THE PALAEONTOLOGY, SEDIMENTOLOGY AND STRATIGRAPHY OF THE UPPER ARNSBERGIAN, CHOKIERIAN AND ALPORTIAN OF THE NORTH STAFFORDSHIRE BASIN

by

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CONTENTS

CHAPTER 4 PALAEONTOLOGICAL DISCUSSION

CHAPTER 5

LITHOFACIES RELATIONSHIPS AND ENVIRONMENTAL INTERPRETATIONS

ABSTRACT

The boundaries of the Upper Arnsbergian, Chokierian and Alportian (late E_2b_1 - H_2c inclusive) are established in the North Staffordshire Basin. The faunal bands in the interval late E_2b_1 - H_2c (inclusive) are recognised and the faunas present are identified.

The position of the sediments in the Basin is defined within the established biostratigraphical framework. Sedimentary units present are placed in lithofacies and sublithofacies on the basis of analysis and interpretation of external and internal structures.

Microfaunas of selected bullion horizons in the Basin are examined and three new subspecies of the Family Ceratoikiscidae (Holdsworth, 1969) are recognised. The distribution of the Ceratoikiscidae and their possible evolutionary trends are discussed.

Distribution of the faunal elements in the faunal bands of the Basin and the implications of this distribution are discussed. Faunal bands are suggested to have either "deep" or "shallow water" genesis. Groupings of "deep" and "shallow" faunal bands alternate and a megacyclic succession is proposed for the Basin in the interval late E_2b_1 - H_2c. Coarse clastic sediment is present only in the "shallow" megacyclic intervals.

Marked vertical changes or breaks are recognised in the faunal phase distribution "pattern" in the Ashover Succession, which are seen to be synchronous with the interval junctions in the Basin. Eustatic control of sea level is suggested as the mechanism producing this synchronisation. Variations in the faunal record are related to eustatic fluctuations in sea level with variable maxima, and the

influence of local epeirogeny in the Ashover area is discussed.

Lithofacies relationships and environmental interpretations in the interval late E_2b_1 - H_2c are considered in the light of the previously discussed sedimentary and palaeontological evidence.

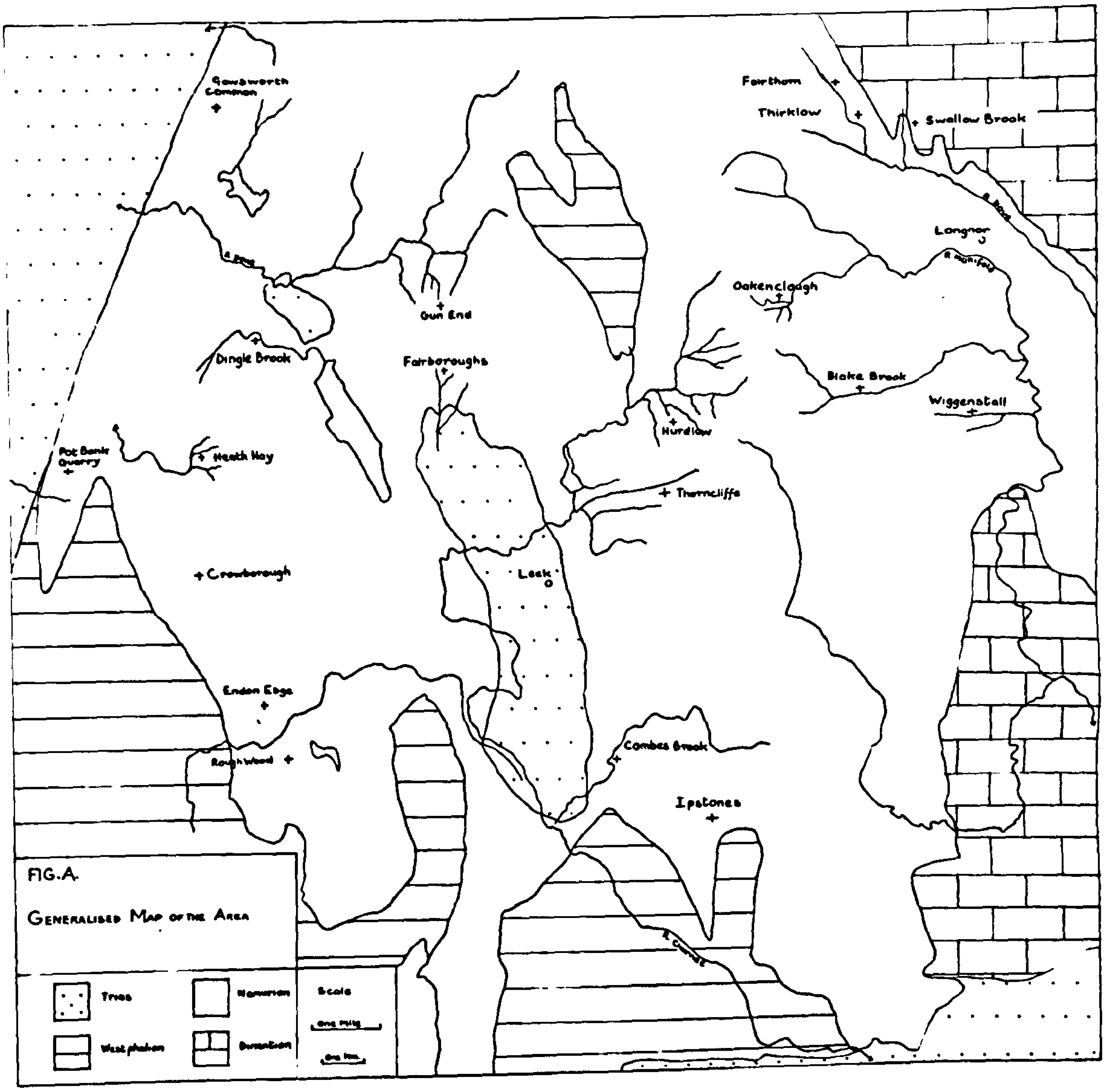

FIG. A.

Generalised Map of the Area

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INTRODUCTION AND BRIEF RESUME OF PREVIOUS WORK

Introduction

This work includes the study of the stratigraphy, palaeontology and sedimentology of part of the Namurian succession in the North Staffordshire Basin. The geographical area studied includes that part of North Staffordshire lying to the north of the Potteries Coalfield and stretching northwards to the vicinity of Macclesfield, having the downfaulted Trias of the Cheshire Plain as the western boundary. The northern limit of the area stretches from Gawsworth to the upper Dove, whilst the eastern boundary of the area is formed by the up-folded Lower Carboniferous strata of the Southern Pennines. The unconformable Triassic rocks of the Midlands define the southern limits of the area of study.

The first detailed modern work to be done in the Basin was carried out by Holdsworth (Ph.D.Thesis, 1963) who dealt with the palaeontology, stratigraphy and sedimentology of Namurian rocks in the Longnor - Hollinsclough - Morridge region of North East Staffordshire and South West Derbyshire. Holdsworth's initial work in this area provided a framework for subsequent researches in the Basin; Trewin (Ph.D.Thesis, 1969) investigated the stratigraphy, palaeontology and sedimentology of the Upper Pendelian and Lower Arnsbergian of the North Staffordshire Basin, whilst Ashton (Ph.D.Thesis, 1974) dealt with the palaeontology, stratigraphy and sedimentology of the Kinderscoutian and Lower Marsdenian of North Staffordshire and adjacent areas. The present work, which was commenced in 1970, is confined to the Upper Arnsbergian, Chokierianand Alportian (late E_2b_1 - H_2c (inclusive)).[1.]

1. Abbreviation of generic names used in the text:

R.	- Reticuloceras	H.	- Homoceras	Hd.	- Hudsonoceras
Hmct.	- Homoceratoides	N.	- Nuculoceras	E.	- Eumorphoceras
C.	- Cravenoceras	Ct.	- Cravenoceratoides	A.	- Anthracoceras
D.	- Dimorphoceras				

The initial stages of this work involved establishing detailed palaeontological control. This entailed a study of all available exposures which were mainly in stream sections and more rarely in quarries. It became obvious during this part of the work that, in the main, exposures were limited in the area and that only minimal value, as far as this work was concerned, would be obtained from the preparation of a geological map. However, small areas including the Churnet and Combes valleys were mapped in detail (figs. IIIA and IVA).

Subsequent to the establishment of a comprehensive palaeontological control, detailed investigation of the coarse clastic sediments in the Basin succession was carried out. Total field characteristics of these sediments were recorded and evaluated, whilst internal structures and petrological characteristics were examined in the laboratory.

The occurrence of some of the faunal horizons in lithologies of the limestone bullion type and the recent studies made by Holdsworth (1964b, 1966a,b,&c, 1967, 1969a) on the micro-faunas of bullions of this type led to the study of some aspects of the micro-faunas in the succession. Attempts were made to correlate the micro-faunas of the Basin with extra-basinal areas but, due to poor preservation outside the North Staffordshire area, these proved unsuccessful.

Previous work in the area studied

Palaeontology

Early palaeontological records from the area covered by this work are of a fragmentary nature. This first known reference is in John Sleigh's "Ancient History of Leek" (1862) in which Wardle writing on the geology in the neighbourhood of Leek mentions the fossils of the Combes area.

Green (in Hull and Green, 1866) also records a fauna from the Combes Brook, he states (p.60), "Beds of black calcareous shales with large limestone bullions, crop in the Coombes Valley, three miles S.S.E. of Leek, by the "S" of Spirit Holes Wood: They were pointed out to me by Mr. Wardle, who has obtained many fossils from them."

The faunal band referred to above which lies above the sandstones and conglomerates of Sharpcliffe (Loc. 086) is now known on the basis of work done by Morris (1967) and Ashton (1974) to be of R_1a age.

The location of the H_2a faunal band occurring in the Pot Bank Quarry (Loc. 010) below Congleton Edge has long been known and details of this fossiliferous locality were first given by Hull and Green (1866). They do not however appear to have located a goniatite bearing horizon at this location since they state, "In a quarry by the roadside, south-west of Hollywood, we have

	ft.	ins.
Dark grey shale, with fossil-bearing nodules of limestone	15	0
Hard dark-grey quartz rock (Gannister), with thin partings of dark shale, containing layers of coal from one-eighth to one fourth of an inch thick. Large stigmariae with rootlets."	20	0

A fauna listed almost certainly from the above locality includes: *Chonetes tuberculata* McCoy, *Discina nitida* Phillips, *Productus longispinus* Sowerby. In what is thought to be an adjacent quarry, although the exact locality is obscure, Hull and Green (p.72) record the following: "Thirty-two chains north-east of Puddle Bank is a quarry in like beds; in the upper shales was a band of earthy limestone with goniatites." This is thought to be the *Hd.proteum* - *H.smithi* band which in the Pot Bank Quarry occurs in one foot of calcareous mudstone.

Other authors to record details of the fauna in the Pot Bank Quarry include Hind (1902, 1907 and 1910) Bisat (1924), Hudson and Cotton (1943) and Evans et al. (1968). Hind's work at this locality led to the identification of an extensive fauna

(64 species) including corals brachiopods, lamellibranchs, gasteropods and goniatites. These last he recorded as Glyphioceras diadema and G. spirale. Bisat (1924) in his description of H. proteum Brown (p.112) states, "this species was often referred to by Hind as G. spirale (var or mut) ......" he also figures (plate Viii) H. proteum and H. diadema from the Wheelton Hind collection in the British Museum, the specimens coming from the "Congleton Edge Quarry Cheshire." According to Bisat (p.103) three forms are included in Beyrich's (1837) Homoceras (Goniatites) diadema

— var. smithi (Brown, 1841)

— var. undulatum (Brown, 1841)

— var. beyrichianum (de Kon., 1843)

All three forms are now full species and the name Homoceras diadema is redundant. Thus the goniatites identified by Hind (1902) from the Congleton Edge Quarry are almost certainly Hd. proteum* and H. smithi.

Pocock et al. (1906) also mention the work of Hind in their account of the Pendleside Series when they refer to a rich marine fauna collected by Dr. Hind from a gannister quarry to the west of Congleton Edge.

In a small pit in the Dingle Brook area, about 250 yards to the north east of a house known as Ashmore Heath, Pocock et al. list a succession of beds with plant remains and others with marine shells of "orthis". They state, "These marine strata may be on the same, or approximately the same horizon as the marine fossil-beds in the gannister quarry near Congleton Edge." The approximate stratigraphic position of this locality, which cannot now be accurately located, is however thought to be between the E_2b_1 and E_2c_2 Subzones and is near to Loc. 52 of Evans et al. (1968) where Ct. cf. nitidus was recorded by the B.P. Exploration Co. Pocock et al. (1906) further indicate that in the

*Erratum – for Hd. proteum read Hd. proteus

Dingle Brook "calcareous nodules" containing fish-spines and goniatites occur below the beds containing the marine fossils,however, they state, "The specimens of goniatites obtained were not capable of specific determination ....." Evans et al. (1968) record at their Loc. 51, which is 46'6" below Loc. 52, 13'0" of grey shale with calcareous lenses, containing a fauna of P.corrugata and Petrodus cf. patelliformis. The occurrence of this fauna and the apparently similar lithologies are thought to be further confirmation that Pocock et al. were mistaken in equating the fauna at their Dingle Brook locality with the fauna in the Pot Bank Quarry, particularly since P.corrugata is absent from the H_1 and H_2 successions in both the North Staffordshire Basin and in the Ashover Boreholes (Ramsbottom et al.,1962).

Bisat's (1924) work on goniatite faunas provided the first viable basis for Namurian subdivision and correlation and in the North Staffordshire Basin the works of Challinor (1929 and 1930) and Hester (1932) were significant contributions to the knowledge of the local Namurian succession. Bisat's zonal scheme was successfully applied by Hudson and Cotton (1943) to boreholes at Gun Hill and Alport Dale and on the basis of the goniatite faunas present they were able to propose a correlation between the two areas.

Holdsworth's (1963) comprehensive work in North East Staffordshire and South West Derbyshire provided much new and detailed information on the faunal horizons present in the local Namurian succession.

The Macclesfield Memoir (Evans et al., 1968) provided a valuable detailed palaeontological control for the western part of the area of study although additional palaeontological data was also found in this area during the course of this work.

Micropalaeontology

Previous work on the micropalaeontology of Namurian limestone bullion faunas was first carried out by Holdsworth (1964a, 1966a,b,&c, 1967 and 1969a) and the present work has been done under his supervision.

The previous work of Holdsworth and the initial work done by the writer indicated that significant differences existed between the microfaunas of some of the macrofaunal horizons in the succession. It seemed possible that these differences might provide an effective means of subdivision within the Basin succession which would supplement that based on the goniatite faunas.

Particular attention was paid to non-spumellarian Radiolaria of the Genus Ceratoikiscum since Holdsworth (1969) indicated that from a biostratigraphic point of view this genus was likely to prove to be one of the more important groups of Palaeozoic Radiolaria.

Unlike the spumellarian Radiolaria the different species of Ceratoikiscum display marked morphological differences which in many cases facilitates the identification of even fragmentary specimens.

Holdsworth (1969) recorded the occurrence of four species of Ceratoikiscum in the E_2b_2 - R_{1a} interval in the North Staffordshire Basin and was able to show that at least one faunal horizon could be correlated at two distinct geographical localities in the area on the basis of the contained microfauna.

The results of the present work revealed the presence of three more horizons in the E_2b_1 - H_2a interval each carrying a new and distinctive form of Ceratoikiscum. However although these horizons have a value in subdivision, attempts to compare the new faunas both within the North Staffordshire Basin area and at localities outside the Basin, including the Ashover area and the Lancaster Fells, were unsuccessful due to lack of preservation of the Radioloaria in faunal horizons at localities other than the type localities.

The Radioloaria have however been of great value in palaeoenvironmental interpretation and it is thought most probable that further work on Namurian microfaunas will emphasise their value in both zonal subdivision and in correlation.

Stratigraphy

The first detailed geological sections across England are attributed to Farey (1806-8) who depicted on his section across the Peak district the following Carboniferous succession for the Macclesfield area:-

Grit

The Great Shale Stratum

Limestone Stratum (containing three beds of Toadstone)

Hull and Green (1864) produced a geological map of North Staffordshire and also elaborated on Farey's succession by subdividing his "Grit" into two groups their succession being:-

Millstone Grits

Yoredale Quartzites

Shale and thin Limestone

Carboniferous Limestone

Hind and Howe (1901) recognised that the Yoredale Quartzites of North Staffordshire were higher in the succession than the Yoredale rocks of the Yore valley and proposed the term "Pendleside Series" be substituted for this part of the succession. Pocock et al. (1906) also used the term Pendleside Series in the Geological Survey Memoir for the country around Macclesfield, Congleton, Crewe and Middlewich in which the succession in the area was given as follows:-

Millstone Grit	(Two or more thick beds of sandstone and shale and one or two thin coals.
Pendleside Series	(Chiefly shales with sandstones, calcareous mudstones and thin earthy limestones. (Thick beds of quartzite or crowstone
Carboniferous or Mountain Limestone	(Limestone in thin beds at top, massive below.

The exact stratigraphical limits of the Pendleside Series are not clearly defined by Pocock et al. although they indicate that the series is characterised by a fauna which includes Glyphioceras reticulatum (H.smithi) and G.spirale (Hd.proteum). The "Crowstones" of the "Pendleside Series" are described by Pocock et al. as having a "variable aspect". The "normal type of Crowstone" they refer to as a ",,..close-grained quartz rich rock......fairly termed a quartzite." "Crowstones" of this type they record as being present in the northern part of the district, whilst in the Ipstones and Gun End districts the "Crowstones" are described as coarse grits or quartzose conglomerates. Another variation they record from the Lask Edge anticline where they state, "....crowstones occur with fine grained sandstones resembling those of the Millstone Grit Series above."

Clearly some of the "Crowstones" occur in the E_2b_1 - H_2c interval since many of the localities referred to by Pocock et al., for example Ipstones, Lask Edge, Congleton Ege, Gawsworth Common and Whitemoor Hill are assigned to this interval by Evans et al. (1968) and also by the writer. Other outcrops of "Crowstone" such as those mentioned by Pocock et al. at Shirkley, Gun End, Bosley and Wincle Minn are older in age. Evans et al. (1968) named that part of the succession in which these beds occur the MinnBeds after the extensive outcrops on Bosley Minn and Wincle Minn, thus placing them in the E_1 and E_2a zones. Also mentioned by Evans <u>et al</u>. and occurring in the Stoke-on-Trent district are "Crowstones" of R_2 age. They indicate that these beds have a south to south westerly origin.

Challinor (1929) avoided the use of the term "Crowstone" in his subdivision of the Namurian of North East Staffordshire which is as follows:-

Roches Grits

Churnet Shales

Morredge Grits

However, the term "Crowstone" was reintroduced into the geological literature of North Staffordshire by Hudson and Cotton (1943) when they used the term Alport "Crowstones" to define part of the Namurian succession in the Alport borehole. Hudson (<u>in</u> Hudson and Cotton, 1945a) also uses the term Crowstone when describing the succession in the Gun Hill borehole, he proposes a tripartite lithological subdivision of the Morredge Grits as follows:-

Thorncliffe Sandstones

Crowstones

Onecote Sandstones

It is apparent (<u>ibid</u>.) that the term "Crowstone" has been used in both a lithofacies and a rock stratigraphic sense in the North Staffordshire area and in the writer's opinion its further use can only serve to perpetuate ambiguity. Holdsworth (1964) states, with reference to the palaeogeography of North Staffordshire, "....the continued use of the term "crowstones" in a lithofacies sense can only hinder modern detailed work", whilst with respect to the stratigraphical usage of the term he states, "Crowstones in a rock stratigraphical sense is thus doubly ambiguous, being used with respect to units of at least two contrasting lithofacies developed in different zonal intervals of the Namurian column."

A revision of the lithostratigraphical nomenclature of the Staffordshire South West Derbyshire region was proposed by Holdsworth (1963) as follows:-

Roches Sandstone Formation	Longnor Sandstone Member (at base)
Churnet Formation	Thorncliffe Sandstone Member (at base)
Gun Hill Siltstone Formation	
Onecote Sandstone Formation	

The term "Onecote Sandstones" was first used by Hudson (ibid.) for a succession of shales, thin limestones, calcareous sandstones and sandy limestones occurring in the Gun Hill borehole between 830 ft and 1113 ft (Hudson also referred to this interval as the "Onecote Sandstone series"). The stratigraphical position of the top of the Onecote Sandstones is not clearly defined, the upper 20 ft of shales being placed above a horizon of C. leion, whilst shales with calcareous shelly sandstones and limestones occurring in the lower 27 ft are stated to be of P_2 age.

The Gun Hill Siltstones are proposed by Holdsworth to be of equivalent age to the Crowstones of Hudson (1945a) and are placed by him entirely within the Pendleian.

The top of the Churnet Formation is placed by Holdsworth below the base of the Longnor Sandstone Member (which occurs within the R_1c - R_2a (inclusive) interval) which is the lowest markedly felspathic sandstone in the regional succession. The base of the Churnet Formation is fixed at the Thorncliffe Sandstone Member - Gun Hill Siltstone junction and thus the Formation incorporates the Arnsbegian, Chokierian, Alportian and part of the Kinderscoutian Stages. In the Basin succession this interval contains two major sandstone units, the lower which is present in the Hurdlow and Thorncliffe sections has been termed the

Hurdlow Sandstone (Aitkinhead, 1974) and is also thinly developed in the Blake, Oakenclough and Wiggenstall sections. This sandstone unit is present in the succession above the horizon of N. stellarum and below the lowest N. nuculum horizon. The second sandstone unit occurs in the succession between the highest H. beyrichianum horizon and the Hd. proteum horizon. This unit is present at several localities; including the Ipstones-Sharpcliffe area where together with the Sharpcliffe Conglomerate it forms the lower of two sandstones in the Ipstones Edge Sandstones of Morris (1967), the Lask Edge Endon area (Stanley Grit, Evans et al., 1968) and in the Blake Wiggenstall and Oakenclough areas (Lum-Lady Edge Sandstone Member, Holdsworth, 1963). Both these sandstone units are composed of mineralogically mature sediment and conform to the definition protoquartzite (Pettijohn, 1957, p.316). These protoquartzites are thought to equate with some of the crowstone beds of Pocock et al. (1906) and probably also form part of the Yoredale Quartzites of Hull and Green (1864), whilst Trewin and Holdsworth (1973) indicate that protoquartzite lithofacies range upwards in the Basin succession from E_1 - R_1c and locally to R_2 (Evans et al., 1968).

