding standstill is debatable. If the suggested mechanism for turbidity current genesis, set out below, is correct, then it is likely that quite a large part of the Grindslow Shales was laid down during a period of falling sea level.

The suggested eustatic rise, which manifests itself in the north as a marine band above the Todmorden Grit, the Parsonage Sandstone and the Caley Crag Grit may be responsible,

by its ponding up effect, for stopping turbidity current genesis in the north. The fact that no marine band is found at the base of the Grindslow Shales in the thesis area may be due to the fact that the upper parts of the Shale Grit were deposited during the second phase of delta advance, when the main slope advanced from its position between Hebden Bridge and Todmorden to some position to the south and west of the limits of outcrop. In the absence of any clear marine band in the upper part of the Shale Grit, this theory cannot be confirmed. The occurrence of Promytilus in the upper part of the Shale Grit (Walker, 1966a) may possibly indicate this event.

Turbidity Current Genesis in the Central Pennine Basin.

Walker did not discuss in any detail the question of the genesis of the turbidity currents, which he thought to have deposited the Shale Grit. He did, however, seem to assume that they were the result of resedimentation of material which was initially deposited on the 'delta platform'. He suggested that some turbidity currents, at least, developed as slumps on the upper parts of the main slope, though he recognised the drawbacks of this hypothesis in the scarcity of observable slump beds and the absence of anything which could be recognised as a slump scar.

As has been noted earlier, there is an apparent transition between the fills of large channels in the lower part of the Grindslow Shales and those in the base of the Kinderscout Grit. The channels in the lower part of the Grindslow Shales are filled with Walker's Facies 'C' Sandstone, while those in the top of the unit are filled largely with Facies 8, Massive Bedded Coarse Sandstone. Upwards through the Grindslow Shales, therefore, the channel fills show a decrease in the grain size, both of sand and of siltstone clasts, an increase in matrix content, a less well developed bedding and a decreasing occurrence of siltstone or mudstone partings. The apparently transitional nature of these changes suggests a more likely mechanism of turbidity current genesis. High flow regime traction currents, flowing in the major channels on the delta top could, if heavily laden with suspended sediment, possibly change into high speed turbidity currents at the top of the delta slope (Fig. 51 D). The currents, cutting into the fine grained sediment of the channel walls, would enrich themselves in the finer grain sizes at the expense of the coarser sediment, which would be preferentially deposited. As the turbidity currents would only operate at time of flood, finer material could then settle from suspension during dry periods. There would also be less likelihood of wholesale erosion of earlier

sediment by each flood at the lower levels, compared with what might be expected in the fluviatile channels on the delta top. Density currents might be expected to have less erosive power than the fluviatile traction currents and also the presence of fine grained sediment on the depositional surfaces of the lower channels might also increase the resistance to erosion.

This theory of turbidity current genesis is tentatively put forward to explain some of the more puzzling features of the lower part of the succession. More work is needed to establish the nature of the facies changes within the major channels and to thereby give clues as to the precise nature of the transition from traction to turbidity currents.

APPENDIX

Plots of Grain Size Cumulative Curves and Compositions of Specimens of Several Facies.

Figure A 1. Cumulative Curves of Grain Sizes from thin section data.

Figure A 2. Plots of Compositions of Fine Grained Facies.

Figure A 3. Plots of Compositions of Coarse Sandstone Facies.

The specimens examined are indicated by a number. Their facies are shown symbolically and their localities and stratigraphical positions are indicated on the Charts of the Sub-Areas in Volume 3.