In the writer's opinion, the various lithostratigraphic names given to sandstone (protoquartzite) units in the succession, which on faunal evidence are of the same age, makes for a confusing stratigraphic terminology especially when applied to a very small area of the Namurian of the Central Province. The practise in this account is, therefore, to define a portion of the succession as being within a given palaeontological interval and the introduction of new lithostratigraphic terms has been avoided. Trewin and Holdsworth (1973) encountered a similar problem in the E_1a - E_2a (inclusive) interval where, for example, they indicated that the introduction of five or six named subdivisions of the Minn Sandstones (Evans *et al.*, 1968) was not justified particularly as the individual units could only be recognised by reference to intercalated goniatite bands.

The most recent subdivision of the North Staffordshire Namurian Succession due to Evans *et al.*, (1968) is as follows:-

Rough Rock Group

Middle Grit Group

Upper Churnet Shales (Kinderscout Grit Group)

Middle Churnet Shales

Lower Churnet Shales

Minn Beds

Lask Edge Shales

The boundaries of the Lask Edge Shales are placed at the "base of the *Cravenoceras Leion* Zone" to "the base of the strata of Crowstone facies." The latter being termed the Minn Beds, has its upper boundary fixed "at the base of the *Cravenoceratoides edalensis* beds." This horizon, in the opinion of the writer, is a well chosen upper boundary for the Minn Beds since marked lithological and faunal changes occur in the Basin succession at this level.

That part of the succession studied by the writer, the interval late E_2b_1 - H_2c (inclusive), lies entirely within the Churnet Shales which have a threefold subdivision. The Lower Churnet Shales includes strata from "the base of *Cravenoceratoides edalensis* band to the base of the lowest *Homoceras subglobosum* band." The Middle Churnet Shales are defined by Evans *et al.* as being of H age and the Upper Churnet Shales of R_1 age. Over much of the North Staffordshire Basin the exposures of the various faunal bands are sufficient to define the boundaries of the Churnet Shales although in parts of the area of study a detailed palaeontological subdivision cannot be applied. Such an area is the Gawsworth Common locality where, with the exception of a single faunal band, the bulk of the succession, which equates with the Churnet Shales, is a sandstone succession from which faunal horizons appear to be absent. Holdsworth (1963) described various lithofacies occurring in the Namurian of the Longnor - Hollinsclough - Morridge region of the North Staffordshire Basin and he defined their positions in the succession on the basis of palaeontological data. A similar approach has been made by the writer to the various lithofacies present in the late E_2b_1 - H_2c (inclusive) interval for the whole of the Basin area. Due to the diverse nature of the lithofacies encountered in the area, together with their various positions in the succession, this approach has proved to be satisfactory for stratigraphical and palaeoenvironmental interpretations in the interval late E_2b_1 - H_2c (inclusive).

CHAPTER I

PALAEONTOLOGY

INTRODUCTION TO PALAEONTOLOGY

Initial work to establish a biostratigraphical frame-work into which the lithostratigraphical units could be placed, involved the examination of twenty stream sections and several isolated exposures. Approximately 100 fossil localities were examined and collected.

Identification was based initially on the comparison of collected material with specimens referred to and figured in published accounts of Namurian palaeontology. (Bisat, 1924; Hudson and Cotton, 1943; Hodson, 1956; Ramsbottom *et al.*, 1962; Yates, 1962 and Holdsworth, 1963) and secondly by comparison with specimens collected by Dr. B. K. Holdsworth from the Namurian of North East Staffordshire and South West Derbyshire. Verification of the initial specimen identification was made in consultation with Dr. B. K. Holdsworth, and in communication with Dr. N. Aitkinhead and Dr. W. H. C. Ramsbottom.[1] Thick-shelled goniatites were collected from faunal horizons within the Arnsbergian, Chokierian and Alportian stages of the Namurian, and are concentrated in one of the following sediment types:-

Black carbon-rich mudstone, this rock type has a tough uniform composition and shows no preferential planes of splitting.

Dark blue grey mudstone, which is tougher than surrounding mudstone due to a higher carbonate content.

Limestone, in the form of a continuous bed, usually less than one foot thick, and also in the form of lenticular bullions.

The continuous beds of limestone are blue grey in colour and can best be described as ankerites, they commonly contain fossils as external moulds

1. Confirmation of identification of specimen at Loc. 107 as *Homoceras beyrichianum* and at Loc. 066 as *Nuculoceras nuculum*.

or impressions, which are frequently difficult to detect. The bullions are of two types, calcite rich bullions which contain uncrushed shelly material and ankeritic bullions which display preservation characteristics similar to those exhibited by the thin bedded ankeritic limestones. Preservation within a silica rich or chert bed was also encountered in the area of study.

Faunal horizons were examined and identified in the Arnsbergian above the level of Cravenoceratoides edalense Bisat, and the complete faunal content of the Chokierian and Alportian stages (up to Homoceratoides prereticulatus Bisat) was examined.

The Stages, Zones, Subzones and Faunal Bands which were examined in the course of this research are tabulated below:-

Stratigraphical Subdivision	Stage	Zone	Subzone	Faunal Band
	Alportian (H_2)	H_2c		Hmct. prereticulatus.
		H_2b		H. undulatum.
				H. smithi.
Middle		H_2a		Hd. proteum.
Churnet	Chokierian (H_1)	H_1b		H. beyrichianum.
Shales				H. beyrichianum.
				H. beyrichianum.
		H_1a		H. subglobosum (iii).
				H. subglobosum (ii).
				H. subglobosum (i).
	Arnsbergian (E_2)	E_2c	E_2c_2	N. nuculum; E. bisulcatum (iii).
				N. nuculum; E. bisulcatum (ii).
				N. nuculum; E. bisulcatum (i).
Lower			E_2c_1	N. stellarum.
Churnet		E_2b	E_2b_3	E. rostratum; Ct. nititoides.[1]
Shales			E_2b_2	C. aff. holmesi.
				C. holmesi.
				Ct. nitidus.
			E_2b_1	Ct. edalense.

Key. Ct. = Cravenoceratoides. C. = Cravenoceras. E. = Eumorphoceras

H. = Homoceras Hd. = Hudsonoceras Hmct. = Homoceratoides

N. = Nuculoceras.

1. Specimens of Ct. nititoides have not been recorded from this faunal band but are known from this horizon in other localities.

THE FAUNAL SUCCESSION

In the following account the successive faunal bands are described in ascending sequence with details of exposure lithology and faunal content recorded at the various localities.

THE FAUNAL BANDS IN THE E_2b_2 SUBZONE

In the Ashover Boreholes (Ramsbottom et al., 1962) several faunal bands are recorded in this Subzone, and in the area covered by this research closely comparable sections are present in the Oakenclough and Wiggenstall streams. In the Wiggenstall Stream, Section 11T, the following succession was recorded:-

		ft in.	m
The Cherts, E.rostratum, Loc. E_2b_3.		2'0"	0.61
Mudstone, blue grey, silty.		10'0"	3.05
Limestone bullion bed, ankeritic, C.holmesi, Loc. 125, E_2b_2.	max	0'5"	0.12
Mudstone, blue grey, silty.		12'0"	3.66
Limestone bullion bed, blue grey, calcitic, small poorly preserved goniatites on the outer rim. Ceratoikiscum sp., Loc. 126.	max	0.5½"	0.14
Silty mudstone, ankeritic lens 7'0" above base with P.corrugata.		31'0"	9.45
Limestone, ankeritic, (Stannery Limestone) with abundant P.corrugata on a bedding plane 2" from the top, Loc. 127.		1'2"	0.35
Mudstone, partially exposed.		23'0"	7.01
Limestone bullion bed, Ct.nitidus, Loc. 128, E_2b_2.(1)	max	0'8"	0.20
Mudstone partly exposed with Ct.edalense at base.(2)		21'0"	6.40
Limestone bullion bed, Ct. edalense, Loc. 130.		0'6"	0.15

(1) Location of N. Aitkinhead. Identification of Ct.nitidus by W. H. C. Ramsbottom.

(2) (3) (4) Locations of N. Aitkinhead. Identification of Ct.edalense by W. H. C. Ramsbottom.

Dark grey calcareous shale, Ct. edalense.(3)		3'0"	0.91
Dark grey shale.	C.	8'0"	2.44
Calcareous shale, Ct. edalense, Ct. cf. bisati.(4)		3'0"	0.91

Less complete sections within this Subzone from the Blake Brook and Oakenclough Stream are recorded in Appendix l. The Oakenclough Section is also recorded in Holdsworth (Thesis, 1963) and by Trewin and Holdsworth (1972).

The Stannery Limestone forms a persistent marker horizon in the east of the area covered by this research but is absent from the area to the west of the Morridge axis. Holdsworth records this marker horizon with a fauna of P.corrugata from several localities in the north of the area of research.

In the Wiggenstall Stream a bullion bed occurs 31' (9.45m) above the level of the Stannery Limestone, etched surfaces of this material reveal well preserved Radiolaria including Ceratoikiscum sp. In the Blake Brook, the Stannery Limestone is present at Loc. 147 and in addition to the fauna of P.corrugata, contains a single specimen of a small subglobose goniatite tentatively identified as an immature specimen of Cravenoceras.

The Stannery Limestone in the Blake Brook lies 28'6" (9.00m) below an ankeritic limestone bullion bed which is thought to be the equivalent of the Ceratoikiscum sp. level at Loc. 126 in the Wiggenstall Stream, unfortunately etched surfaces of this material reveal that the process of dolomitisation has largely destroyed the microfauna.

At Loc. 125 a bullion bed containing C.holmesi is present in the Wiggenstall Stream 12'0" (3.66m) above the level of Ceratoikiscum sp. at Loc. 126 and 10'0" (3.05m) below the Cherts. In the Oakenclough Stream a bullion horizon at Loc. 167 containing C.holmesi location 206b, Holdsworth, 1963) is present 9'0" (2.68m) below the Cherts (N.B. This interval measured by Trewin and

Holdsworth (1972) is given as 3.33m)

Identification of Cravenoceras holmesi Bisat

Only one specimen of C.holmesi was collected, this was from Loc. 125, and is in the form of a solid specimen exposed in transverse section which passes through the umbilicus.

A comparison of measurements made on the specimen of C.holmesi collected from Loc. 125 with similar data from Bisat (1932) and Holdsworth (1963) is as follows:-

	Diameter	Maximum Thickness	Thickness: Diameter	Umbilical Diameter
Cravenoceras holmesi Bisat (From Bisat 1932)	12mm	-	-	5mm
	13mm	9mm	1.44	-
Cravenoceras cf. holmesi Bisat (From Holdsworth 1963)	12mm	8mm	1.50	5mm
	14.5mm	10mm	1.45	8mm
Cravenoceras holmesi Bisat (From Loc. 125)	15mm	11mm	1.36	3.5mm

The above measurements correspond closely, with the exception of the low figure for the umbilical diameter of C.holmesi from Loc. 125 suggesting that the transverse section from which the measurement was taken was slightly off the central point of the specimen. The C.holmesi from Loc. 125 exhibits an acute raised umbilical rim which is apparent on the final whorl. This, together with the above dimensions, is considered to be sufficiently diagnostic of this species.

THE FAUNAL BAND IN THE E_2b_3 SUBZONE

The single faunal band characteristic of this Subzone is present in the Wiggenstall Stream at Loc. 124, 10'0" (3.05m) above the horizon of C.holmesi. In the Blake Brook this E_2b_3 horizon is present 13'5" (4.10m) below the level of N.stellarum. All three faunal bands are exposed in the Oakenclough Stream where the intervals E_2c_1 - E_2b_3 - E_2b_2 are respectively 13'10" (3.80m) and 9'0" (2.68m).

In the area of study the E_2b_3 faunal band has a distinctive lithology consisting of repetitive thin bands of chert which may amalgamate to produce a continuous bed, averaging 3'0" thick, or may be separated by thin partings of black shaley mudstone. At all localities the beds contain a distinctive fauna which in addition to the zone fossil E.rostratum comprises molluscs, brachiopods, crinoids and trilobites.

Holdsworth (1963) recorded the E_2b_3 faunal band from several localities to the north of this area and also in the Oakenclough Stream. At all Holdsworth's E_2b_3 localities the characteristic cherty lithology occurs and the name 'The Cherts' has been applied to this E_2b_3 horizon.

An E_2b_3 horizon of similar lithology has been recognised in the Edale area (Hudson and Cotton, 1945) and in the Alport borings (Hudson and Cotton, 1943). More recently the Ashover Borehole records (Ramsbottom et al., 1962) indicate that above the level of C.holmesi the equivalent band is present but is contained in beds of different lithology, which are logged as "mudstones striped with bands of grey cank," or "mudstones calcareous with bands of fine grained fairly dark grey limestone up to 1 inch thick." These horizons in the Ashover Boreholes are undoubtedly at the same level as those to the west, but do not appear to exhibit the silicification which is characteristic of the Cherts.

Sections, Localities and Fauna in the E_2b_3 Subzone

Blake Brook, Section 6T

	ft in.	m
Limestone, blue grey, ankeritic, N.stellarum, Loc. 145, E_2c_1.	0'2½"	0.06
Mudstone, blue grey, siderite nodules, max. 2" at 2'0" from top.	8'2"	2.50
No exposure.	5'3"	1.60
Chert, greenish grey, carbonaceous partings, Loc. 146.	0'3½"	0.09
Black silty shale, crinoid ossicles.	0'1½"	0.04
Chert (as above), Weberides sp. (pygidium only).	0'2"	0.05
Shale, black silty.	0'5"	0.13
Chert (as above).	0'2"	0.05
Shale, black silty.	0'1"	0.03
Chert (as above), Eumorphoceras sp.	0'1"	0.03
Shale, black silty.	0'0½"	0.01
Chert (as above), E.rostratum, Chonetes sp., Orbiculoidea sp.	0'3½"	0.09
Shale, black silty, Chonetes sp.	0'1½"	0.04
Chert (as above).	0'2"	0.05
Shale, black silty, with silty streaks.	0'2½"	0.06
Sandstone, fine grained with carbonaceous partings.	0'2½"	0.06
Mudstone, silty with siltstone streaks.	1'0"	0.31
No exposure.	32'0"	10.00
Limestone bullion bed, blue grey ankeritic.	max 0'5"	0.13
Mudstone, partly exposed.	28'6"	9.00
Blue grey, ankeritic limestone (The Stannery Limestone) P.corrugata abundant on bedding plane 2½" from the top, also a single immature subglobose goniatite. Loc. 147.	0'7"	0.18

The details of the E_2b_3 succession in the Wiggenstall streams Loc. 124 and Loc. 129, the Oakenclough Stream Loc. 166 and the Combes Brook Loc. 084 are available in Appendix 1.

Fauna of the Cherts

The following faunal assemblage is characteristic of the E_2b_3 faunal band in the Wiggenstall streams Locs. 124 and 129 and in the Blake Brook Loc. 146. A more restricted faunal assemblage was collected from the Cherts in the Combes Brook, Loc. 084, consisting of fragments of E.rostratum, Eumorphoceras sp. and Dimorphoceras sp. In the Oakenclough Stream Loc. 166, Holdsworth (1963, Loc. 266) records a sparse fauna of Chonetes s.l.sp. and trilobite (? Weberides sp.). Re-examination of this section (Trewin and Holdsworth, 1972) revealed the presence of Eumorphoceras rostratum.

Total faunal list at Locs. 124, 129, 146:-

Eumorphoceras rostratum Yates

Eumorphoceras sp.

Dimorphoceras sp.

Posidonia corrugata

Productus sp. (P.1.1)

Chonetes s.p. (P.1.2)

Orbiculoidea sp. (P.1.3)

Weberides sp. (P.1.4)

Orthocone nautiloid fragments

Wood fragments

Crinoid ossicles (mainly seen in the shale)

A commonly occuring smooth to finely ornamented goniatite.

P.1.1.

Productus sp.

x 3.

From the Cherts faunal band, E_2b_3, in the Blake Brook, Loc. 146.

P.1.2.

Chonetes sp.

x 4.

From the Cherts faunal band, E_2b_3, in the Blake Brook, Loc. 146.

P.1.1.

P.1.2.

P.1.3.

<u>Orbiculoidea sp.</u>

x 7.

From the Cherts faunal band, E_2b_3 in the Blake Brook, Loc. 146.

P.1.4.

Pygidium of <u>Weberides sp.</u>

x 4.

From the Cherts faunal band, E_2b_3 in the Blake Brook, Loc. 146.

P.1.3.

P.1.4.

Identification of Eumorphoceras rostratum Yates

Specimens of Eumorphoceras sp. collected at Loc. 146, are mainly immature, 5-7 mm in diameter, displaying regularly arranged strong straight ribs. A fragment of a more mature individual, estimated diameter 14mm displays a marked forward curvature of the ribs, which assume an attitude tangental to the lingual groove before dying out, this specimen is tentatively identified as Eumorphoceras rostratum Yates.

At Loc. 124 specimens of Eumorphoceras sp. displaying only fragments of the lingual groove have a maximum diameter of 18 mm. Whilst one specimen of 11 mm diameter exhibits the characteristic flexing of the ribs which for half the rib length, in the final whorl,lie tangental to the lingual groove and appear to die out in the lateral area without actually reaching the groove, this specimen is also tentatively identified as E.rostratum.

Common to all localities is a small evolute goniatite, with a very small umbilicus, which exhibits very tight coiling in adolescence. The final whorl is less tightly coiled and appears smooth although some specimens exhibit a very faint delicate transverse ornament. Holdsworth (1963) also records this species from the Cherts and suggests that they are either Dimorphoceras sp. or Cravenoceras sp.

THE FAUNAL BAND IN THE E_2c_1 SUBZONE

A single faunal band containing the index fossil Nuculoceras stellarum (Bisat) is present in this Subzone and has been recorded at two localities[1.], Section 15T, Loc. 165, and Section 6T, Loc. 145.

In the Oakenclough Stream Section the horizon of N.stellarum, Loc. 165, was intially identified by Holdsworth (1963) at his Loc. 206c, at which he records a fauna of Ct. aff. stellarum some 13'0" above the level of the Cherts.

1. A Churnet tributary Loc. of Dr. N. Aitkinhead (1974) at Grid Ref. SK 03036170 occurring 0.46m below the Hurdlow Sandstone carries N.stellarum and Pd. aff. vetusta.

this figure is comparable with that in the Blake Brook, where the faunal band containing N. stellarum occurs 13'5" above the Cherts.

Subsequently Holdsworth (1963) redescribed the fauna occuring at Loc. 206c and pointed out that the features exhibited by the specimens at this locality, in particular the spiral ornament and raised umbilical rim, display a closer affinity with the Genus Nuculoceras than with Cravenoceratoides and accordingly he proposed that the name Nuculoceras stellarum (Bisat) should be adopted for this the index fossil of the E_2c_1 Subzone. The Zone E_2d is now obsolete and the E_2c Zone is now divided into two Subzones, E_2c_1 and E_2c_2, the latter being characterised by the index fossil N. nuculum.

Sections in the E_2c_1 Subzone

Blake Brook, Section 6T

	ft in.	m
Mudstone, blue grey .	1'0"	0.36
Limestone, grey, ankeritic .	0'2"	0.05
Mudstone, blue grey .	0'2"	0.05
Limestone, blue grey, ankeritic, N. stellarum, Dimorphoceras sp., Loc. 145, E_2c_1.	0'2½"	0.08
Mudstone, blue grey, siderite nodules max 2" at 2'0" from top.	8'2"	2.50
No exposure .	5'3"	1.60
Cherts, E. rostratum, Loc. 146, E_2b_3 .	3'4"	1.00

Oakenclough Stream, Section 15T

Mudstone, blue grey, silty .	0'8"	0.20
Limestone, muddy, ankeritic, grey, N. stellarum, Loc. 165, E_2c_1 .	0'3"	0.08
Mudstone, blue grey, silty .	1'5"	0.425
Siderite nodules, with poorly preserved lamellibranchs .	0'4"	0.10

	ft in.	m
Shaley mudstone passing into shale .	8'0"	2.44
Siderite band .	0'1½"	0.04
Shale .	4'0"	1.22
Cherts, E.rostratum, Loc. 166, E_2b_3 .	3'10"	1.16

Identification of Nuculoceras stellarum (Bisat)

The lithology and position in the succession of the E_2c_1 faunal band in the Blake Brook is identical with that at Loc. 165, and there is a similar preservation of fauna, mainly as crushed impressions with adherent, thin, shell material.

Dimensions of specimens at Loc. 145

D	U	ribs/cm on venter	D/U	rib shape
14	2.5		5.6	ribs straight
16	2.5	16	6.4	ribs straight
26	-	20		ribs straight
30	-	15		ribs very slightly curved

The dimensions of the specimens of N.stellarum at Loc. 145 compare closely with those taken from Holdsworth's (1965) data, and the presence of a weak spiral ornament is further confirmation of the identification of these specimens.

The profile of the ribs, described by Holdsworth as tented in elevation, together with the raised umbilical rim (when preserved) and the slightly lower rib frequency are features which may be employed to distinguish this species from N.nuculum . In addition, the ratio of diamter to umbilical diameter (D/U) in N.stellarum is between 5.6 and 6.4 whilst in specimens of N.nuculum a larger ratio, between 7 and 11, obtains. Specimens of N.stellarum at Locs. 145 and 165, display dichotomy of the ribs on the lateral area, which is variable in occurrence. Adjacent ribs may dichotomise and then several single ribs may be present before dichotomy of the ribs is again evident. The point of dichotomy is also variable in position and in immature specimens may occur at the umbilical margin, whilst in mature specimens it may occur either on the lateral area some 2-3mm ventral to the umbilical rim, or may take place at the umbilical rim. These two positions for the point of dichotomy may be present in the rib pattern of a single mature specimen of N.stellarum.

THE FAUNAL BANDS IN THE E_2c_2 SUBZONE

Within the E_2c_2 Subzone in the area covered by this research, a maximum of three faunal bands each containing Nuculoceras nuculum Bisat, occur and in this account they are designated E_2c_{2i}, E_2c_{2ii}, and E_2c_{2iii}. Evans et al. (1968), referring to the area covered by the Macclesfield Memoir (110), state "The topmost 200-300 ft of the Lower Churnet Shales include marine bands with Nuculoceras nuculum. There are probably two of these, each with one or two thin limestone bands. Three faunal bands are however known over a wide area of the north of England, but because of poor exposure, coupled with tectonic complications, it has not been possible to establish the presence of a third N.nuculum band in this district."

In the Ashover Boreholes, Ramsbottom et al. (1962) record the occurrence of three distinct horizons each containing N.nuculum in addition Eumorphoceras bisulcatum was identified in the upper two faunal bands and the presence of Eumorphoceras ? was recorded from the lowest E_2c_2 faunal band.

Bisat (1924) referring to localities of occurrence of the Genus Nuculoceras (Nov.) states, "The species is associated in each locality with E.bisulcatum." In the course of the present work the presence of E.bisulcatum was confirmed from each of the three E_2c_2 faunal bands.

Thickness of Strata within the E_2c_2 Subzone

What are most probably the upper and lower E_2c_2 faunal horizons are recorded from the Dingle Brook Section by Evans et al. (1968), at Survey Locs. 47 and 48, they are estimated to be circa 135 ft (41m) apart whilst the highest of these horizons is circa 85 ft (25m) below the lowest H_1a faunal band present in this section at Loc. 030b. The above figures probably represent the maximum development of sediments in the E_2c_2 Subzone, which appears to thin eastwards, and in the Ashover Boreholes (Ramsbottom et al. 1962) the three N.nuculum horizons are contained in 11'0" of strata, whilst the highest E_2c_2 horizon is 5-10 ft below the first H_1a horizon.

The Hurdlow Section 10T, and the Gun End Section 7T, display the most complete exposures in E_2c_2 Subzone in the area studied. Two horizons containing N.nuculum occur in the Hurdlow Section and are separated by 82'3" (25.3m) of silty mudstone containing thin beds of siltstone and fine grained sandstone, the upper horizon is 17'3" (5.2m) below the first H_1a horizon and is thought to be the highest of the three faunal bands in the E_2c_2 Subzone.

The beds in the Gun End Stream, Section 7T, display a similar lithology to those present in Section 10T, and the interval between the two N.nuculum horizons, 97 ft (29.6m) is closely comparable with this interval in the Hurdlow Section. The interval between the highest E_2c_2 faunal band and the first H.subglobosum horizon in Section 7T was measured at 25'6" (7.75m) and is again closely comparable with this interval in Section 10T.

In the Hurdlow Section the E_2c_{2ii} horizon is not exposed, whilst in the Gun End Section, a dark grey silty ankeritic limestone occurring 32 ft (9.75m) below the E_2c_{2iii} horizon and containing a sparse fauna of Posidoniella sp. is thought to be the equivalent of the E_2c_{2ii} faunal band.

In only one section, the Combes Brook, 16T, have all three N.nuculum bands been positively identified, they are present in 140 ft (42.7m) of argillaceous sediment which is however not continuously exposed and may have been subject to faulting.

Localities and Sections within the E_2c_2 Subzone

Section 10T, Hurdlow Stream

An E_2c_2 faunal band previously suggested (ibid) as being the upper E_2c_2 faunal band is present in this section and is contained in a 12 inch thick greenish grey ankerite limestone which forms a continuous bed and outcrops in a shale cliff on the east bank of the Hurdlow Stream at Loc. 066. Whilst a faunal band which is probably the lowest E_2c_2 faunal band (see previous discussion) is also present in this section and is contained in a similar ankerite which readily splits into thin slabs, and outcrops in a shale cliff on the east bank of the Hurdlow Stream at Loc. 067.

	ft in.	m
Mudstone, grey .	1'0"	0.31
Mudstone, black, N.nuculum[1] .	0'8"	0.20
Mudstone, blue grey, N.nuculum .	1'2"	0.35
Limestone, ankeritic, greenish grey, N.nuculum, E.bisulcatum. Posidoniella sp., plant fragments, Loc. 066 E_2c_{2iii} .	1'0"	0.31
Shale, grey silty, with rare thin fine grained sandstones. A layer of contorted shale circa1m thick is present in the lower 2m .	82'3"	25.06
Limestone, ankeritic, greenish grey, well bedded, N. Nuculum E. bisulcatum mut.B, Dimorphoceras sp., Aviculopecten sp., plant foliage of Pecopteris sp., Loc. 067, E_2c_{2i} .	1'0"	0.31

1. Identification of N.nuculum confirmed by Dr. Ramsbottom.

Section 7T, Gun End Stream

The E_2c_2 faunal bands present in this section are contained in thin grey ankeritic limestones and the lower one is duplicated by faulting, the succession is as follows:-

	ft in.	m
Blue grey silty shale, with thin sandstone streaks.	7'6"	2.28
Limestone, grey, ankeritic, N.nuculum, E.bisulcatum, Dimorphoceras sp., P.corrugata, Calamites sp., Posidoniella sp. abundant on a bedding plane 1" from the top of the bed., Loc. 044, E_2c_{2iii} .	1'0"	0.31
No exposure .	10'0"	3.1
Shale, blue grey .	8'0"	2.44
Siltstone .	0'3"	0.08
Shale, blue grey .	14'0"	4.3
Limestone, dark grey, silty, ankeritic, Posidoniella sp., (? E_2c_{2ii}) .	0'6"	0.15
Shale, blue grey .	6'0"	1.83
Siderite, nodules .	0'3"	0.08
Shale, blue grey .	10'0"	3.1
Mudstone, silty calcareous .	0'4"	0.10
Shale, blue grey .	16'0"	4.9
Faulted ground .	6'0"	1.83
Shale, blue grey .	24'0"	7.32
Sandstone, fine grained .	0'1"	0.03
Shale, blue grey .	0'4"	0.10
Sandstone, fine grained .	0'1"	0.03
Shale .	2'4"	0.71
Limestone, grey, ankeritic, N.nuculum, Dimorphoceras sp., plant debris, Loc. 046, E_2c_{2i} .	0'10"	0.24

	ft in.	m
Fault gouge .	0'6"	0.15
No exposure .	10'0"	3.1

Succession from second sandstone above Loc. 046 repeated.

The Eumorphoceras collected from the faunal band at Loc. 044 is poorly preserved and no detail of the rib structure is present. Within the upper 2" of the limestone at Loc. 044 a bedding plane crowded with Posidoniella sp. occurs, this type of occurrence appears to be unique at this level in the succession.

Section 12T, Old Quarry at Roughwood End near Endon

A single E_2c_2 faunal band is present at this exposure, Loc. 023, and is contained in a partially decomposed ankeritic limestone which occurs below a succession of sandstones outcropping at the southern end of a disused 'marl pit'. The quarry is overgrown and partially infilled, no strata are exposed below the E_2c_2 faunal horizon.

	ft in.	m
Sandstone, fine grained .	0'3½"	0.09
Shale, black P.corrugata .	1'3"	0.35
Limestone, ankeritic, dark grey, N.nuculum, Eumorphoceras bisulcatum s.l. Girty, Dimorphoceras sp., Aviculopecten sp., Loc. 023, E_2c_2 .	1'5½"	0.43

Section 9T, Thorncliffe Stream

Only one faunal band with an E_2c_2 fauna has been recorded from this section, it is contained in an ankeritic limestone which outcrops at the base of a shale cliff on the south bank of the stream at Loc. 105, close to the confluence of a small stream with the main Thorncliffe Stream, the succession is as follows:-

	ft in.	m
Limestone, ankeritic, H.subglobosum, Loc. 103, H_1a_i .	0.4½"	0.09
Shaley, mudstone, blue grey, silty, containing a single unfossiliferous ankeritic bullion (max 8") 16'0" below Loc. 103, which is the probable equivalent of the E_2c_{2iii} horizon .	25'0"	7.62
No exposure .	59'0"	17.98
Mudstone, blue grey, silty .	6'0"	1.83
Limestone, greenish grey, parting planes parallel to the bedding, Anthracoceras sp.	1'0"	0.31
Mudstone, blue grey, silty .	6'0"	1.83
Limestone, dark blue grey, ankeritic, N.nuculum, E.bisulcatum, Posidoniella sp., fragments of plant stems, Loc. 105, E_2c_{2i} .	0'6"	0.15

The position of the E_2c_2 horizon at Loc. 105 is 97 ft (29.5m) below the first H_1a horizon, and on the basis of comparison with the Gun End and Hurdlow sections it would appear that this is the lowest E_2c_2 band. Further evidence to suggest this is present in the Ashover Borehole Logs (Ramsbottom et al., 1962) which record the presence of an Anthracoceras or Dimorphoceras sp. horizon 6'9½" above the E_2c_{2i} faunal band in the Tansley Borehole and within 8'0" of the lowest E_2c_2 horizon in the Uppertown Borehole.

Section 15T, Oakenclough Stream

	ft in.	m
Limestone, blue grey, ankeritic, with closely spaced vertical joints, N.nuculum, E.bisulcatum, P.corrugata, Dimorphoceras sp., plant foliage cf. Annularia sp., Loc. 162, E_2c_{2iii} .	0'9"	0.23
Mudstone, blue grey .	1'8"	0.50
No exposure, possible fault .	5'0"	1.52
Partially exposed blue grey mudstone .	54'0"	16.46
Mudstone, black, N.nuculum.	0'6"	0.15

	ft in.	m
Limestone, decomposed, decalcified, blue grey, muddy, iron stained, N.nuculum and ? E.bisulcatum, Loc. 163, E_2c_{2i} .	0'8"	0.20
Mudstone, blue grey, with ½" streak of quartzitic sandstone 9" from top	7'0"	2.13

Note: This section has previously been recorded by Holdsworth (1963) and his Locs. 127 and 284b are respectively Locs. 162 and 163 of the above. In addition to the above faunas Holdsworth (1963) records Cravenoceras sp. at Loc. 127.

Section 16T, Combes Brook

The lowest E_2c_2 faunal band is exposed in this section in the bed of the Combes Brook at the foot of a mudstone cliff which is located on the outer side of a large meander, Loc. 083. The band is contained in an ankeritic limestone, 0.60m thick, which is continuously exposed along the strike for some 10m and is bisected by a small fault which produces a dislocation of circa 1m. Downstream from Loc. 083 the middle and upper E_2c_2 faunal bands are present in the stream bed, visible only at low water. An isolated exposure of what is probably the lower E_2c_2 faunal band, occurs in the bed of a small tributary of the Combes Brook, the Black Hill Wood Stream, at Loc. 085, at a point some 3m downstream from a small culvert which takes the stream below a stone wall. (see map Fig. IVA)

Succession

	m.	ft in.
Partially exposed, blue grey, silty, mudstone.		
Limestone, dark blue grey, ankeritic, N.nuculum, P.corrugata, Loc. 081, E_2c_{2iii} .	0.07	0'3"
Partially exposed, blue grey, silty, mudstone .	19.00	62'0"
Limestone, greenish grey, ankeritic, Dimorphoceras sp.	0.10	0'4"

	m.	ft in.
Partially exposed, blue grey, silty, mudstone .	14.00	46'0"
Limestone, dark blue grey, ankeritic, N.nuculum, Posidoniella aff. vetusta, Loc. 082, E_2c_{2ii} .	0.10	0'4"
Partially exposed, blue grey, silty, mudstone with thin siderite bands .	6.24	20'6"
Siderite band .	0.08	0'3"
Mudstone, blue grey, silty .	1.68	5'6"
Limestone, dark blue grey, ankeritic, N.nuculum, E.bisulcatum, Calamites sp., Cordiates sp., Loc. 083, E_2c_{2i} .	0.60	2'0"

The Swallow Brook Section

The Swallow Brook Section which was previously recorded by Holdsworth (1963) was re-examined and bullion material was collected from the various exposures, for the purpose of examining the microfauna. During the course of this work a previously unidentified Ceratoikiscum was recorded at Loc. 210. Four in situ faunal horizons carrying N.nuculum and one carrying Dimorphoceras sp. occur in this section and have been assigned to the appropriate faunal bands on the basis of comparison with other sections in the Subzone.

The succession in the Swallow Brook, which is difficult to measure due to varying shallow dips and limited exposure, is as follows:-

	ft	m.
Limestone bullion bed, (in situ) Loc. 211, H.subglobosum .	1 (max)	0.30
Mudstone, black, partially exposed .	100	30.50
Limestone bullion bed, (in situ) Loc 284 (Holdsworth, 1963) N.nuculum, E.bisulcatum aff. mut.B, Albaillella Sp. (rare), E_2c_{2iii} .	1 (max)	0.30
Mudstone, black .	2	0.60
Limestone bullion (Loose), fauna as for Loc. 284 .	1 (max)	0.30

	ft	m.
Mudstone, black, partially exposed .	14	4.30
Limestone bullion bed (in situ), Loc. 210, N.nuculum, E.bisulcatum, Ceratoikiscum sp., Radiolaria Genus B, Albaillella sp., Albaillella aff. pennata, E_2c_{2iii} .	1 (max)	0.30
Mudstone, black, partially exposed .	7	2.15
Limestone bullion bed (in situ), Loc. 309 (Holdsworth, 1963) Dimorphoceras sp., Albaillella sp. (rare), Ceratoikiscum sp. (a rare, minute bicancellate form) .	1 (max)	0.30
Mudstone, black, partially exposed .	24	7.3
Limestone bullion (Loose), Loc. 308 (Holdsworth, 1963), N.nuculum, Ceratoikiscum tricancellatum, Ceratoikiscum triangulatum, Ceratoikiscum lorum, Albaillella aff. pennata (N.B. stratigraphic horizon believed to be as for 306B) .	1 (max)	0.30
Mudstone, black, partially exposed .	10	3.0
Limestone bullion bed (in situ), Loc. 307 (Holdsworth, 1965) N.nuculum, E.bisulcatum, E_2c_{2ii} .	1 (max)	0.30
Mudstone, black, partially exposed .	30	9.1
Limestone bullion (Loose), Loc. 306 (Holdsworth, 1963), N.nuculum, E.bisulcatum s.l., E.bisulcatum mut.B, Posidoniella cf. variablis, Ceratoikiscum tricancellatum (rare), Albaillella sp. (rare). A culvert is present in the stream immediately above Loc. 306 (N.B. Stratigraphic horizon near to 306B)*	0.5 (max)	0.15
Mudstone, black, partially exposed .	40	12.2
Limestone bullion bed (in situ), Loc. 306B (Holdsworth, 1963), N.nuculum, Ceratoikiscum tricancellatum, Ceratoikiscum sp., Albaillella sp., E_2c_{2i} .	1 (max)	0.30
Mudstone, black, partially exposed .	60	18.3
The Cherts .	circa 2	0.60
Mudstone, black, partially exposed .	40	12.2
Stannery Limestone .	circa 3	1.0

* The 306 limestone is totally unlike that of 306B, but 306B compares very closely in lithology with 308.

Preservation of fauna in the E_2c_2 Subzone

In the area of study the E_2c_2 faunal bands commonly occur in thin, persistent, blue grey, ankeritic limestones, and infrequently as lenticular bullions of the same lithology. In the proposed deep, land remote parts of the Basin, e.g. Swallow Brook, E_2c_2 faunal bands may, however, be present in dark grey to black calcite bullions. In all the E_2c_2 faunal bands present in the North Staffordshire area mature goniatites are only sparsely represented.

In the ankeritic limestones the zone fossil, N.nuculum, is commonly preserved as a crushed and flattened impression of which some 80-90% appear as fragmentary impressions of the venter, although in the calcite bullions, uncrushed specimens occur, which may display fragmentary preservation of the shell structure.

The ornament of N.nuculum is variously represented in the ankerites, some specimens display strong acute radial ribs and traces of a subordinate spiral ornament. In other specimens from the same locality, and the same horizon, the rib preservation is less acute and appears undulose in cross-section.

Two types of undulose rib structure are present, namely curved undulose and flattened undulose. This varying rib morphology may indicate that initially selective preservation of the various shell layers occurred prior to the formation of the impression.

Specimens of N.nuculum displaying shell structure, have been obtained from calcite bullions at Locs. 306A and 127 of Holdsworth (1963). Examination of these specimens reveals a two layered shell structure, an outer layer, the ostracum, and an inner layer the hypostracum.[1.] In cross-section the outer surface of the ostracum displays an acute rib relief, whilst the inner surface of the hypostracum

1. Terminology applied to the shell structure of the Mollusca by Shrock and Twenhofel (1953)

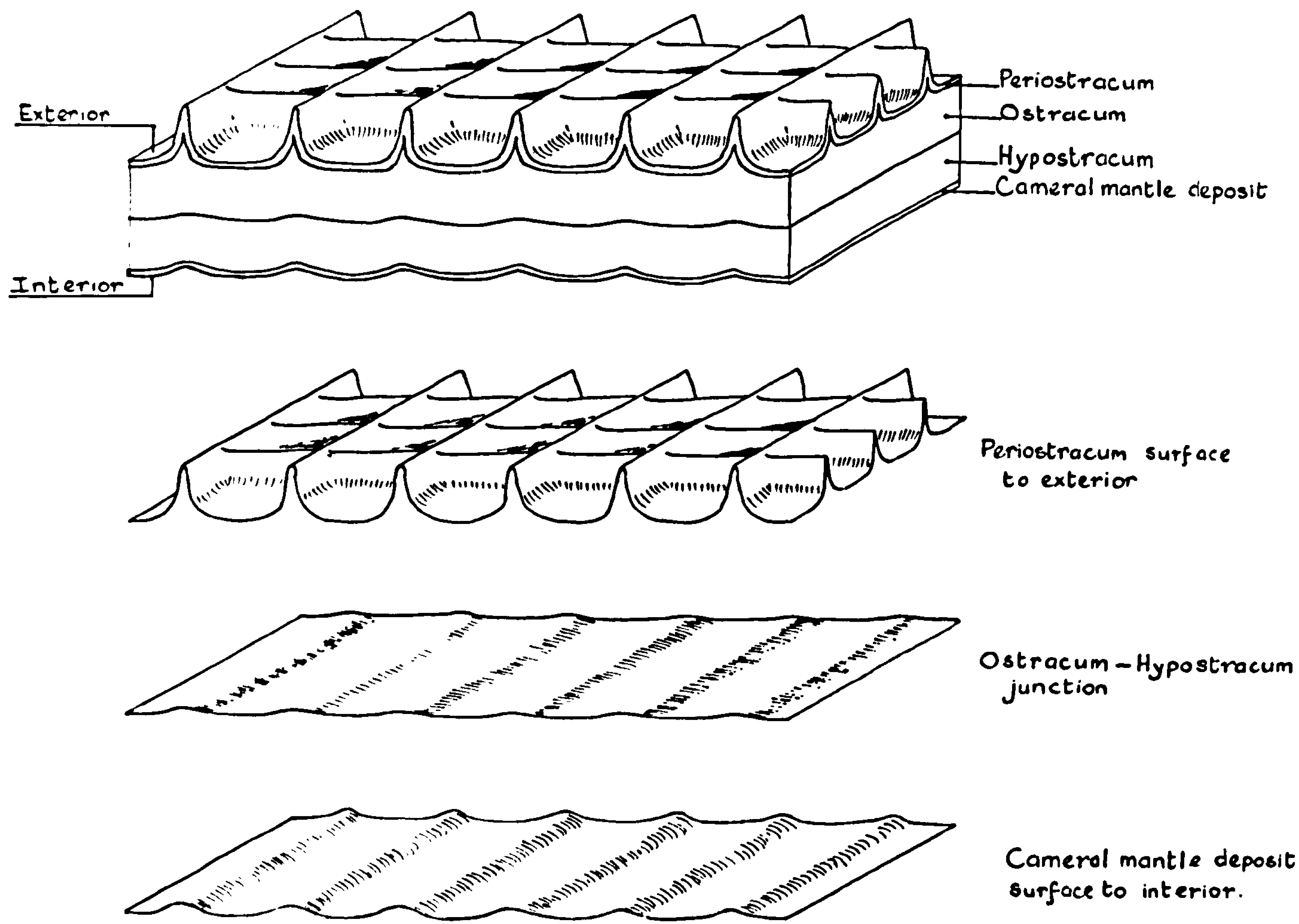
has a curved undulose profile (Fig. lA). The junction between the ostracum and the hypostracum displays a flattened undulating profile.

In the ankerites traces of the subordinate spiral ornament have only been observed in association with the acute form of rib structure and are believed to represent external impressions of the original shell surface. It was also observed, in the calcite bullion specimens, that the external ribbing is reflected by and corresponds exactly with the undulose structures present at the inner surfaces of the shell material.

It is suggested that the variation in ornament exhibited by the specimens of N. nuculum is due to their formation either as impressions of the external or internal surface. Whilst specimens displaying a flattened undulating profile may represent impressions of the surface between the ostracum and hypostracum or may be the result of poor preservation of the external or internal surface. The ostracum and hypostracum shell layers which, by analogy with pelecypod shell structure, probably consisted respectively of calcite and aragonite (Newell, 1937), are thought to have been destroyed during diagenesis of the ankerites by the crystallisation of dolomite. No trace of the internal shell structure is present. It is proposed that the impression of the external ornament of N. nuculum was made by periostracum layer. This organic layer is thought to have formed a barrier to the growth of dolomite crystals, during diagenesis, and has subsequently become carbonised so that it now forms a thin dark film on the impression.

The organic material forming the periostracum (conchiolin or chitin) was probably resistent to bacterial decay and if burial was rapid enough it is suggested that this layer would be preserved. Hetch, in Zobell (1939) states that chitinoclastic bacteria are less active in oxygen poor environments and it is thought possible that rapid burial may have reduced the oxygen level sufficiently to allow for the preservation of the periostracum layer.

FIG.1.A. The shell structure of N.nuculum.



Impressions displaying a curved undulating rib profile but lacking a spiral ornament are thought to have been formed at the inner surface during diagenesis. This layer is thought to have been composed of cameral mantle deposits which are proposed by Fischer and Finley (1949) to be the product of the cameral mantle, and although the composition of the layer is unknown (Flower, 1946), a carbonised film similar to that found on external impressions is present.

It is proposed, therefore, that impressions of the external shell surface resulted from the rapid burial of goniatites with the periostracum layer still intact, whilst specimens in which erosion or bacterial decomposition of the periostracum had taken place are represented by internal impressions.

The absence of spiral ornament on impressions displaying a curved undulose profile is thought to further indicate that their origin was at the interior and not the exterior shell surface. Impressions displaying a flattened undulose profile may have been produced at the junction between the ostracum and hypostracum, and if this is the case the existence of a chitinous layer is implied at this junction. Alternatively, impressions of this type may be poorly preserved impressions of the interior of the shell.

Fauna of the E_2c_2 faunal bands

The complete faunal list of all three E_2c_2 horizons is given below:-

Nuculoceras nuculum, Bisat

Eumorphoceras bisulcatum s.l., Girty

Eumorphoceras bisulcatum Girty mut.B Schmidt

Dimorphoceras sp.

Posidonia corrugata

Posidoniella sp.

Aviculopecten sp.

Calamites sp.

Pecopteris sp.

Annularia sp.

The above fauna, with the possible exception of Eumorphoceras bisulcatum mut. B, occurs in all three faunal bands within the E_2c_2 Subzone.