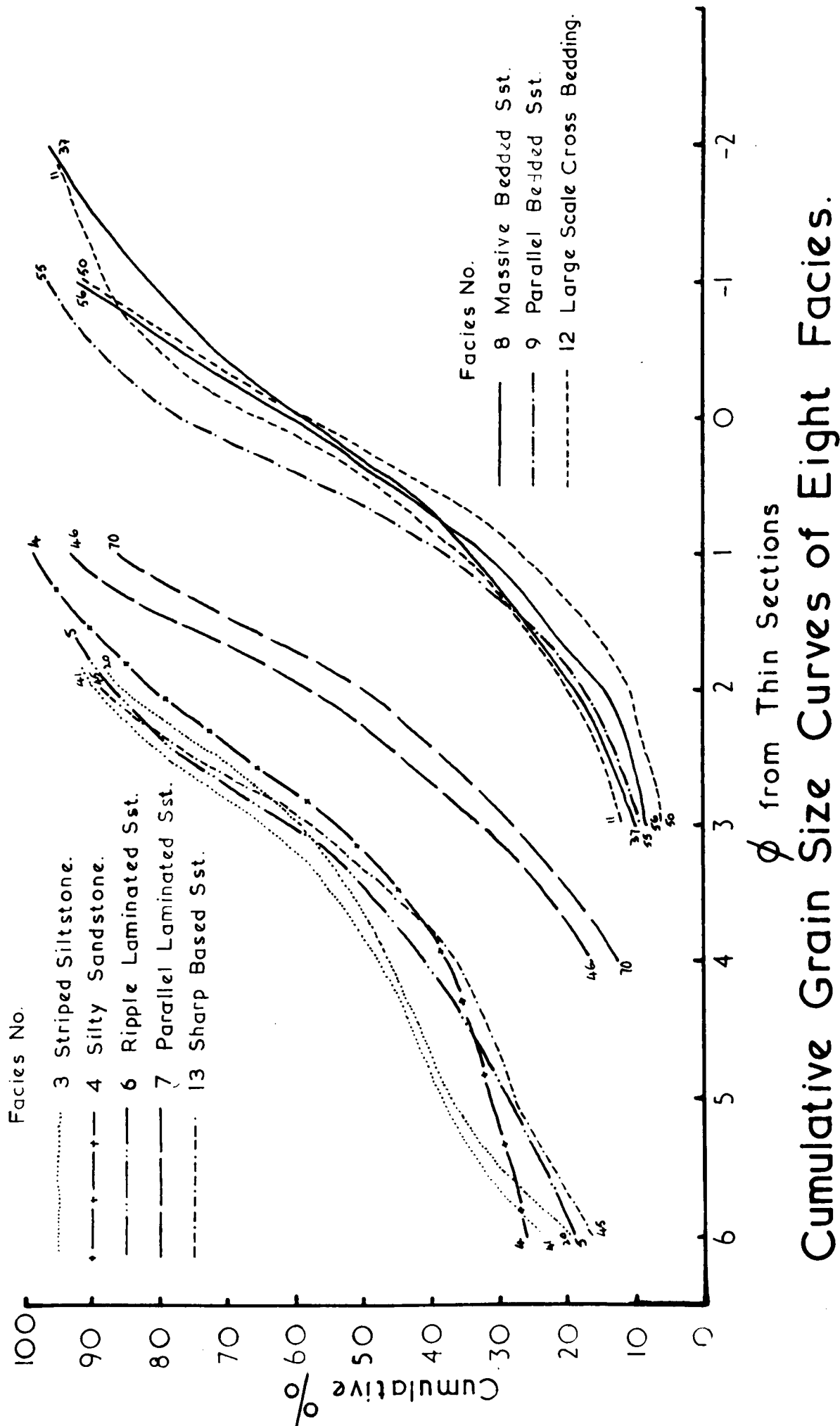


Figure A 1.