Identification of N.nuculum

Complete specimens of N.nuculum have not been collected from the faunal bands in this Subzone. The fragmentary specimens all display straight ribs on the lateral area which curve as they pass over the venter to produce a shallow hyponomic sinus. Well preserved external impressions may display traces of a subsidiary spiral ornament which in association with the strong radial ribs produces a weak reticulate ornament, this feature was noted by Bisat (1924) in his original description of the genus, where he states, "Ornament practically identical in adult with reticulatum (type form)....." Rarely specimens are preserved parallel to the median plane and between 14 and 22 mm diameter they possess a characteristically small umbilicus 2-3 mm diameter which may be bordered by a rounded umbilical rim. However, the umbilical rim may not be an original morphological feature and is possibly a product of incomplete crushing of the test on the margin of the umbilicus at a point where greater resistance to deformation has occurred. The ratio of diameter to umbilical diameter (D/u) varies between 7 and 11. Bifurcation of successive ribs in the lateral area has also been observed in some mature specimens. Rib frequency varies in adult forms and it is thought that the variation is sufficiently marked to suggest the occurrence of dimorphism. The recognition of two sexual dimorphs one with rib frequencies, in mature forms, between 20-30 ribs per cm (measured along the venter) and the other with 30-60 ribs per cm is proposed (Fig.1.C.) although measurements of other shell dimensions give no apparent indication of this dimorphism.

Differentiation of the E_2c_2 faunal bands

Holdsworth (1963) suggested that the absence of E.bisulcatum from the lowest N.nuculum band was a feature which allowed for some measure of differentiation, although Ramsbottom et al.,(1963) record the presence of Eumorphoceras ? in association with the lowest N.nuculum horizon in the Ashover Boreholes. In the E_2c_2 localities investigated E.bisulcatum has been recorded from all three N.nuculum horizons. The frequency of occurrence of E.bisulcatum is, however, much less than N.nuculum, which in itself can at best be described as only sparse and it is suggested that the association of the two species in each E_2c_2 faunal band could easily pass unobserved.

The only feature which may enable a distinction to be made between specimens of N.nuculum from different levels in the succession is the variation of the depth of the hyponomic sinus, and provided that sufficient specimens are available for measurement, it has been found possible to distinguish between the N.nuculum population in the highest E_2c_2 faunal band and that in the lowest. The procedure adopted is to measure the depth of the sinus from the mid point of a line tangenial to the adjacent crests and at the same time to record the rib frequency within the areabeing measured. These two variables are plotted (Figs.1.B., 1.C., 1.D., and 1.E.) as the abscissa (depth of sinus) and the ordinate (rib frequency) and a distribution diagram of the area of occurrence of the specimens of N.nuculum from the respective faunal bands is defined. The plotted points are then further analysed and their relative density of occurrence is determined. Finally contours are drawn about areas of equal density of occurrence. In some instances the measurements plot in two well defined areas of the graph and this is interpreted as being the result of sexual dimorphism in the population measured. In an attempt to reduce experimental error, several examinations of the same material were made and in most cases the average of three measurements was plotted. At all horizons as many specimens as possible were examined. However, some exposures were so sparsely fossiliferous that it was not possible to collect sufficient specimens for a viable statistical analysis. The technique is particularly useful in determining the level of isolated E_2c_2 faunal bands, when sufficient specimens are available at such localities.

Two stream sections in which the succession is fully exposed from the lowest H_1a faunal band to the lowest E_2c_2 faunal band were taken as the standards for correlation with other localities. The first of these, the Hurdlow Stream Section, 10T, provided sufficient specimens for analysis at the levels E_2c_{2iii} and E_2c_{2i}, and the distribution diagrams of these horizons are shown in Fig. 1.B. and Fig. 1.C. The respective horizons plot in different areas of the graph and the respective density maxima are in distinctly separate areas. The effects of dimorphism are well displayed in Fig. 1.C. and are thought to be present in Fig. 1.B. where a narrow zone of low frequency of occurrence is present at about 30 ribs/cm.

The number of measurable specimens collected from the second standard section, the Gun End Stream Section, 7T, was somewhat less than obtained from the Hurdlow exposures, however, there is a marked similarity between the distribution diagrams of the E_2c_{2iii} horizons from the respective sections (Fig. 1.B. and Fig. 1.D.). The effect of dimorphism is again evident and is perhaps more marked in the E_2c_{2iii} horizon plotted on Fig. 1.D. than in Fig. 1.B. The E_2c_{2i} horizon plotted on Fig. 1.D. occurs in a similar position to one of the dimorphic forms of N.nuculum depicted in Fig. 1.C. and although the specimens measured are few in number it is thought that they are reasonably characteristic of this faunal band.

An isolated exposure of a faunal band within the E_2c_2 Subzone, occurs at Rough Wood End, Section 12T, Loc. 023, this is the only faunal band exposed in the Lower and Middle Churnet Shales in this area. This band contains a fauna of N.nuculum together with a sparse population of E.bisulcatum. The specimens of N.nuculum at this locality are plotted on Fig. 1.E. and comparison of this graph with the two standard sections indicated that the faunal band at Loc. 023 is the highest N.nuculum horizon. In addition Fig. 1.E. has two density maxima both plotting at the 0.4 - 0.5 mm depth range for the hyponomic sinus, one at 25-27 ribs per cm and a second at 40 ribs per cm, these maxima are thought to indicate dimorphism within the N.nuculum population at this locality.

Another isolated exposure of N.nuculum occurs at Loc. 064, a locality adjacent to Section 10T, this faunal band is exposed in a small stream flowing from the north east into Blackshaw Moor Reservoir (SJ 0185 6020). The fauna, which includes E.bisulcatum, is sparse and only a few specimens of N.nuculum are suitable for measurement, however, the majority plot within the area of the graph characteristic of the E_2c_{2iii} horizon.

On the north of the Hurdlow Stream, Section 10T, a major tributary of the Churnet flows through Big Wood (SJ 0264 6110), on the southern bank of this tributary a decomposed ankeritic limestone is exposed at Loc. 065 which on the basis of the associated lithologies equates with the lower N.nuculum horizon in the Hurdlow Stream. Measurement of the hyponomic sinus of the specimens of N.nuculum at Loc. 065 support the lithological evidence and indicate a position within the characteristic graph field of the E_2c_{2i} faunal horizon.

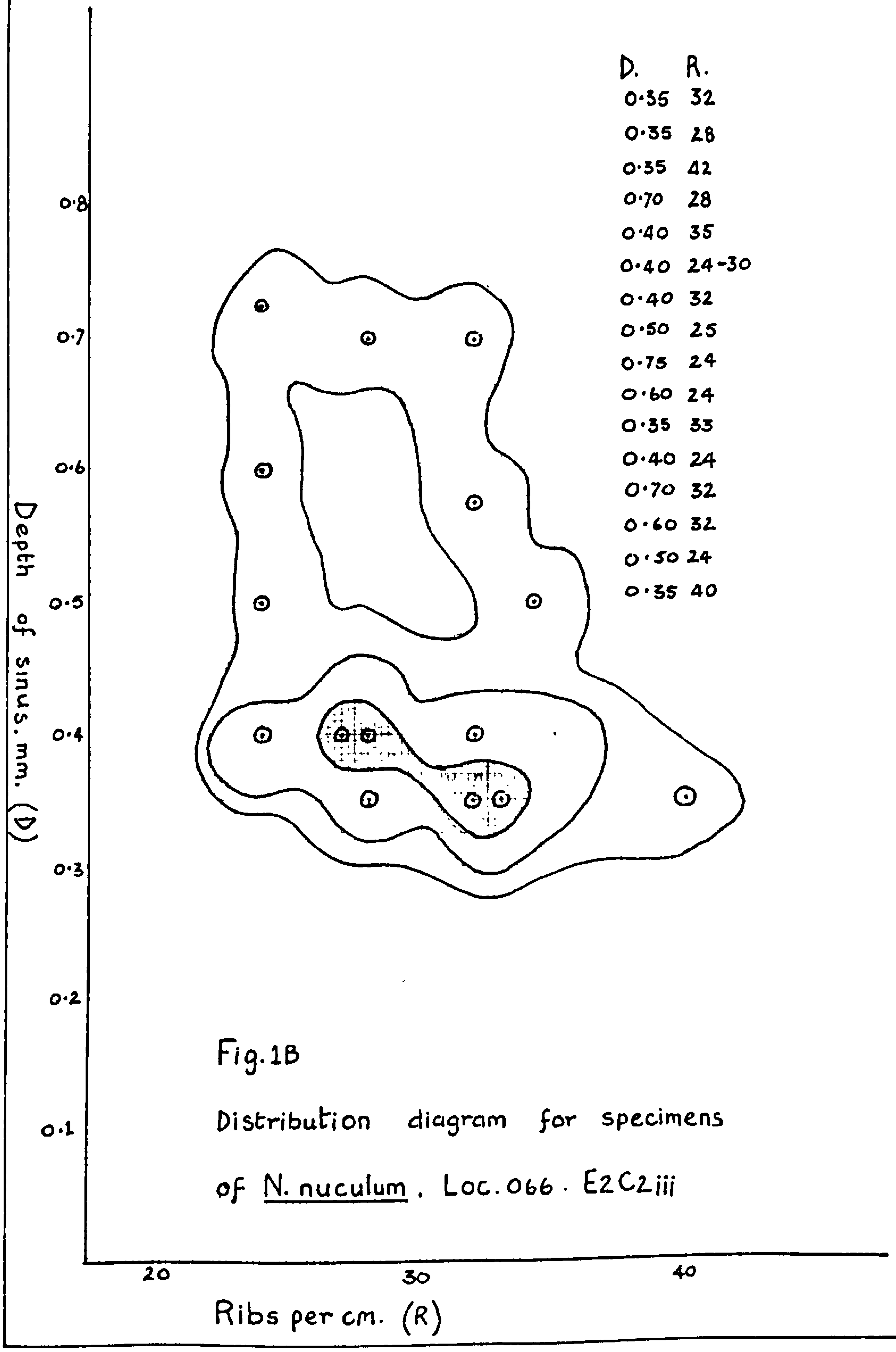
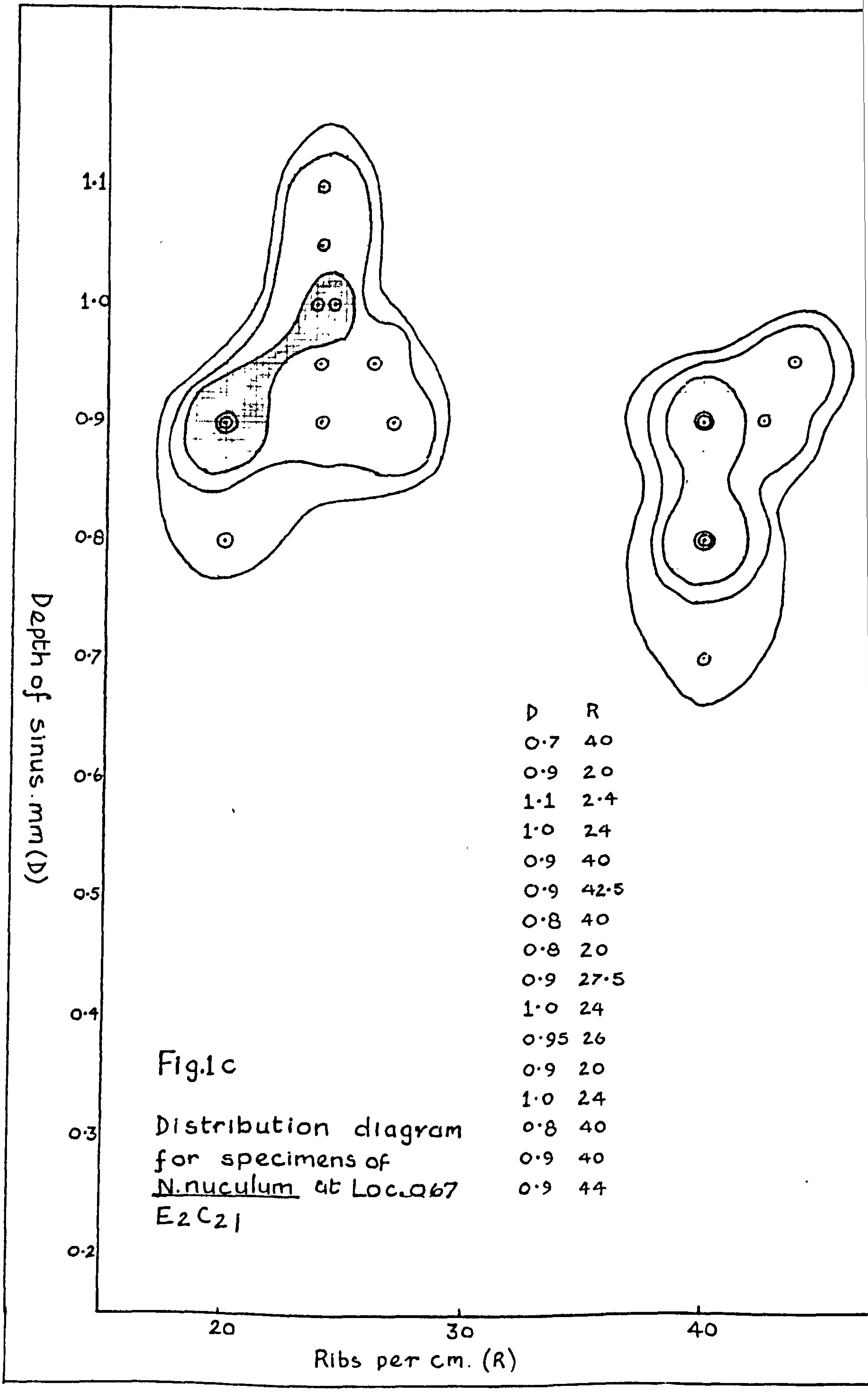


Fig. 1B

Distribution diagram for specimens of N. nuculum. Loc. 066. E2C2iii



D	R
0·7	40
0·9	20
1·1	2·4
1·0	24
0·9	40
0·9	42·5
0·8	40
0·8	20
0·9	27·5
1·0	24
0·95	26
0·9	20
1·0	24
0·8	40
0·9	40
0·9	44

Fig.1c

Distribution diagram for specimens of *N.nuculum* at Loc.067 E_2C_{21}

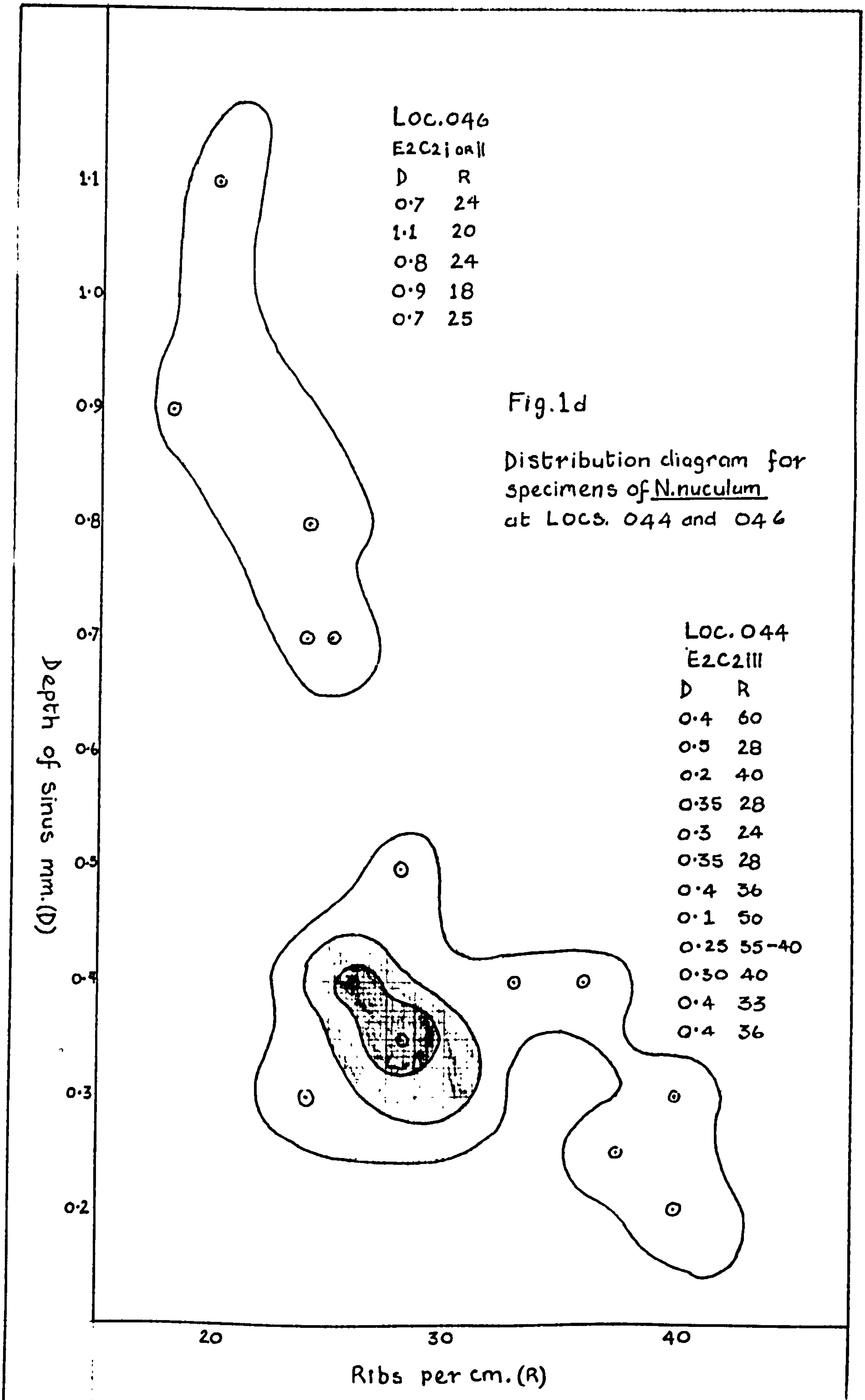


Fig. 1d

Distribution diagram for specimens of N. nuculum at Locs. 044 and 046

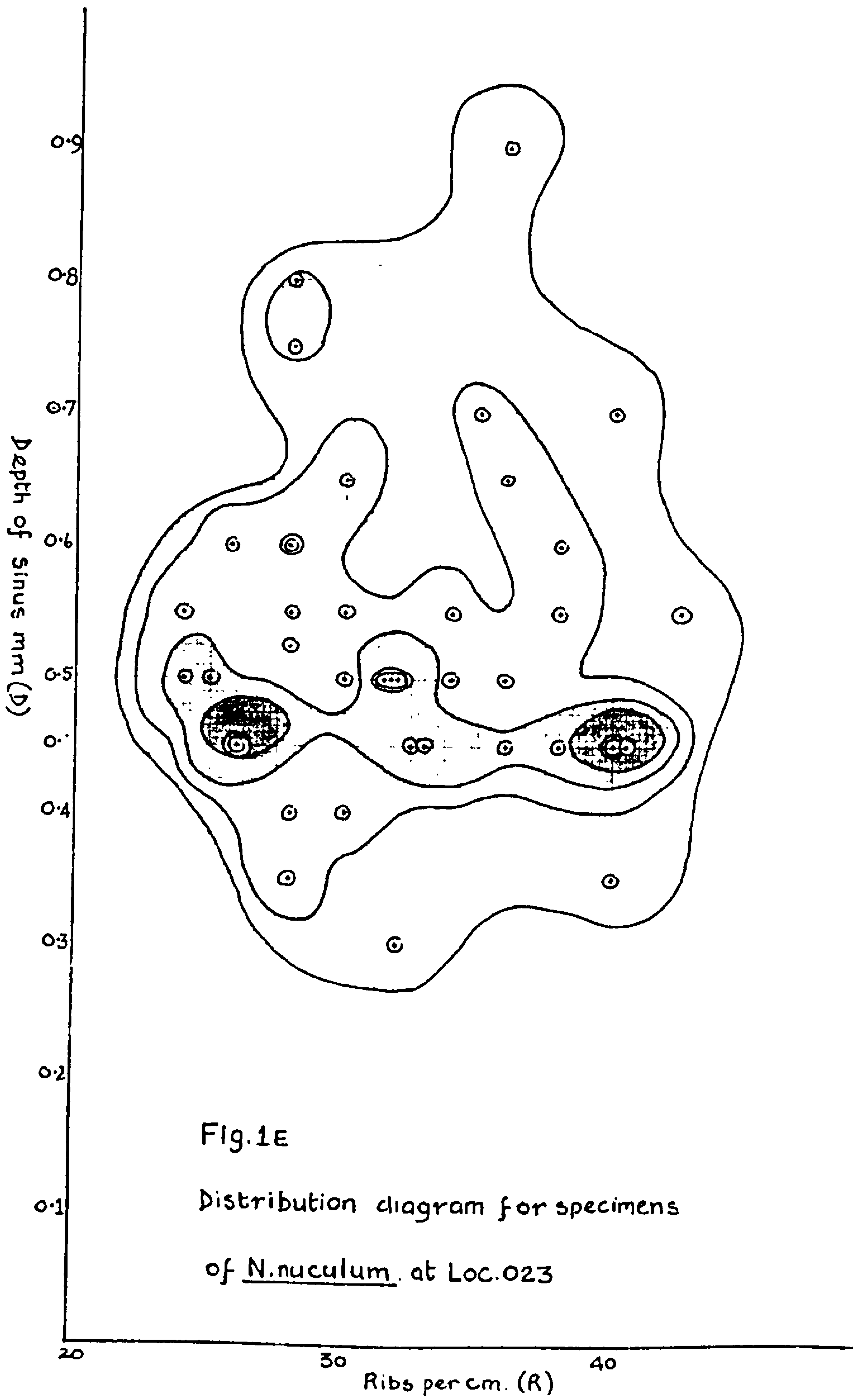


Fig. 1E

Distribution diagram for specimens of N. nuculum at Loc. 023

D	R
0·35	40
0·80	28
0·30	32
0·45	32-34
0·45	30-35
0·45	40
0·40	26
0·35	28
0·75	28
0·45	40
0·45	36
0·65	30
1·10	34
0·70	35
0·65	36
0·90	36
0·50	30
0·70	40
0·60	28
0·50	32
0·40	30
0·50	24
0·50	25
0·45	36-40
0·55	36
0·60	38
0·45	40
0·55	30
0·45	26
0·85	26
0·60	26
0·55	24
0·50	34
0·55	28
0·40	28
0·50	36
0·50	32
0·50	34
0·50	26
0·55	40-45
0·50	28
0·60	28

In the Oakenclough Stream, Section 15T, an E_2c_2 faunal band is present at Loc. 162, some 10m below an H_1a horizon at Loc. 161, and 18m above an E_2c_2 horizon at Loc. 163. The highest E_2c_2 faunal band in this section (Loc. 162) contains a fauna of N.nuculum together with specimens of E.bisulcatum which are only sparsely represented. The plot of the measurements made on the specimens of N.nuculum from Loc. 162 lies in the graph field characteristic of the E_2c_{2iii} faunal horizon, confirming the position of this horizon based on the field evidence. Three faunal bands each containing N.nuculum are present in the Combes Valley, Section 16T, measurements made on specimens from the highest of these horizons plot in the graph field of E_2c_{2iii} as defined by Fig. 1.B. and Fig. 1.D. The lowest E_2c_2 horizon in this stream section is very sparsely fossiliferous and insufficient data is available for a viable statistical analysis.

The occurrence and identification of Eumorphoceras bisulcatum in the E_2c_2 faunal bands

Specimens of Eumorphoceras bisulcatum have been identified from all three E_2c_2 faunal bands, and in particular they have been collected from sections where the relative stratigraphical position of the respective E_2c_2 faunal bands is not in question. Such a section is exposed in the Hurdlow Stream, Section 10T, here the $E_2c_{2\ iii}$ faunal band, Loc. 066, contains external impressions of E.bisulcatum, which have a diameter of 10mm, and at this size carry 16-18 ribs/whorl. The majority of the ribs curve slightly forward prior to merging with the sulcus, although some shorter ribs are present in the second half of the final whorl which do not reach the sulcus and do not appear to curve. Marked irregularity in rib spacing appears to be a feature of the second half of the final whorl although this irregularity cannot be interpreted as being due to rib pairing. The diameter of the specimens collected from Loc. 066 suggests that they may be immature forms since specimens of E.bisulcatum occurring in association with N.nuculum at Pennant Clough, Lancashire, and described by Bisat (1924) have a test diameter of 14 mm. The preservation of the specimens at Loc. 066 is such that no description of the fine ornament, due to the presence of growth lines, as mentioned by Girty (1909) and Bisat (1924) can be given. The specimens of E.bisulcatum collected from Loc. 066 differ from Eumorphoceras bisulcatum described by Girty (1909) mainly in the development of the previously discussed irregular rib spacing, neither can they be equated, in the absence of rib pairings with the specimens described by Schmidt (1934) as E.bisulcatum mut B., which were also found in association with N.nuculum. They are however closely allied if not idientical with Holdsworth's (1963) specimens 306^5 and 306^6, and on this basis are identified as Eumorphoceras bisulcatum s.l. Girty. (P.1.5)

Within Section 10T, several specimens of E.bisulcatum were collected from the E_2c_{2i} faunal horizon at Loc. 067 and in particular one specimen displays almost complete preservation (90%) in the median plane. This specimen has a diameter of 14 mm and a rib count of 18-20 ribs in the final whorl. In the second half of the final whorl a distinct pairing of the ribs occurs, the ribs become shorter as the apperture is approached and do not cross the lateral area to merge with the sulcus, the final rib pair are very short and are restricted to the umbilical margin. On the other hand the ribs present on the first half of the final whorl are unpaired and are similar to those found in specimens from Loc. 066. However, the two are readily distinguished by the marked difference exhibited by the ribbing in the second half of the final whorl. The characteristics displayed by the specimens of E.bisulcatum present in this the lowest N.nuculum horizon are clearly identical with those proposed by Schmidt (1934) for E.bisulcatum mut B., that is a form of 15 mm diameter, having 18 ribs per whorl, in which pairing of the ribs occurs in

P.1.5.

Eumorphoceras bisulcatum S.l., Girty.

x 4.

From the E_2c_{2iii} faunal band in the Hurdlow Stream at Loc. 066.

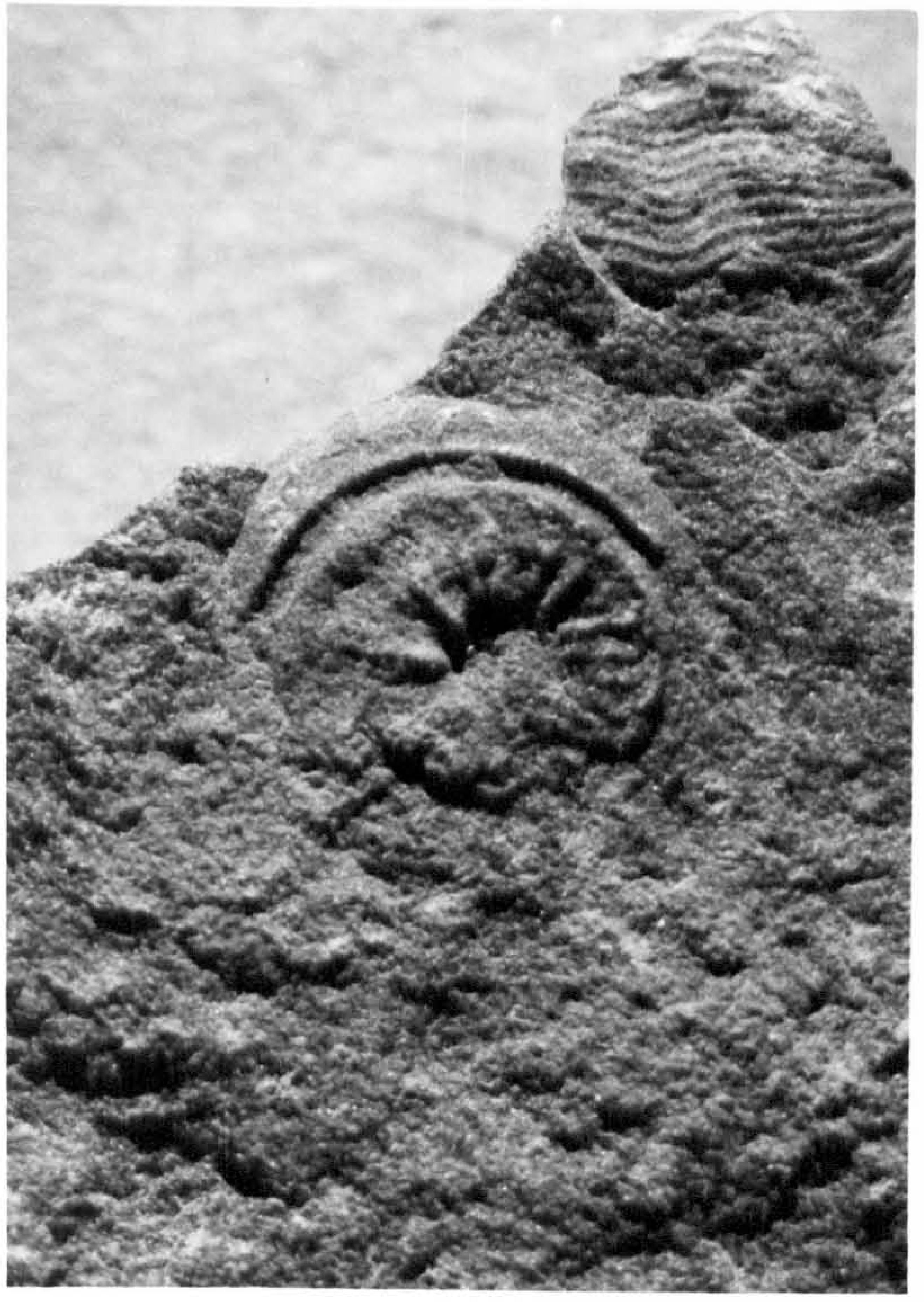
P.1.6.

Eumorphoceras bisulcatum Girty mut.B Schmidt

x 4.5

From the E_2c_{2i} faunal band in the Hurdlow Stream at Loc. 067.

P.1.5.



P.1.6.

in the adult stage, and on this basis the specimens present at Loc. 067 are identified as Eumorphoceras bisulcatum Girty mut B. Schmidt. (P.1.6.)

From the above it might appear that E.bisulcatum mut B. is characteristic of the lowest N.nuculum faunal band whilst the highest E_2c_{2iii} faunal band is characterised by a mutant of E.bisulcatum in which an irregular rib pattern is present in the second half of the final whorl, and has been identified (ibid) as E.bisulcatum s.l. Girty. The record of the Ashover Boreholes (Ramsbottom et al., 1962) shows, however, that the highest N.nuculum horizon, E_2c_{2iii}, in the Highoredish borehole contains, in addition to the eponymous goniatite, both E.bisulcatum mut B and E.bisulcatum s.l. (not mut B). Holdsworth (1963) records E.bisulcatum aff. mut B from the E_2c_{2iii} horizon in the Swallow Brook.

Thus it would appear that a distinction between the upper and lower E_2c_2 horizons on the basis of the occurrence of different mutants of E.bisulcatum at different levels is not possible. It is thought that a more likely explanation for the different forms of E.bisulcatum present in this Subzone is, that like the associated goniatite N.nuculum, they are present as sexual dimorphs. In adolescence the dimorphs display identical rib development and pattern, and only in maturity is a distinction apparent. Measurements of the specimens of E.bisulcatum present in Section 10T also indicate a slight size difference which according to Makowski (1962) and Palframan (1966) is another feature of dimorphism in the Ammonoidea.

THE FAUNAL BANDS IN THE H_1a ZONE

The base of the Chokierian Stage is denoted by the lowest faunal horizon containing Homoceras subglobosum Bisat. Commonly three well defined faunal bands containing H.subglobosum are present in the H_1a Zone, and in this account they are designated H_1a_i, H_1a_{ii}, and H_1a_{iii}. In the area covered by the Macclesfield Memoir (110), Evans et al. (1968) state, "The Homoceras subglobosum Zone occurs in typical fashion with at least three bands which contain abundant H. subglobosum." The H_1a faunal bands present in the Ashover Boreholes (Ramsbottom et al., 1962) occur as three distinct horizons in the Tansley and Highoredish boreholes.

Thicknesses of strata within the H_1a Zone

A complete exposure of strata between the lowest and highest H_1a faunal bands occurs in the Dingle Brook, Section 14T, and here the interval is 54'6" (16.5m). In the Hurdlow Stream, Section 10T the same interval is less well exposed and was measured as being 39'0" (11.6m), in this section the exposure between the lowest H_1a and the highest E_2c_2 faunal bands is complete and is measured at 17'3" (5.2m), whilst the distance between these to faunal bands in the Gun End Stream, Section 7T, is 25'6" (7.75m). Evans et al. (1968) suggest that in the area covered by the Macclesfield Memoir (110) that the thickness of the H_1a Zone is circa 90' and that the interval containing the H_1a faunal bands is about 50', the latter figure agrees well with the thicknesses measured by the writer on the west of the area covered by this research, although a thinning of this interval by some 10' to 15' is apparent in the more easterly localities.

Localities and Sections within the H_1a Zone

Section 14T, Dingle Brook

The faunal bands present in this section outcrop in the stream bed at Locs. 030, 030a, and 030b and are contained in bullion horizons of dark grey to black limestone:-

		ft in.	m
Limestone, blue grey, silty, well bedded, Homoceras sp., Posidonia sp. .		0'4"	0.10
Mudstone, grey, silty .		2'0"	0.60
Calcareous mudstone, dark grey .		0'6"	0.15
Mudstone, silty .		7'6"	2.28
Sandstone, fine grained .		0'3½"	0.09
Mudstone, silty .		8'0"	2.44
Limestone bullion bed, dark grey to black, Loc. 030, H.subglobosum, H_1a_{iii} .	(max)	0'4"	0.10
Mudstone, silty .		6'6"	1.98
Single limestone bullion, sparse population of immature H.subglobosum.	(max)	0'3½"	0.09
Mudstone, grey, silty .		6'0"	1.83
Calcareous mudstone, dark grey, Posidonia sp. .		0'3"	0.07
Mudstone, blue grey, silty .		11'6"	3.50
Mudstone, dark grey, calcareous, Dunbarella sp., small poorly preserved goniatites, H.sp.		0'6"	0.15
Mudstone, blue grey, silty .		6'0"	1.83
Limestone bullion bed, dark grey to black, Loc. 030a, H.subglobosum, H_1a_{ii} .	(max)	0'4"	0.10
Mudstone, blue grey, silty, with thin sandstone streaks .		22'5¾"	6.86
Limestone bullion bed, dark grey to black, Loc. 030b, H.subglobosum, H_1a_i .	(max)	0'6"	0.15

Thorncliffe Stream, Section 9T

This section possesses three faunal bands containing mature specimens of H. subglobosum which are exposed in the banks and the bed of the Thorncliffe Stream at Locs. 101a, 102 and 103:-

		ft in.	m
Shale, dark grey, calcareous, iron stained, Loc. 101a, H. subglobosum, Dimorphoceras sp., Posidonia sp., Aviculopecten sp., H_1a_{iii} .		1'9"	0.53
Shale, dark grey, H. subglobosum, Dimorphoceras sp.		2'0"	0.61
Shale, dark grey .		1'6"	0.45
Mudstone, blue grey, calcareous, passing laterally into black limestone bullions containing a sparse population of immature H. subglobosum, Loc. 101 .	(max)	1'0"	0.31
Shale, blue grey, silty .		20'0"	6.10
Sandstone, coarse grained .		5'0"	1.52
Fault (throw estimated to be less than 5'0") .			
Shale, blue grey, silty .		5'0"	1.52
Limestone bullion bed, blue grey, ankeritic, Loc. 102, H. subglobosum, plant foliage of. Annularia sp., H_1a_{ii} .	(max)	0'6"	
Shale, blue grey, silty .		19'0"	5.79
Shale, black, Loc. 103, H. subglobosum, Dimorphoceras sp., Posidonia sp., H_1a_i .			
Limestone blue grey ankeritic, sparse fauna of immature H. subglobosum, Posidonia sp., Posidoniella sp., in top 1" of this bed .		0'4½"	0.09

Hurdlow Stream, Section 10T

Three H_1a faunal bands are present in this section. At Loc. 061b a limestone bullion bed contains the first H_1a faunal band and is exposed in a low cliff forming the east bank of the stream. A small waterfall at the confluence of the Hurdlow stream and the main Churnet tributary marks the outcrop of a limestone bullion bed containing the second H_1a faunal band at Loc. 061a. In the main Churnet tributary the highest H_1a faunal band is present within a grey clay overlying a brecciated ankeritic limestone bullion bed which outcrops on the north bank of a sharp bend in the stream at Loc. 061. The succession is as follows:-

		ft in.	m
No exposure .		34'0"	10.36
Grey clay, lenticular (possibly a decalcified Limestone bullion horizon), H.subglobosum, Dimorphoceras sp., plant stems.	(max)	0'5"	0.12
Limestone bullion bed, blue grey, ankeritic, brecciated, Loc. 061, H.subglobosum, H_1a_{iii} .	(max)	0'5"	0.12
Mudstone, blue grey, shaley .		3'0"	0.91
No exposure .		5'0"	1.52
Shale, black, with jarosite, passing upwards to blue grey shale .		8'0"	2.44
Shale, black, H.subglobosum, Dimorphoceras sp.		1'6"	0.45
Limestone bullion bed, Loc. 061a, H.subglobosum, H_1a_{ii} .	(max)	0'6"	0.15
No exposure .		5'0"	1.52
Shale, blue grey, silty .		5'0"	1.52
Single ankeritic limestone, bullion 5" x 12"	(max)	0'5"	0.12
Shale, blue grey, silty .		8'0"	2.44
Shale, blue grey, H.subglobosum .		0'6"	0.15
Limestone bullion bed, Loc. 061b, H.subglobosum[1], H_1a_i .	(max)	4½"	0.12

1. Confirmed by Dr. Ramsbottom.

Gun End Stream, Section 7T

Only one H_1a faunal band is present in this section at Loc. 043, this band which is exposed in the stream bed is present in a continuously exposed succession overlying the highest E_2c_2 faunal band in the section and is therefore judged to be the lowest of the H_1a faunal horizons. The succession is as follows:-

	ft in.	m
Shale, grey, hard .	1'0"	0.31
Shale, grey calcareous, parting plane containing abundant Posidonia sp., and plant fragments .	0'6"	0.15
Limestone, black (probably large bullion) Loc. 043, H. subglobosum, H_1a_i .	(max) 1'0"	0.31
Calcareous shale, contains faint impressions of H. subglobosum .	2'0"	0.61

Heath Hay Stream, Section 8T

Three locations containing Homoceras sp., are recorded from this section by Evans et al. (1968), Loc. 97, 98 and 99. During the course of this research Locs. 98 and 99 were identified and H. subglobosum was collected at these localities. The writer was unable to find the Loc. 97 of Evans et al. (1968). The succession is as follows:-

	ft in.	m
Mudstone, blue grey, at base Aviculopecten sp., Dimorphoceras sp.	12'0"	3.66
Limestone, blue grey, silty, ankeritic, Loc. 020, (Loc. 99 Evans et al.), H. subglobosum, Dimorphoceras sp., Aviculopecten sp., H_1a_{iii} .	0'5"	0.13
Mudstone, blue grey .	1'0"	3.66
Sandstone, fine grained, buff .	0'8½"	0.06
Limestone, silty, ankeritic, iron stained, well jointed or crushed Loc. 020a, (Loc. 98 Evans et al.), H. subglobosum, Aviculopecten sp., Dimorphoceras sp., H_1a_{ii} .	0'3"	0.08

Wiggenstall Stream, Section 11T

This section affords the most complete exposure in the H_1a Zone in the east of the area of study, three H_1a faunal bands are present at Locs. 122, 122a and 123. The succession is as follows:-

		ft in.	m
Limestone bullion bed, brecciated, ankeritic, Loc. 122, H.subglobosum, Dimorphoceras sp., H_1a_{iii} .	(max)	1'0"	0.31
No exposure .		8'0"	2.44
Mudstone, blue grey .		5'0"	1.52
No exposure .		3'0"	0.91
Limestone bullion, grey, ankeritic, Loc. 122a, Homoceras sp., H_1a_{ii} .	(max)	1'0"	0.31
Partially exposed mudstone .		13'0"	3.96
Mudstone, dark grey, shaley .		6'0"	1.83
Mudstone, dark grey, shaley, Loc. 123, H.subglobosum, H_1a_i .		0'6"	0.15

The brecciated and recemented ankeritic bullion bed at Loc. 122 displays what appears to be the typical lithogy for this horizon in all the exposures in the east of the area studied and this lithology is also present at this level in Section 10T.

Oakenclough Stream, Section 15T

The succession in the H_1a Zone is as follows:-

		ft in.	m
Sandstone/mudstone unit, Loc. 160 .		13'0"	3.96
Mudstone, blue grey shaley .		8'0"	2.44
Limestone bullion bed, ankeritic, brecciated, Loc. 161, H.subglobosum, H_1a_{iii} .	(max)	0'7"	0.18
No exposure .		30'0"	9.14
Mudstone, blue grey .		22'0"	6.71
Limestone, ankeritic, well jointed, Loc. 162, $E_2c_{2\,iii}$.		0'9"	0.23

Blake Brook, Section 5T

A single H_1a faunal band is present in this section at Loc. 143 and is similarly placed in the succession to the faunal bands at Locs. 161 and 122, in addition it is contained in a brecciated ankerite bullion bed which is the characteristic lithology for this upper H_1a horizon in the east of the area studied.

Fauna of the H_1a faunal bands

The following is the full fauna obtained from all the H_1a fossil localities, the presence or absence of one or more of the forms does not appear to be diagnostic of any particular H_1a horizon.

Homoceras subglobosum Bisat.

Dimorphoceras sp.

Posidonia sp.

Posidoniella sp.

Aviculopecten sp.

Mollusc spat, Radiolaria and spong spicules
(seen on etched surfaces)

Identification of H.subglobosum

The specimens of *H.subglobosum* collected from all the localities in the area of study conform to the original description (Bisat 1924) The fine straight ribs, the small but deep umbilicus, and the presence of constrictions on immature specimens are features which are diagnostic when combined with the subglobose shape and the small size of the conch (circa 10 mm diameter). When preserved in limestone the conch is usually uncrushed, and solid specimens may show details of the simple gently angular stage 3 type suture (Bisat 1924) (P.1.7.). Preservation in mudstone takes the form of flattened external impressions, here the fine frequently developed straight ribs, deep small umbilicus and small median diameter are considered to be sufficient evidence for identification. At some localities (Loc. 061a), the two types of preservation are present within the same faunal band, comparison of specimens from other localities with the above types of specimen preservation proved to be a useful aid in identification.

During the course of examination of the H_1a fauna it has not proved possible to differentiate, on the basis of palaeontological evidence, between the three major H_1a faunal bands. They all contain specimens of H.subglobosum exhibiting varying degrees of maturity, ranging from spat sized forms to a single specimen of 27 mm median diameter, whilst the majority of specimens are within the range 8-10 mm median diameter and specimens of more than 15 mm median diameter occur very infrequently. No differences in the umbilicus were apparent from level to level in the specimens examined, which display umbilical diameters between 1.5 and 2.5 mm, a range common to all horizons in the H_1a Zone. Examination of median transverse sections was undertaken in order to derive a ratio between maximum whorl thickness and total diameter at this whorl size, and to establish if this was a feature which could be used in a differential manner. In all cases the ratio total diameter to maximum whorl thickness was within 1.25:1, to 1.45:1, with the ratio 1.3:1 being the commonest, and giving an indication of the globose nature of the conch. However, there is no evidence to indicate that this ratio shows any significant variation between the faunal bands present in the H_1a Zone.

Another morphological feature which was investigated as a possible differentiating characteristic was the rib frequency. Bisat (1924) measured rib (striae) frequencies at the centre of the venter and found frequencies of about 3 per 2 mm at D - 20 mm, similar measurements made on specimens collected from the North Staffordshire localities indicate rib frequencies of 4 - 5 per mm at D - 8 mm and 3 - 4 per mm at D - 10 - 12 mm. Apparently no significant difference in rib frequency exists between the individual H_1a horizons, although it should be pointed out that measurements were made, largely on immature specimens and it is a possibility that mature specimens may possess different rib frequencies at the different horizons.

Bisat (1924) records the presence of constrictions which he suggest begin to develop on immature specimens of H.subglobosum at D - 2.5 mm and average about 4 per whorl, similar morphological features are present on immature specimens collected from the localities in the area of study. It has been noticed however, that in some cases the incidence of forms displaying constrictions is not uniformly distributed throughout the H_1a Zone, for example in the Thorncliffe Stream, Section 9T, it was observed that immature specimens of H.subglobosum displaying constrictions occur in all the H_1a faunal bands, but, they appear to have a higher frequency of occurrence in the H_1a_{iii} faunal band, (Loc. 101a) than in the lower horizons present in this section and it is suggested that this may be a feature which is distinctive of this highest H_1a faunal horizon.

In Sections 14T and 9T there is evidence of a fourth H_1a faunal horizon containing H.subglobosum which is present, no more than 7'0" (2.13m) below the H_1a_{iii} faunal band and its recognition in a partially exposed succession is of value in determining the position of the upper H_1a faunal band.

This fourth H_1a faunal horizon *is present in the Dingle Brook Section in a* single ankeritic bullion, 6'6" (2.0m) below Loc. 030, and contains a sparse population of immature specimens of H.subglobosum. In the Thorncliffe Section the equivalent faunal horizon is present at Loc. 101, in a black limestone bullion horizon also containing immature specimens of H.subglobosum, the majority possessing a diameter of circa 5 mm but with some individuals present up to 13 mm

P.1.8a.