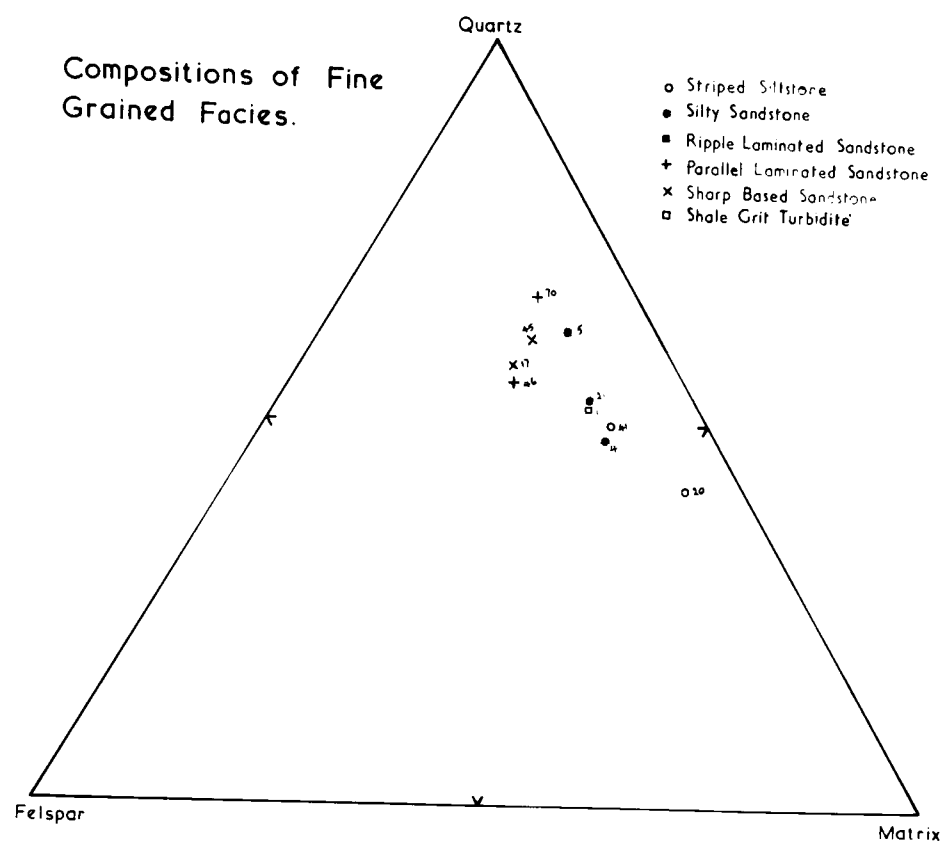


Figure A 2.

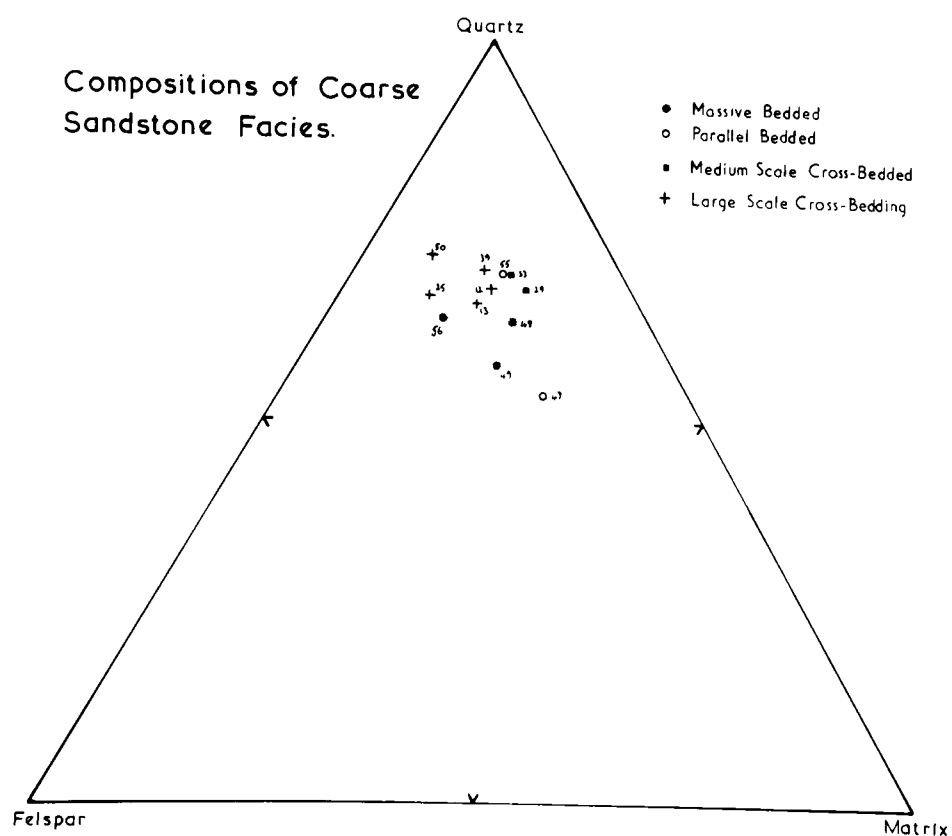


Figure A 3.

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