Homoceras beyrichianum. Displaying dichotomy of the ribs.

x 3.

From the lowest H_1b faunal band in the Wiggenstall Stream at Loc. 170.

P.1.8b.

Homoceras beyrichianum. Detail of the umbilicus.

x 3.

From the lowest H_1b faunal band in the Wiggenstall Stream at Loc. 170.

P.1.7.

P.1.8b.

P.1.8a.

diameter. On this evidence it is suggested that a short lived or weakly developed marine episode occurred in North Staffordshire within the H_1a Zone below the horizon of H_1a_{iii}.

THE FAUNAL BANDS IN THE H_1b ZONE

In the area covered by this research mainly fragmentary exposures occur in the H_1b Zone, and most sections are limited to a maximum of one faunal band containing a fauna characteristic of the H_1b Zone. However, in the Wiggenstall Stream, three distinct faunal bands occur containing the zone fossil Homoceras beyrichianum (de Koninck). Similarly in the Ashover Boreholes (Ramsbottom et al., 1962) three faunal bands containing H.beyrichianum are present within the H_1b Zone.

Thicknesses of Strata within the H_1b Zone

In the Alport borehole (Hudson and Cotton, 1943) strata containing H.beyrichianum were recorded between 190 - 196 ft, whilst in the Ashover Boreholes Ramsbottom et al (1962) recorded the presence of three faunal bands containing H.beyrichianum within 5'6½" of strata in the Tansley borehole. The section within the H_1b Zone in the Wiggenstall Stream, is present, poorly exposed, in the upper course of the stream, separated by faulting from the Cherts at Loc. 124a. Measurement of the true thickness of this part of the succession is complicated by the fragmentary nature of the exposures, the gentle dip and the gradient of the stream bed; however a tentative estimate of 15 - 20 ft (4.5 - 6.0m) is given for the distance between the upper and lower H_1b faunal bands in this section.

Localities and Sections within the H_1b Zone

Section 11T, Wiggenstall Stream

Beds within the H_1b Zone* are exposed in the stream bed on the west side of the Longnor Road (B5053), the succession which is incomplete due to poor exposure is as follows:-

	ft in.	m
Mudstone, grey shaley, containing a thin horizon crowded with H.beyrichianum and Homoceras sp., Loc. 170b, H_1b. Partially exposed mudstone .	5'0"	1.52
Mudstone, dark grey, shaley, H.beyrichianum, Loc. 170b, H_1b .	1'0"	0.31
Partially exposed mudstone .	18'0"	5.5
Mudstone, black, iron stained, H.beyrichianum, Loc. 170, H_1b .	1'0"	0.31

Section 7T, Gun End Stream

A single H.beyrichianum horizon is present in this section at Loc. 042, 39'9½" (12m) below the horizon of Hd. proteum at Loc. 041, details of the exposure at Loc. 042 are as follows:-

	ft in.	m
Shale, blue grey, silty .	1'9"	0.53
Limestone, dark grey, ankeritic, H.beyrichianum .	0'4"	0.10
Shale, grey, H.beyrichianum, Dimorphoceras sp., Loc. 042, H_1b .	0'4"	0.10
Limestone bullions, grey, ankeritic H.beyrichianum .	0'6"	0.15
Shale, silty .	7'0"	2.13

* H.beyrichianum was also identified at this locality by Dr. Aitkinhead.

Section 9Ta, stream to the south of Thorncliffe

A single H_1b faunal band is present in this stream section and the presence of H.beyrichianum from this horizon at Loc. 107 has been confirmed by Dr. Ramsbottom.* The faunal band at Loc. 107 is interpreted as the highest H_1b horizon since it occurs in the succession 6'0" below the horizon of H.smithi, which is exposed at Loc. 106b, the succession is as follows:-

	ft in.	m
Mudstone black, with jarosite, H.smithi, Loc. 106b, H_2a .	2'0"	0.61
Mudstone, blue grey .	1'0"	0.31
Mudstone, calcareous, iron stained, Posidoniella sp.	1'0"	0.31
Mudstone, blue grey, rare Posidoniella sp.	4'0"	1.22
Mudstone, dark blue, calcareous H.beyrichianum, Loc. 107, H_1b .	1'0"	0.31
No exposure .		

Fauna of Homoceras beyrichianum de Koninck

The three faunal bands present in the H_1b Zone in the Ashover Boreholes (Ramsbottom et al., 1962) contain a sparse total fauna of H.beyrichianum, Homoceras sp., Anthracoceras or Dimorphoceras sp., Dunbarella sp., and Posidoniella sp. A similar total fauna is representative of the H_1b localities investigated during the course of this research except for the absence of Dunbarella sp. and Posidoniella sp., in the localities studied. In many cases, as in the Ashover Boreholes, H.beyrichianum was the only fossil present in the faunal band.

Homoceras beyrichianum de Koninck is described by Bisat, 1924 (p.103), under the general description of the Genus Homoceras, as possessing a test ornamented with transverse non-crenulate striae often dichotomising and frequently

* Personal communication via Dr. Aitkinhead.

strong, the hyponimic sinus is slight. Specimens from Loc. 107, section 9Ta, identified by Dr. Ramsbottom as Homoceras beyrichianum are present in mudstone and occur as crushed specimens, the majority being flattened parallel to the median plane.

The conch is evolute with a cone shaped umbilicus which has a diameter of 4 mm at 15 mm D and 6 mm at 24 mm D. An acute umbilical rim may be present although this structure is frequently obscured in crushed specimens. The ornament consists of coarse angular ribs which display a slightly irregular distribution. The majority of specimens present possess straight ribs, which cross the venter without the development of a hyponomic sinus, however some forms display a slight forward curvature of the ribs in the lateral area which may be partly due to deformation during preservation. In the main specimens display a median diameter between 20 - 30 mm although immature specimens are present down to circa 5 mm D.

Dimensions of H.beyrichianum

	D.mm	Ribs per cm	D.mm	Ribs per cm
Loc. 107	17	22	25	-
	18	24 - 28	36	18
	24	20	36	about 20
	30	20	42	16 - 18
Loc. 042	28	18		

In the Wiggenstall Stream, Section 11T, the specimens of H.beyrichianum present at Locs. 170 and 170b appear to be identical, and possess the typical straight coarse angular ribs characteristic of this species (P.1.8.). However, at the intermediate horizon in this section Loc. 170a, the specimens of H.beyrichianum display a slightly finer rib structure and are thought to be the equivalent of the specimens encountered at Loc. 042. The H_1b faunal horizon at this location is the only one present in Section 7T and may well be the second of the three H_1b faunal bands. The H_1b faunal horizon present at Loc. 107 in Section 9Ta contains the typical coarse ribbed form of H.beyrichianum. This faunal band, on the evidence of the adjacent faunal horizon at Loc. 106a, is considered to be the highest of the three H_1b faunal bands.

THE FAUNAL BANDS IN THE H_2a ZONE

The goniatites Hudsonoceras proteum (Brown), Homoceras smithi (Brown) and Homoceras of. undulatum (Brown) occur in this Zone.

Four distinct faunal horizons are present in the H_2a Zone (see Fig. 1.F.) . The lowest horizon containing Hd. proteum (solo) may be followed by an horizon in which Hd. proteum and H. smithi occur on the same parting plane in the faunal band. A third horizon contains H.smithi (solo) whilst the highest horizon contains H.smithi and may also contain H.cf. undulatum.

Localities and Sections within the H_2a Zone

Section 9Ta stream to the south of Thorncliffe, (location of exposure SK00165812)

This is Loc. 54 of Morris (1959) who records the following succession in, "bluish pyritous mudstones ..... In stream bank at 00165812"

4. H.sp., Dimorphoceras sp.

interval 0'9"

3. H.undulatum band

interval 5'0"

2. H.undulatum band (identified by Professor Hodson)

interval 1'0"

1. H.smithi band

The following succession was recorded by the writer from Section 9Ta (SK00165812)

	ft in.	m
Mudstone black, H.smithi, Aviculopecten sp., Dimorphoceras sp., Posidoniella sp., Loc. 106a, H_2a .	4'0"	1.22
Mudstone, blue grey .	5'0"	1.52
Mudstone, black, with jarosite, H.smithi, Dimorphoceras sp., Aviculopecten sp., Posidonia sp., Loc. 106b, H_2a .	2'0"	0.61
Mudstone, blue grey .	1'0"	0.31
Mudstone, calcareous, iron stained, abundant Posidoniella sp.	1'0"	0.31
Mudstone, blue grey, rare Posidoniella sp.	4'0"	1.22
Mudstone, dark blue, calcareous, H.beyrichianum, Loc. 107, H_1b .	1'0"	0.31
No exposure .		

The identification of the specimens of H.beyrichianum at Loc. 107 was confirmed by Dr. Ramsbottom and it appears from the succession recorded by Morris (1959) that this is his "1. H.smithi band". The calcareous mudstone occurring 1'0" below the first H.smithi horizon at Loc. 106b, contains a parting plane crowded with Posidoniella sp. This horizon is thought to be the lateral equivalent of the Hd. proteum horizon and its occurrence may imply that low salinity levels obtained in this locality during Hd. proteum times (see palaeontological discussion). The H.beyrichianum band at Loc. 107, based on evidence present in adjacent sections, is considered to be the highest of the three H_1b faunal horizons.[1]

1. The H_1b faunal band present in Section 7T at Loc. 042, is 40'0" below the Hd. proteum horizon and is thought to be the lowest of the three H_1b faunal bands.

Section 7T, Gun End Stream

		ft in.	m
Fault .			
Shale, dark grey .		4'0"	1.22
Mudstone, black, iron stained, H.smithi, Aviculopecten sp., Posidoniella sp., Posidonia sp., Loc. 040, H_2a .		0'8"	0.20
Shale, grey .		3'4"	1.01
Limestone bullion, greenish grey, ankeritic, Hd. proteum,	(max)	0'8"	0.20

Section 3T, Fairthorn Farm Stream

The faunal bands in this section are exposed at Locs. 180 and 181 in a black mudstone succession which is referred to elsewhere in this thesis as a basinal mudstone. Arenaceous sediment is absent from the succession and it is suggested that in this area, adjacent to the Carboniferous Limestone Massif, that the H_2a Zone displays its minimum thickness (in the area studied) which is of the order of 10'0". To the south east the Ashover Boreholes indicate that the thinning continues over the Carboniferous Limestone Massif and the Hd. proteum - H.smithi interval is contained in 2 - 3 ft of strata.

The succession at Section 3T, is:-

	ft in.	m
Mudstone, black, with jarosite .	2'0"	0.61
Mudstone, dark grey, hard, plant fragments .	0'6"	0.15
Mudstone, black, with jarosite, H.smithi, Dimorphoceras sp., Orthoceras sp., Posidoniella sp., Posidonia sp.	1'0"	0.31
Mudstone, black, with jarosite, abundant H.smithi, Loc. 180, H_2a .	1'0"	0.31
Mudstone, black, with jarosite, H.smithi, Dimorphoceras sp., Aviculopecten sp., Dunbarella sp., Posidonia sp.	1'6"	0.46

		ft in.	m
Mudstone, black, pyritic, with jarosite, H.smithi, Dunbarella sp., Posidoniella sp., Calamites sp.		0'6"	0.15
Limestone bullion, dark grey, ankeritic, Hd. proteum, Loc. 181, H_2a .	(max)	1'0"	0.31
Mudstone, black, shaley, with jarosite, Dunbarella sp.		2'0"	0.61

The detailed succession above is thought to indicate the development of two maximum marine phases represented by the fauna at Locs. 181 and 180. The second H.smithi faunal horizon is not exposed in this section, but is present in the vicinity in Section 4T.

Section 4T Thirklow Farm Stream

This section is recorded at Holdsworth's (1963) Locality 148.

		ft in.	m
Mudstone, grey, with iron cement, plant fragments at base .		1'6"	0.46
Mudstone, grey with pyrite streaks, Dunbarella sp.		0'6"	0.15
Mudstone, black, with jarosite, H.smithi, H. cf.undulatum, Loc. 191, H_2a .		2'0"	0.61
Mudstone, black, with jarosite, Dunbarella sp.		1'0"	0.31
Mudstone, black .		1'0"	0.31
Mudstone, black, Posidoniella sp., Homoceras sp.		0'6"	0.15
Mudstone, grey, with plant fragments .		2'6"	0.76
Mudstone, black, H.smithi, Dunbarella sp., Loc. 190, H_2a .		1'0"	0.31
Mudstone, black, Dunbarella sp., H.sp.		0'6"	0.15
Mudstone, dark grey, Calamites sp.		1'0"	0.31
Mudstone, grey, calcareous, bituminous, H.sp.		0'7"	0.18
Limestone bullion, dark grey, ankeritic, Loc. 148 (Holdsworth)	(max)	0'5"	0.13

P.1.9.

Hudsonoceras proteum.

x 3.

Displaying spiral and transverse striae.

Loc. 010. Pot Bank Quarry, Congleton Edge.

P.1.9.

Specimens of Hd. proteum were not recovered, by the writer, from Holdsworth's Loc. 148, although there seems little doubt that this is the "Hd. proteum Limestone" occurring as it does in the succession below the lower horizon of H.smithi.

The upper H.smithi horizon also contains H.of undulatum, a similar association to this is recorded from one of the Ashover Boreholes (Tansley Borehole) by Ramsbottom et al. (1962).

Section 2Ta, Pot Bank Quarry

The association of H.smithi and Hd. proteum in the Pot Bank Quarry below Congleton Edge, Astbury Loc. 010, is recorded by several authors including: Bisat (1924), Holdsworth (1963) and Evans et al. (1968). The succession and associated fauna present at Loc. 010 are fully recorded in Appendix 1.

Identification of Hudsonoceras proteum (Brown)

The majority of specimens of Hd. proteum (P.1.9.) occur as fragmentary external impressions although rarely solid specimens of 15 - 20 mm D have been collected which display the characteristic compressed discoidal form of the test. Identification must however be frequently based on the recognition of impressions of curved fragments of the lateral area, and the venter, which usually only display traces of the dominant ornament, the spiral striae. Such impressions are found in the ankeritic limestone bullion horizons which with one exception are characteristic of the lithology of the Hd. proteum faunal horizon in the area of study. These bullion limestones frequently contain complete casts of immature specimens of Hd. proteum which are readily identifiable by the diamond shaped cross-section of the whorl. A goniatite displaying ornamentation similar to that seen in Hd. proteum is Hd. ornatum (R_1b), although in well preserved specimens it is apparent that Hd. ornatum possess a smaller umbilicus than Hd. proteum and also that the spiral striae exhibit a more regular spacing in the former.

Identification of Homoceras smithi (Brown)

The use of the association Hd. proteum - H.smithi is perhaps the most positive way of identifying H.smithi, although this is not always possible as is evidenced by the absence of Hd. proteum in Sections 9Ta and 4T.

The major problem in identification arises in distinguishing H.smithi from the associated species H.undulatum, which, quoting Holdsworth (1963) "..... appears to be only barely distinct, ...". Bisat's (1924) descriptions of Homoceras var smithi (Brown 1841) and Homoceras var undulatum (Brown 1841) indicate that apart from a slightly greater rib frequency in H.undulatum, the main difference lies in the presence of a shallow hyponomic sinus in H.undulatum which according to Bisat begins to develop at test diameters of 14 mm.

Another criterion for distinguishing between the two species is suggested by Ramsbottom in Holdsworth (1963), who states that the acuity of rib decreases with increased diameter in H.undulatum, whilst in H.smithi acute ribs persist in the adult form.

In order to try to establish parameters, other than the above, for the identification of H.smithi, specimens of H.smithi from the Hd. proteum - H.smithi interval were examined and comparisons made with specimens of H.smithi from horizons where the Hd. proteum association did not occur.

In Section 3T specimens of H.smithi collected from the first six inches of mudstone above the Hd. proteum bullion horizon at Loc. 181 exhibit the following dimensions:-

D	u	ribs/cm	rib shape	a: b - (The ratio of the (radius of the test (to the depth of the (lingua.
7	2	-	straight	-
9	2	-	straight	-
14	3.5		slightly undulose	-
26	-	24	undulose	3.3:1
28	-	22 - 24	undulose	4:1

Specimens of H.smithi were then examined at six inch intervals up to 4'0" above the Hd. proteum horizon at Loc. 181, and were seen to display the same features as the specimens examined from the shale adjacent to the Hd. proteum bullion level. In particular it was observed that the acute transverse ribs remained straight in adolescent specimens, and an undulose rib structure was developed in the lateral area, producing a forwardly projecting lingua, only in specimens of greater than 14 mm diameter. Examination of immature specimens of H.smithi from Section 3T revealed that the rib development is difficult to detect in specimens less than 5 mm diameter. Whilst in both the adolescent and mature specimens the ribs pass over the venter without the development of an hyponomic sinus.

A second section in which the Hd. proteum - H.smithi association occurs is the Gun End Section, 7T, here the H.smithi faunal band at Loc. 040 contains specimens possessing the following dimensions:-

D	u	ribs/cm	rib shape	a: b
9	4	-	straight	
11	3	-	straight	
12	3	30	straight	
14	3.5	23	slightly undulose	incipient lingua
16	-	-	undulose	5.3 : 1
20	-	30	undulose	3.3 : 1

D	u	ribs/cm	rib shape	a : b
24	-	-	undulose	4.5 : 1
25	-	-	undulose	3.1 : 1
30	-	18	undulose	3.8 : 1
30	-	-	undulose	4 : 1

With exceptions which may be due to deformation of specimens during preservation and possibly due to errors of measurement, it can be seen that these figures are comparable with those from Loc. 181. An important feature underlined by the above figures is that the lingua, increases in depth in early maturity, although this trend appears to be reversed in late maturity. In addition the presence of strong acute ribs on all mature specimens from Loc. 040 supports the identification of this species, whilst the rib frequency is in accordance with Bisat's (1924) figure of 2 to the mm at 15 mm D. Dichotomy of the ribs appears to begin at about 14 mm D, the point of dichotomy may occur at the umbilical rim or near the mid point of the lateral area. In some specimens the dichotomy could more aptly be described as an interdigitation of a subsidiary rib which does not reach the umbilical margin.

Specimens identified as <u>H.smithi</u> from Section 9Ta at Locs. 106a and 106b, from Section 2T at Loc. 010 and from Section 4T at Locs. 190 and 191 all possess similar characteristics to the specimens of <u>H.smithi.</u> from Sections 3T and 7T, and in the range 20 - 25 mm D they exhibit an umbilical diameter of 4 mm with 20 - 26 ribs/cm and a ratio a: b of 3 - 3.5 : 1. In addition the rare venter impressions display an absence of an hyponomic sinus which tends to confirm the initial identification as <u>H.smithi</u> and not <u>H.undulatum</u>.

Discussion of the H_2a Faunal Horizons

In the H_2a faunal band described by Hodson and Van Leckwijck (1958) from the Büsbach section, two faunal horizons separated by a barren interval are recorded. The lower contains Hd. proteum and the upper Hd. proteum and H.smithi in association. In this discussion the lower horizon is called the "Hd. proteum (solo)" horizon.

The Hd. proteum (solo) horizon is present at several localities in the North Staffordshire succession. In the Gun End Stream Section it is contained in an ankeritic bullion limestone of 0.02m maximum thickness at Loc. 041. Ankeritic bullion limestones containing the Hd. proteum (solo) horizon are also present in the Blake Brook at Loc. 141, the Wiggenstall Stream at Loc. 120, the Fairthorn Farm Section at Loc. 181, the Thirklow Farm Section at Loc. 148 (Holdsworth, 1963) and in the Dove at Locs. 203 and 272 a (Holdsworth, 1963).

In the Ashover area the Hd. proteum (solo) horizon is recorded by Ramsbottom et al.(1962) present in an argillaceous succession and is directly overlain by an horizon containing H.smithi (solo). A similar association occurs in the Astbury area at Loc. 010 where a calcareous mudstone 12 inches thick carries the Hd. proteum (solo) horizon in the bottom 10 inches and an horizon of H.smithi (solo) in the top 2 inches. At the junction of these two horizons Hd. proteum and H.smithi are present on the same bedding plane. In the Büsbach section above an Hd. proteum (solo) horizon and separated from it by 0.05 m of coaly shale, Hodson and Van Leckwijck (1958) record a thickness of 0.05 m of shale carrying "a basal layer crowded with Hd. proteum alone and an upper layer with H.smithi only, but, between the two is a band with the two species associated together." A thickness of 0.03 m of shale with productids and Orbiculoidea is recorded from above the H.smithi (solo) horizon in the Büsbach section.

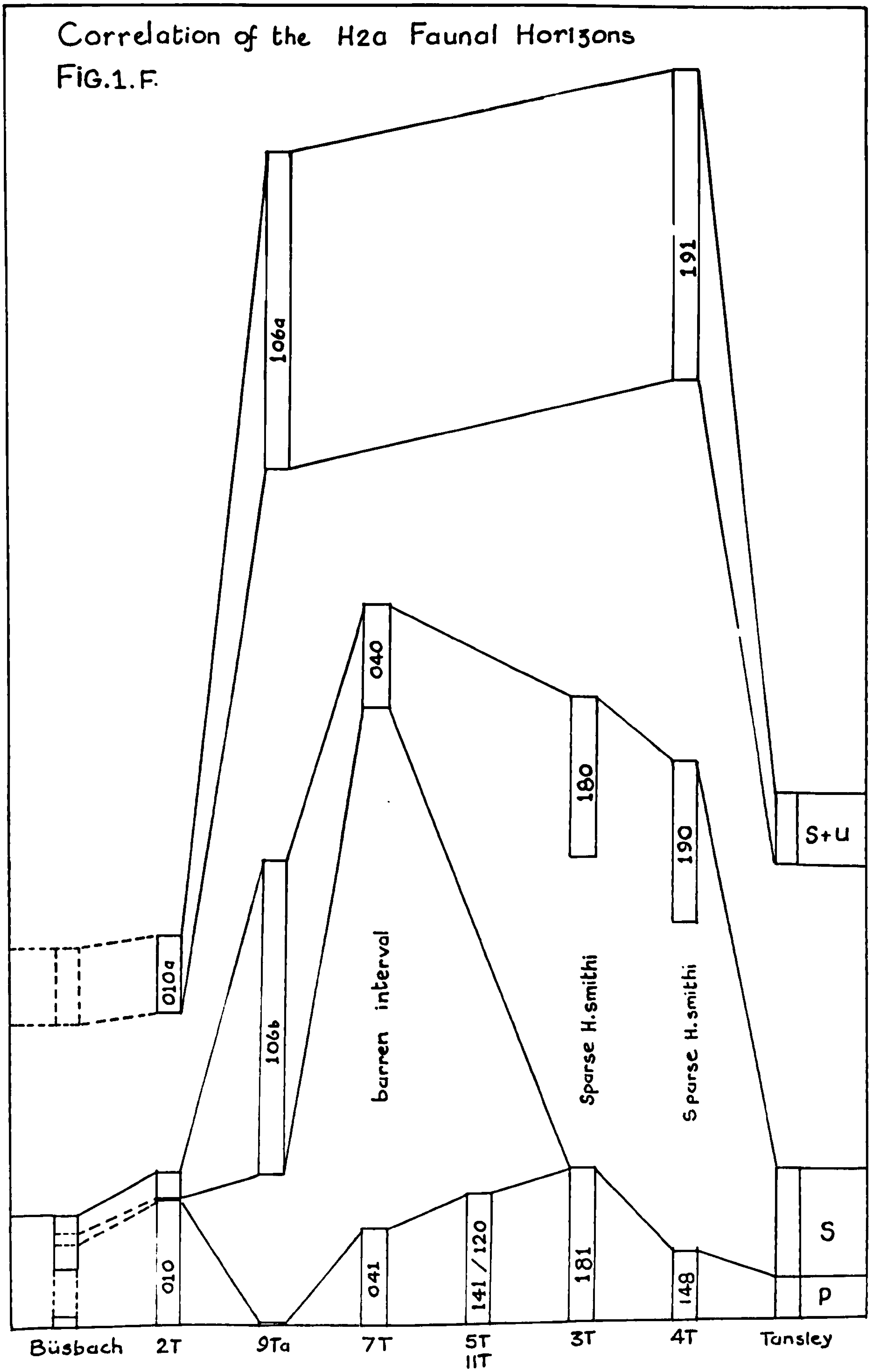
In the Gun End section the Hd. proteum (solo) horizon at Loc. 041 is separated from an horizon containing only H.smithi by 1.01m of barren grey mudstone. It is thought that part or all of this barren interval equates with the Hd. proteum - H.smithi horizon seen in the Astbury succession. In the Thirklow and Fairthorn sections the Hd. proteum - H.smithi horizon cannot be recognised on faunal evidence although the black mudstone carrying an H.smithi (solo) fauna rests directly on limestone bullions containing Hd. proteum (solo) the two faunas are separated by a parting plane. This parting plane, on the evidence of the Büsbach and Astbury successions is presumed to equate with the Hdproteum - H.smithi horizon.

The presence of the barren interval in the Gun End section and its absence in the Fairthorn and Thirklow sections may indicate an extremely slow rate of sedimentation in the latter. Whilst the non-occurrence of a goniatite fauna in the interval between the Hd. proteum (solo) and the H.smithi (solo) horizons in the Gun End section can either be attributed to a lack of preservation (see palaeontological discussion), or, as is thought more likely, its absence is due to the temporary establishment of a localised environment which was unsuitable for goniatite colonisation. This environment is thought to have been produced by a gradual influx of sediment laden fresh water from a local fluvial source, which reduced salinity levels in a restricted area of the Basin. A similar situation is thought to be represented in Section 9Ta, here a thin faunal horizon containing Posidoniella sp. which at this location is thought to be in part the Hd. proteum (solo) - equivalent is separated by 0.31m of barren mudstone from the H.smithi (solo) horizon at Loc. 106b. It is suggested that this barren interval either in part or in total equates with the Hd. proteum - H.smithi faunal horizon and that prior to the genesis of the H.smithi faunal horizon at Loc. 106b, local salinity levels were too low to support a gonitatite population.

An upper H.smithi horizon[1] present in Section 9Ta at Loc. 106a is correlated with an upper H.smithi horizon in the Tansley Borehole (Ramsbottom et al., 1962). The highest H_2a horizon in the Tansley Borehole contains in addition to H.smithi, H. cf.undulatum and is separated from the lower H.smithi (solo) horizon by 1'11½" of mudstone from which the thicker-shelled goniatite phase is absent. In the Thirklow Section the presence of H.undulatum in a faunal horizon with H.smithi is thought to confirm that this is the upper H.smithi horizon in this locality..

In the Astbury succession upper and lower H.smithi horizons cannot be distinguished (see Fig. 1.F.). It is suggested either that the two horizons are present in the 1'8" of argillaceous stratawhich occurs above the Hd. proteum (solo) horizon and carries an H.smithi (solo) fauna, or that the brachiopod and lamellibranch fauna present above the highest H.smithi occurrence at Loc. 010a, is the lateral equivalent of the upper H.smithi horizon. The first alternative seems less likely in view of the distinct separation of the two H.smithi faunal horizons in the Thorncliffe section and it appears more probable that the benthonic fauna above Loc. 010a, is in part, the lateral equivalent of the upper H.smithi horizon. The Astbury area is suggested as being adjacent to the paralic margin in H_2a times (see Lithofacies Associations and proposed Palaeogeography) and Ramsbottom (1967) commenting on the occurrence of benthonic faunas states, "In regions closest to the inferred shorelines, goniatites may fail and marine bands can become productid/crinoid beds or Lingula bands". Rare specimens of H.smithi have been

1. In Section 9Ta, adjacent to Thorncliffe, the upper of two H.smithi horizons is present at Loc. 106a, at this locality the writer identified H.smithi, whilst Morris (1959) indicates that H.undulatum is present at this level.



Correlation of the H2a Faunal Horizons
FIG.1.F.
106a
191
040
180
190
S+U
010a
106b
barren interval
Sparse H.smithi
Sparse H.smithi
010
041
141 / 120
181
148
S
P
Büsbach
2T
9Ta
7T
5T
11T
3T
4T
Tansley

recorded (Loc. 104 g. Evans et al., 1968) from the succession containing the benthonic fauna above Loc. 010a and it is suggested that they may have drifted into the area after death.

In conclusion it is suggested that the four H_2a faunal horizons are the product of three eustatic maxima which produced the Hd. proteum (solo) horizon, the H.smithi (solo) horizon and the H.smithi - H.cf. undulatum horizon. Whilst the Hd. proteum - H.smithi horizon seen in the Büsbach and Astbury successions is thought to be the product of a very limited mechanical intermingling of specimens which occurred in the early stages of diagenesis.

THE FAUNAL BANDS IN THE H_2b AND H_2c ZONES

In all the sections examined in this part of the succession H. cf. undulatum was recorded only once at Loc. 191, whilst Hmct. prereticulatus is present in several sections.

In the Ashover Boreholes, (Ramsbottom et al., 1962) H. cf. undulatum is recorded twice in the succession; in a lower faunal band it is recorded as H. cf. undulatum in association with H.smithi and at a higher horizon, where H. cf. undulatum occurs in isolation.

In the Thirklow Stream, Section 4T, a similar association was observed. In the upper H.smithi faunal band at Loc. 191 a single specimen exhibiting a shallow hyponomic sinus was identified as H.cf.undulatum. A poorly exposed weathered, yellow mudstone at Loc. 192, 12'6" above Loc. 191 contains a fauna of poorly preserved specimens of H.cf.undulatum and is thought to be the equivalent of the upper faunal band containing H.cf. undulatum recorded in the Ashover Boreholes. The specimens at Loc. 192 were similar to specimens of H.smithi but exhibited a less acute development of the rib structure and on this basis were identified as H.cf. undulatum.

Faunal bands containing Homoceratoides prereticulatus Bisat, occur in the following sections:-

Heath Hay Stream, Section 8T

	ft in.	m
Limestone, grey, ankeritic, Hmct. prereticulatus, Aviculopecten sp., Loc. 029, H_2c .	0'6"	0.15
Mudstone, shaley, dark grey, calcareous in upper levels H.cf. eostriolatum .	0'9"	0.23
Fault, broken ground .	6'0"	1.83

The occurrence of Hmct. prereticulatus and H.eostriolatum at Loc. 029 has also been recorded by Evans et al., (1968) at their Loc. 101.

Blake Brook, Section 5T

	f t in.	m
Mudstone, black, shaley, Hmct. prereticulatus, Loc. 140, H_2c .	1'6"	0.45
Limestone, bullions, ankeritic, unfossiliferous .	(max)1'0"	0.31
Mudstone, black, shaley, partially exposed .	19'0"	5.79
Limestone, blue grey, Hd. proteum, Loc. 141, H_2a .	(max)1'0"	0.31

Note. The mudstone above Loc. 141 was examined in detail and the presence of H.smithi was not recorded.

The Thorncliffe Stream, Section 9T

	ft in.	m
Shaley, mudstone, blue black, with jarosite, Hmct. prereticulatus, Loc. 100, H_2c .	1'0"	0.31

Note. This exposure is present in the succession 7m below an R_1a faunal horizon Loc. 020 of C. Ashton. (1974).

P.1.10.

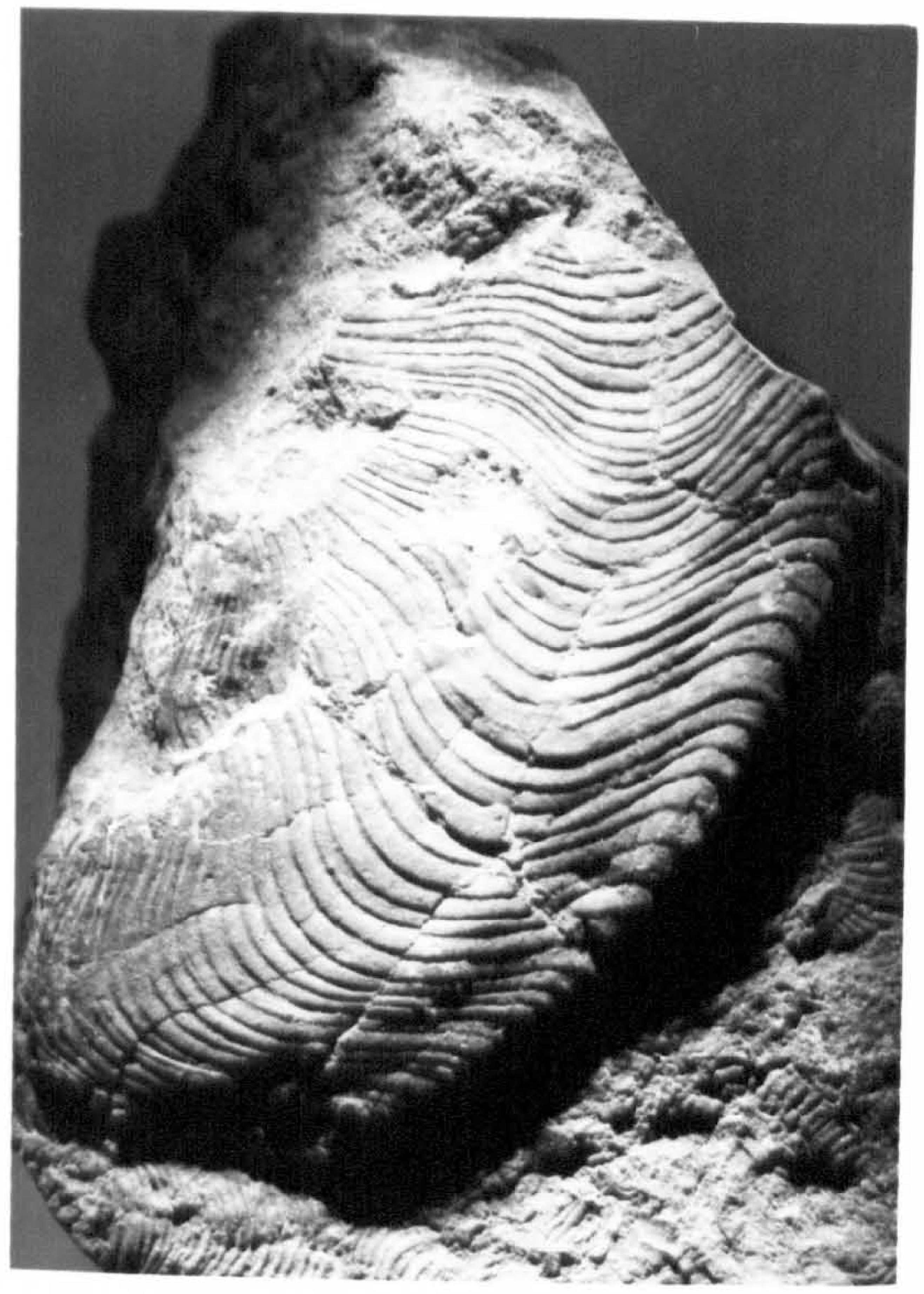
Homoceratoides prereticulatus

x 3.

Detail of strong rib pattern and lingua.

Loc. 029. Heath Hay Stream.

P.1.10.



The Gun End Section 7T

This section is faulted above the Hd. proteum horizon at Loc. 041, but in a stream to the north of this locality the Hmct. prereticulatus faunal band is exposed in grey mudstone at Loc. 045 on the downthrow side of this fault. Posidonia sp. and Aviculopecten sp. have also been recorded at Loc. 045.

The Churnet Stream, Section 10T

	ft in.	m
Limestone bullion, R.circumplicatile, Loc. 007 of C. Ashton (1974), R_1a .	(max) 1'3"	0.37
Mudstone grey, with jarosite, H.henkei at base .	3'7"	1.08
Shale, silty, blue grey. At base Hmct. prereticulatus, Loc. 060, H_2c .	4'0"	1.22

North of the above section the Hmct. prereticulatus faunal band is again exposed at Loc. 062.

The Dingle Brook, Section 14T

An isolated exposure is present in this section at Loc. 039 consisting of a Limestone bullion (max. 2'0"), containing Hmct. prereticulatus, in a silty mudstone succession. In the mudstone, 2'0" below the Limestone bullion at Loc. 039, Evans et al. (1968) record the presence of H.cf.eostriolatum (Loc. 85c).

Identification of Homoceratoides prereticulatus Bisat

Bisat's original description of this species indicates that many similarities exist between Hmct. prereticulatus and H.smithi and H.undulatum.

The specimens of Hmct. prereticulatus from Loc. 029 (Loc. 101 of Evans et al., 1968) display strong curved ribs in which the ratio of test diameter to depth of lingua is 3: 1, at D 30 mm, a figure which is approximately the same in specimens of H.smithi at this diameter. Rib frequency is variable but appears to be slightly less than in H.smithi and H.undulatum at comparable diameters. (P.1.10.).

The ribs start to show a slight curve at + 4 mm D and by 7 mm D a shallow lingua has developed, this is earlier than in both H.smithi and H.undulatum where the lingua is only seen to develop at + 14 mm D.

Specimens displaying preservation of the venter are rare at all localities, but in all cases they exhibit the characteristic hyponomic sinus. Immature specimens at Loc. 100 display an incipient sinus at 2.5 mm D, whilst in the type material Bisat records a very slight hyponomic sinus at 1.5 mm D. This early development of the sinus in Hmct. prereticulatus serves to distinguish it from H.undulatum in which the sinus does not develop until + 14 mm D although the maximum depth of the sinus, 1.5 mm, is similar in mature specimens of the two species.

Dimensions of Hmct. prereticulatus

D	D	ribs/cm on lingua	rib shape	a: b	ribs seen to develop at + 3 mm D.
Loc 140	30	10-14	curved	2.5 : 1	
	26		curved	3.2 : 1	
	22		curved	3.1 : 1	
	20		curved	2.5 : 1	
	16		curved	2.7-3.2 : 1	
	12		curved		
	7		slightly curved		

	D	ribs/cm on lingua	rib shape	a: b	ribs seem to develop at 2.5 mm D.
Loc. 100	36	14	curved	3 : 1	
	35	15	curved	3 : 1	
	15		slight curve		

Due to the rare preservation of the venter and the common fragmentary preservation of both H. smithi and Hmct. prereticulatus it is not always possible to distinguish the two on the presence or absence of the hyponomic sinus. However, one of the main criteria distinguishing the two species is the onset of ribbing which in Hmct. prereticulatus begins at + 1 mm D whilst in H. smithi it is only apparent after 5 mm D. Bisat (1924) also notes the late development of ribs in the Genus Homoceras and he states, "The genus is distinguished from Reticuloceras by the absence of ribs in the young (serpenticone stage) .....," whilst in his discussion of the Genus Homoceratoides he indicates that the species Hmct. prereticulatus is ribbed in the serpenticone stage. It is suggested, that with the mainly fragmentary and immature specimens encountered during the course of this work in the North Staffordshire area, that the early onset of ribbing in Hmct. prereticulatus is the main criterion for distinguishing this species from H. smithi and H. undulatum.

Thicknesses of the Zones in the Alportian

In the area covered by this research it is difficult due to lack of exposures, to arrive at a figure for the thicknesses of the individual zones in the Alportian. The only complete exposure of the H_2a Zone is seen in Section 4T where the interval between Hd. proteum and H. cf. undulatum is 7'6" and as previously stated this is thought to be a minimum figure. In the area covered by the Macclesfield

Memoir, Evans <u>et al</u>., (1968) state "Apart from the probable exception of the Gawsworth Common area, beds in the <u>Hudsonoceras</u> <u>proteus</u> Zone are chiefly shales some 40ft thick, which include thin sandstones on Congleton Edge." They further state that the total thickness of the H_2b and H_2c Zones is unlikely to exceed 15ft. The total thickness of the H_2a - H_2c (inclusive) interval is seen only once in the succession in the Blake Brook, Section 5T, where an exposure of 20'0" (6.10m) of barren mudstone with a single barren limestone bullion horizon max 1'0" (0.31m) is present between the faunal bands containing <u>Hd. proteum</u> (solo) and <u>Hmct. prereticulatus</u>, whilst the lowest R_1a horizon, Loc. 012 of C. Ashton (1974) is present 2.0m above the top of the <u>Hmct. prereticulatus</u> faunal band. Thus the total thickness of the H_2b and H_2c zones, on the evidence of the Blake Brook succession is circa 9.0m.

CHAPTER 2

SEDIMENTOLOGY

INTRODUCTION TO SEDIMENTOLOGY

The sediments occurring in the area covered by this research can be broadly subdivided into groups on the basis of external and internal characteristics. These groups are termed lithofacies and it is at times convenient to further subdivide these major groups into sublithofacies which possess the same characteristics as the parent lithofacies but are distinguished by a constant development or suppression of one or more of these characteristics.

Eight major lithofacies are proposed and several sublithofacies, and in the following account emphasis is placed on the coarser grained sediments occurring within the lithofacies.

Descriptive terms relative to bed thickness are used in a precise manner and are referable to the classification proposed by Ingram (1954) which is as follows:-

Very thickly bedded	Thicker than 1.00m
Thickly bedded	0.30 - 1.00m
Medium bedded	0.10 - 0.30m
Thinly bedded	0.30 - 0.10m
Very thinly bedded	0.01 - 0.03m
Thickly laminated	0.003 - 0.01m
Thinly laminated	Thinner than 0.003m

Descriptive terms relative to grain size are based on the particle size limit defined by the Udden (1898) - Wentworth (1922) scale and are as follows:-

Cobbles greater than 64mm

Pebbles 4mm - 64mm

Granules 2mm - 4mm (the term grit is preferred in the text)

Very coarse sand	1mm - 2mm
Coarse sand	0.5mm - 1mm
Medium sand	0.25mm - 0.5mm
Fine sand	0.125mm - 0.25mm
Very fine sand	0.0625mm - 0.125mm
Silt	0.0039mm - 0.0625mm

LITHOFACIES 1 (see Fig. 2.A.)

Thickly bedded to thinly bedded sandstones are characteristic of this Lithofacies. They are frequently associated with thin coal seams and seatearths of the ganister and fireclay types. The organic carbon content of the arenaceous and argillaceous sediments is high and is greater than that present in any of the sediments in the other Lithofacies.

Three Sublithofacies are recognised and are referred to specific environments within a deltaic model.

SUBLITHOFACIES 1a

Brief Diagnosis

Thickly bedded, to very thickly bedded, fine to rarely medium grained, quartz rich sandstones are present. Individual sandstones are infrequently overlain by very thinly bedded to thinly bedded coals. Medium bedded black unctuous mudstones are present in the succession, individual mudstones being infrequently overlain by very thinly bedded to thinly bedded coals.

Distribution

Exposures in this Sublithofacies are only present on the western margin of the area studied in the vicinity of Congleton Edge (SJ 86955930), occurring in the

Succession at Loc.011 in the Pot Bank Quarry within the interval H1a–H1b (inclusive)

Pot Bank Quarry, Loc. 011, and in the Lime Kiln Stream Section, Loc. 001.

External Features

Bed thicknesses of the sandstone beds in this Sublithofacies vary between 0.50 and 1.70m, and for the most part remain laterally constant, with only slight variations in thickness, possibly due to erosion, when a sandstone bed occurs in sequence directly above a mudstone. This erosion takes the form of scour pockets or incipient scour channels present on the lower bedding plane surface, alternatively these structures may be interpreted as a result of loading of the sand onto the plastic mud. In general however the bases of the sandstones are smooth and planar with a notable absence of any current directional markings. The upper bedding plane surfaces of the sandstones are markedly irregular due to the presence of numerous impressions of large roots of Stigmaria sp., measuring 0.05 - 0.10m across by circa 0.50m along the long axis and having a depth of 0.02 - 0.05m. Points of entry of rootlets into the sandstones are marked by circular to subcircular pits and protrusions (diam. 0.005m) which may contain traces of organic carbon.

Black mudstones are present in this Sublithofacies and exhibit a high degree of plasticity and unctuous feel in the weathered state, they are generally thinner than the sandstones in the succession being 0.10 - 0.20m thick. Stigmarian roots and rootlets also penetrate the mudstones and are seen in freshly exposed surfaces to consist of hollow cylindrical tubes possessing a thin wall of organic carbon. The mudstones are frequently overlain by traces of coal or thin coal seams 0.01 - 0.06m thick. The contact between the two is gradational and a transition layer of coaly mudstone is present. Similarly, thin coal seams are sometimes present above the sandstone beds, but here the contact is sharper and the gradational transition zone is absent. Black mudstones containing stigmarian impressions are also present in the succession directly overlain by sandstones and without an intervening thin coal. The sandstones possess irregular bases as previously described, which may be coated with a film of carbon. The thinly bedded coal seams present in this Sublithofacies display dull and bright laminae and are extremely well cleated. Discontinuous bright laminae referable to the vitrinite maceral are present.

Internal Structures

The arenaceous and argillaceous beds in this Sublithofacies exhibit no internal primary sedimentary structures and possess a uniform grain size throughout. The only internal structures present are those formed by plant roots and rootlets and by isolated irregular traces of organic carbon. Stigmarian roots are present as sand filled internal casts which are outlined by a thin film of organic carbon. Casts of this type are generally eliptical in shape and have diameters varying between 0.05 - 0.10m, they display an attitude which is roughly parallel to the bedding. Rootlets commonly occur and take the form of thin wisps of carbon which are normal to the bedding and frequently display upward pointing bifurcations. Cross-sections through the rootlets reveal a circular to subcircular morphology which is sometimes evidenced by very thin concentric rings of carbon. Carbon laminae possessing a random orientation are also present in the sandstones, they have a limited lateral persistence.

Interpretation

The thin coal seams present in this Sublithofacies display all these evidences of an autochthonous origin proposed by Raistrick and Marshall (1957). Internally they contain alternating clarain and durain lithotypes, and the coarser vitrinite fragments can be detected by the naked eye. Cleat is also well developed, even on a microscopic scale, a feature which is often suppressed in coals of allochthonous origin (Adams, 1960). The beds underlying the coals are either of the "gannister" or "fireclay" type, both displaying stigmarian roots and rootlets in the growth position. The presence of these seatearths is taken as further evidence supporting the in situ origin of the coals in this Sublithofacies. The absence of a uniform texture and the non-occurrence of aquatic fossil remains, further mitigates against the origin of these coals as being sapropelic derivitives.

Seatearths of both mudstone and sandstone occur in the succession without overlying thin coals and in each case are overlain by beds of sandstone. The irregular bases of the sandstones overlying the mudstone seatearths appear to indicate that erosion of the thin coal peat layer and possibly of the underlying mudstone has occurred, or that limited erosion together with loading of the sand into the underlying mud has produced this irregular lower bedding plane. Traces of the original organic materials may also be present as a thin film of carbon coating the irregular sandstone bases, this carbon is possibly all that remains of a thin development of coal peat.

It is thought that erosion, if it did occur took place on a very limited scale, since the uniform fine grain size of the sandstones, together with the lack of any internal primary sedimentary structure suggests that stream power was restricted to velocities in the lower part of the lower flow regime (Simons et al., 1965). The lack of any internal structure is also possibly due to the current checking action of the vegetation barrier represented by the coal swamp. It is envisaged that the fine sand was rapidly deposited from suspension as the current abruptly slowed down and that the traction stage did not occur. Incorporation of the washed-out or eroded-out coal peat into the fine sediments may account for a proportion of the organic content of the sandstones.

The environment of deposition of this Sublithofacies is thought to have been paralic, subject to rhythmic subsidences followed by the accumulation of fluvial sediment and the re-establishment of swamp conditions. Gould, (1970) describing the development of a prograding delta, of the type termed a shoal water delta (Fisk, 1955) or Lafourche delta (Fisher et al., 1969) from the Mississippi Delta complex, suggests that the fine sediments, silt and mud are carried by distributaries to the seaward side of the delta. These sediments are then deposited in the prodelta zone where they build up a platform onto which the fine grained 'sheet sands' of the delta front establish themselves. This model of deltaic deposition is complicated in Sublithofacies la, by the occurrence of successive coal seams and seatearths which are thought to be indicative of cyclothemic sedimentation as described by Wells (1960), Duff et al., (1962) and Elliot (1967). It is suggested that the vegetation of the coal swamps became established in the fresh to brackish water interdistributary zone bordering the delta front. Gould, (1970) describes a swamp environment, promoting luxuriant growth of vegetation, from a similarly placed interdistributary zone within the Mississippi Delta complex. He suggest, that with the onset of subsidence, regression of the delta followed by deposition of fine sheet sand occurred, producing the type of succession typified by the Sublithofacies la sediments. The limited vertical thickness of the cyclothems in this Sublithofacies indicates that only a small amount of subsidence occurred and that the onlapping or transgressive phase was relatively of short duration. Oomkens, (1967) describing depositional sequences in the Rhone Delta complex indicates that the transgressive phase of deltaic deposition occurs when the rate of subsidence exceeds that of sediment build up, and produces an upward coarsening sequence together with an increase in marine faunal content. It would appear then that in the Sublithofacies la sediments a delicate balance between subsidence and transgression of delta front sands existed and that a major transgression of the delta on the scale described by Oomkens (1967) did not occur in the Congleton Edge area.

An alternative to regression of the delta front is thought to be a change in the distributary pattern and the trapping of the fine sand by the barrier of vegetation. This type of mechanism associated with minor rhythmic subsidence, it is suggested, would produce a sequence of Sublithofacies la aspect. Gould (1970) describes the "plugging" of distributary channels in the Lafourche Delta, a prograding delta within the Mississippi Delta complex, and the consequent change in distributary pattern within the delta. The new course of the distributary would traverse an area that was previously an interdistributary swamp area and it is thought that the effect of the vegetation barrier in this area would produce a rapid fallout of sediment from suspension such as is indicated by the sandstones of this Sublithofacies. The weight of evidence however, points to the genesis of this Sublithofacies by repeated subsidence associated with deposition of onlapping delta front sediments. The final transgression at Loc. 010 appears to have been a major one terminating the paralic environment at this locality and incorporating marine fossils in the upper most bed in the la sequence.

SUBLITHOFACIES 1b

Brief Diagnosis

Medium to thickly bedded, frequently lenticular, coarse to medium to fine grained sandstones, containing abundant drifted, carbonsied, plant debris, which are interbedded with thinly bedded siltstones and mudstones are present in this Sublithofacies.

Distribution

This Sublithofacies is exposed at Loc. 011 at the southern end of the Pot Bank Quarry on Congleton Edge (SJ 86955930). Beds attributable to this Sublithofacies are also present in the Limekiln Stream Section, although exposures at this locality are frequently partially obscured by drift. Beds in this Sublithofacies are also present in the Thorncliffe Stream Section (SK 01265848) and occur at Loc. 108, some 6.0m below the horizon of Hmct. prereticulatus and at Loc. 109, circa 5.0m above an horizon of H.subglobosum (Loc. 101)

External Features

The majority of the beds in this Sublithofacies are medium to coarse grained sandstones, generally grey in colour and darkened by the inclusion of much carbonised organic material. Silty partings separate the sandstones and occasionally thicken up to form thinly bedded siltstones and mudstones containing coaly streaks. The sandstones frequently display lateral variations in thickness and may occur as lenticular bodies of 1.0m maximum thickness. When sandstones are present in the succession separated by only thin siltstone partings the lower bedding planes are often irregular and may display evidence of erosion in the form of small channel structures. Linear striations of the tool mark category occur infrequently on the bases of these beds. Sandstone beds overlying the mudstone or siltstone beds infrequently exhibit small scale load cast structures. Upper bedding plane surfaces are planar and do not possess irregularities attributable to roots and rootlets as in Sublithofacies 1a.

Internal Structures

The majority of the beds exhibit a uniform grain size although some of the thicker beds display an upward coarsening of grain size.

Parallel lamination is a feature of some of the sandstones present in this Sublithofacies the sand laminae alternate with thinner organic laminae which on close inspection are slightly irregular to undulose. Parallel lamination may occur in beds which display erosive bases, and is usually confined to an upper zone which is usually less than half the total bed thickness. In sandstones with non-erosive bases parallel lamination may occur throughout the bed.

Cross-bedding was observed in one lenticular sandstone bed, the foresets which are inclined towards 110^{0}, are picked out by concentrations of carbonised organic plant debris which form thin laminae and alternate with thicker sand laminae. A feature of the sediments in this Sublithofacies is the presence of carbonised organic material, plant stems of Calamites sp., circa 0.02m x 0.06m, occur together with a debris of poorly preserved smaller stems and foliage. This organic material although concentrated in laminae is also present in some of the coarser sandstones, and in these beds exhibits a chaotic distribution. Laterally impersistant coaly streaks are infrequently present. In addition to the organic.debris, small oblate mudflakes, 0.015m diameter, occur in the upper laminated zone of some of the sandstones and lie parallel to the bedding.

Interpretation

The genesis of the sediments in this Sublithofacies is thought to have occurred in a minor channel environment and on the basis of the close association of the Sublithofacies la, it is proposed that the particular environment of deposition was that of a deltaic distributary channel.

Gould (1970) describes the "plugging" of distributary channels from the prograding Lafourche Delta, part of the Mississippi Delta complex, and indicates that channels of this type gradually become infilled with sediment as the distributary migrated to another course in the delta. Elliot (1967), and Kelling (1968) describe similar channels and indicate, as is apparent in the Sublithofacies lb sediments, that an upward fining of the channel fill sediments may occur. Elliot (1967), suggests that within washout channels in the East Pennine Coalfield, the bases of massive sandstones, which occur in the lower parts of the washout, almost invariably show signs of erosion, and where studied in three dimensions in colliery workings, are often channelled in a shallow fashion with "boat hull" shaped lows cutting into the underlying stratum; beds in Sublithofacies lb are seen to display similar structures at Loc. 010. Following channel erosion at Loc. 010, accretion of sediment in the channel took place and at the same time it is suggested that lateral erosion of the adjoining interdistributary areas occurred. This erosion is thought to be responsible for the incorporation of much of the plant debris, coaly material and exotic mud, occurring in the coarse to medium grained massive sandstones present in this Sublithofacies. The magnitude of the lateral erosion is limited since large exotic mudstone clasts, probably originating due to collapse of under cut channel margins, and rafts of coaly material, are absent from these sandstones. However Elliot (1967) suggests, that the sub-aqueous roots of channel side vegetation may to some extent prevent the development of excessive lateral erosion of the channel margins, it is thought that the presence of this vegetation would tend to bind together the bankside sediments and prevent their collapse and incorporation as large exotic clasts within the channel sediments.

The lithology and structure of the Sublithofacies lb sediments has marked similarities to those described by Kelling (1968), from channel fills in the Rhondda Beds of South Wales. In these channels the lower beds are massive sandstones commonly carrying numerous oriented logs, and scattered pebbles of coal, iron-stone and shale in chaotic arrangement. The channel fill sequences described by

Kelling (1968) display a reduction in hydraulic power in the upper parts of the fill where beds exhibiting finer grain size and internal structures of lower flow regime origin are present in the succession. Similar characteristics are displayed in the Sublithofacies lb beds at Loc. 010, where the massive sandstones of the base pass upwards into finer grained sandstones displaying both cross-bedding and parallel lamination. Elliot (1967, 1969), proposes a similar sequence from washout channels, in the East Pennine Coalfield, which display cross-bedded sandstones overlying massive sandstones which occur at the base of these structures.

The vertical thickness of channel fill represented by the Sublithofacies lb sediments at Loc. 010 is circa 5.0m and it is suggested that this is close to the maximum thickness of sediment present in this particular channel. Kelling (1968), describing the channels which are incised into the Rhondda Beds, states that they possess vertical thicknesses of 30 to 50m. These channels exhibit relatively steep sides and contain exotic blocks of mudstone up to 1.0m in size, which are thought to have originated at the steep walled sides of the channels as slide breccias. It is suggested that the absence of material of this type from the Sublithofacies lb sediments is an indication of the limited extent of the vertical development of the channels in this instance.

The infilling of channels in the Upper Carboniferous deltaic complex represented by the Rhondda Beds of South Wales is suggested by Kelling (1968) to be due to subsidence and vertical accretion of sediment in conditions of falling current velocity. Whilst Elliot (1969) is of the opinion that cyclic subsidence may have been operative during the infilling of deltaic distributaries in the East Pennine Coalfield, nevertheless he considers that the major cause of the silting-up of such channels is due to a deepening of the channel produced by the differential penecontemporaneous compaction of the strata below. This Elliot suggests, leads to vertical accretion of sand in the channel, and if combined with a change in distributary pattern would result in a gradual lowering of velocity and an upward fining of channel sediment. It is conceivable that rhythmic cyclic subsidence in association with the episodal processes favoured by Elliot could produce channel fills which would display a cyclic fining upward character, of which there is some evidence in this Sublithofacies.

In conclusion the limited evidence afforded by the exposures within this Sublithofacies together with the evidence provided by the sediments in the adjacent Sublithofacies indicates that deposition took place in a minor and shallow deltaic distributary channel of unknown lateral extent. The internal structures present in the sediments forming the channel fill suggest, that initially the channel was cut by strong currents, possibly during a period of high discharge. An abrupt fall in current velocity produced the massive beds which contain the chaotically distributed plant fragments and small mud clasts. Differential compaction of the channel floor or cyclic subsidence allowed a vertical build-up of sediment to occur. The internal structure of this sediment passes upwards from massive to parallel laminated to cross-bedded, coarse and medium grained sandstone, to fine sandstone displaying parallel lamination and it is suggested that this type of internal structure is indicative of falling current velocity. A second cycle of sediment displaying the features listed above is present in the channel fill sediments at Loc. 010 and it is suggested that the presence of this unit is indicative of an episode of subsidence or reflects a further change in the distributary pattern. Following the second episode of vertical accretion of sediment it is presumed that the position of the distributary changed and the channel was abandoned. The evidence provided by the overlying sediments appears to support this proposal since their lithology and structure is of a type which is not compatible with deposition in a channel environment.

SUBLITHOFACIES lc

Brief Diagnosis

Thinly bedded to rarely medium bedded, fine to medium grained sandstones containing abundant finely comminuted plant debris, are present in this Sublithofacies alternating with very thinly bedded to thinly bedded siltstones and mudstones which also contain plant debris.

Distribution

Beds occurring in this Sublithofacies are present in the Pot Bank Quarry (SJ 86935929) and in the adjacent Limekiln Stream Section (SJ 86405855).

External Features

Fine grained sandstones make up the bulk of this Sublithofacies they display gradational contacts with the interbedded siltstones and mudstones. The thinner sandstones have irregular bases which display organic markings due to the activity of burrowing organisms. Burrowed horizons tend to occur in groups in the thinner beds separated by groups of thicker beds in which biogenic structures are absent.

Internal Structures

Grain size variations within the individual beds are not generally apparent, in one case only was grading observed and was present in a medium bedded sandstone which exhibited normal size grading from coarse to fine. Generally speaking the thicker beds display a slightly coarser grain size than the thinner beds. The majority of the beds contain weakly developed parallel lamination which is made more apparent by concentrations of organic carbon in the form of thin carbon laminae. In one bed the frequency of lamination was observed to increase upwards.

Finely comminuted plant debris is a feature of the sediments in this Sublithofacies and in addition to being concentrated in laminae, is also present randomly distributed throughout the sandstones and siltstones.

Bioturbated horizons are present in rare instances within the sandstones and are associated with the thin sandstones which display external evidence of biogenic activity in the form of casts present on the bases of the beds.

Interpretation

The fine nature of the sediment together with the marked biogenic activity at certain levels is thought to indicate a slow rate of deposition for these sediments. The presence of mud and silt layers, interbedded with the sandstones, which display gradational contacts with these fine sediments, is thought to indicate a periodicity in the genesis of the sediments and a fall in current velocity to the point where the fine sediment is deposited from suspension. The presence of parallel lamination, which is a constant feature of these sediments, is taken by some authors to indicate the existence of upper flow regime conditions whilst others notably Reineck and Wunderlich (1969), and Clifton (1969) were able to demonstrate that parallel lamination in sediments could be produced in conditions of flow which are appropriate to a position low in the lower flow regime.

In the Mississippi delta, Moore and Scruton (1957) suggest that laminated sediments are produced adjacent to active distributaries. Coleman and Gagliano (1965) also describing sediments from the Mississippi Delta complex, indicate that fine grained parallel laminated sandstones, of similar bed thicknesses to those occurring in this Sublithofacies are commonly present in interdistributary bay areas and are of the opinion that the lamination is the product of a subaqueous environment in which a diffrential settling of particles occurs, due to either changes in current velocity or changes in water chemistry. Coleman and Gagliano (1965) further associate parallel laminated sediments of this type with the inclusion of finely comminuted plant debris and the presence of burrowed structures.

Elliot (1969) describing sediments from the East Pennine Coalfield suggests that parallel laminated sandstone siltstone successions, similar to those represented by the sediments in this Sublithofacies, are the product of deposition of sediment within an interdistributary bay or lake. He further suggests that where such deposits are thin that they represent the distal edge of their distribution. In deposits of this type Elliot suggests that the rate of sedimentation was low enough to permit a rich colonisation by burrowing animals causing bioturbation, but punctuated by periods of rather more rapid deposition causing the burrowing life forms to extend their burrows upwards, these are probably eschape-burrows, the Fluchtbahen of Reineck (1958).

It is suggested that the Sublithofacies lc sediments are interdistributary sediments which were deposited in a lake or bay. The deposition of these sediments is thought to be linked to either a lateral movement of the distributary or a change in the position of the delta front, consequent on regression of the delta due to a rise in sea level. This variation is evidenced in bed thickness distribution, and presence or absence of biogenic activity. It is suggested that as the bed thickness increases, that either the source of supply of sediment approaches the area of deposition or the current velocity increases, carrying more sediment into the area. In either case there is a cessation of burrowing activity. Elliot indicates that an upward burrowing, eschape burrowing, took place in the East Midland Coalfield sediments when this change in bed thickness occurred. In Sublithofacies lc sediments, no trace of eschape-burrows was observed and it is suggested that the burrowing activity moved not vertically but laterally to a more source distal area where sediment deposition took place at a slower rate and in reduced quantity.

The presence of finely comminuted plant material as opposed to tree roots, logs, or in situ tree trunks further indicates that the area of deposition was a distal or seaward side of the delta where an appreciable depth of, possibly brackish or saline water existed which precluded plant growth in the area of deposition. The absence of marine body fossils from this Sublithofacies suggests however, that true marine conditions were not established in the area of deposition.

The association with Sublithofacies 1a and 1b in the Pot Bank Quarry area is thought to be indicative of variations in the position of the delta front at this location. Sublithofacies 1b representing a distributary channel environment is succeeded by an interdistributary deltic succession. Sublithofacies 1c, which in turn is succeeded by a swamp environment represented by Sublithofacies 1a. The latter is thought to indicate a prograding of the delta in this area and a seaward extension of the coal swamp vegetation which becomes established in an area previously the site of accummulating delta front sediment of Sublithofacies 1c aspect.

LITHOFACIES 2

Brief Diagnosis

Medium bedded to predominantly thickly bedded coarse sandstones, which in some instances contain pebbles, comprise the bulk of the sediments in this Lithofacies. The coarse grained sandstones may be interbedded with medium grained sandstones of lesser bed thickness. Mudstones are absent from this Lithofacies and siltstones are of very infrequent occurrence. Bed boundaries may be sharply defined and planar, or bed amalgamation may occur, especially in the coarser grained beds. Primary sedimentary structures occurring at bed boundaries are restricted in occurrence to rare examples of primary current lineation, and isolated small scour channels. Biogenic structures may be present in some of the finer grained beds.

Distribution

The strata present in Lithofacies 2 occur at several localities including; Morris House Quarry, Loc. 026 (SJ 91455425) on Brown Edge, and at the adjacent Crowborough cross roads exposure, Loc. 027 (SJ 90685693). At Loc. 027, sediments within this Lithofacies directly overlie an H. subglobosum horizon, which is exposed in a drainage ditch on the side of the road. The beds exposed at Loc. 026 and Loc. 027 can be traced along Brown Edge to the Endon district, Loc. 022, and across the Endon Valley to Stanley Moor. On Stanley Moor they are exposed at Roughwood End, Loc. 025 (SJ 92005139) where they form a prominent scarp feature which extends around Stanley Pool (SJ 93005180), the very coarse sandstones in this locality are termed the Stanley Grit (Evans et al., 1968).

The base of the Lithofacies 2 sediments at Loc. 025 lies 17m above an horizon containing N. nuculum, Loc. 023, this marine band is interpreted as the highest of the E_2c_2 marine intervals. Above the Lithofacies 2 sediments at Roughwood End, Loc. 025, occur sediments of R_1 age partially exposed in the stream section to the north of Greenway Hall (SJ 92005110).

From the vicinity of Crowborough, Loc. 027, Lithofacies 2 beds can be followed northwards as far as Ridgefield (SJ 90805820), and are next encountered in the Heath Hay Stream Section (SJ 90915032). In this section Lithofacies 2 sediments are represented by a thin development of sandstone, which is present in the succession above the H_1a_{iii} horizon at Loc. 020 and below the level of Hmct. prereticulatus at Loc. 029.

Field Characteristics

In the field the majority of beds appear to be massive that is internally structureless, although parallel lamination and very rarely cross-bedding have been observed. At Loc. 022 thinly bedded sandy siltstones are overlain by massive medium to coarse grained sandstones of maximum thickness 2m. The contact between the two is erosional and the sandstone thins to zero, along the strike, in circa 50m. At a point near the maximum development of the massive sandstone the underlying siltstone is cut into by a steep sided downwardly convex structure which has a long axis aligned west-east. The dimensions of this structure are circa lm broad by lm deep although the lateral extent is unknown.

External Structures

The majority of the sandstone beds within this Lithofacies are present as parallel sided beds displaying only slight variations in thickness. Bed amalgamation frequently occurs in these parts of the succession, whilst less frequently sharp erosive contacts are present, usually when a coarse grained thickly bedded sandstone overlies a thinner medium grained bed, producing variations in bed thickness and infrequently the lower bed may thin to zero.

Primary sedimentary structures indicative of palaeoccurrent orientation are of limited occurrence in this Lithofacies. One example of primary current lineation was observed at Loc. 025 which indicated a west-east orientation for the formative current. At Loc. 026 a minor scour channel was recorded which displayed a south-west north-east orientation, and weakly incised tool marks present on the base of this structure, are thought to be indicative of a south-westerly derivation for the sediment in this channel.

Biogenic structures are mainly represented by sub-circular hypichnial casts, present on the lower bedding planes of the massive sandstones, whilst poorly preserved horizontal hypichnial burrows or indeterminate trail marks have infrequently been observed preserved as casts on this surface.

Rounded oblate mudstone clasts, circa 0.04m diameter, infrequently occur on the upper bedding plane surfaces, and in weathered exposures the mudstone may have been removed and a relic impression of the clast remains. The presence of impressions either of mudstone clasts or organic fragments resembling brachiopod shells was noted on the upper bedding plane surface of the highest bed in this Lithofacies at Loc. 025. Similar, but better preserved, impressions of brachiopods were noted on the upper bedding plane surfaces of sandstones of shallow water genesis in Sublithofacies la.

Internal Structures

Internal structure is difficult to distinguish in the field, the majority of the beds appear to be structureless and possess a uniform grain size throughout. Some of the medium grained sandstones weather to display closely spaced parting planes at circa 0.05m intervals which possibly represent parallel lamination. Alternatively the individual laminae may represent thinly bedded sandstones and bed amalgamation of several of these thin beds has produced units of circa 0.30m thickness.

Some of the coarse grained sandstones, designated massive beds, show faint traces of parallel lamination throughout, which is evidenced by dark and light colour variations on fresh surfaces. Similarly faint traces of cross-bedding have been observed on fresh surfaces in the coarse grained "massive" beds and once again the internal structure is recognised by differential colouration within the bed. This type of internal structure is only rarely apparent in the field. It is suspected that cross-bedding and parallel lamination is a more commonly occurring internal structure in the beds of this Lithofacies than has been detected. The lack of evidence of parallel lamination and in particular cross-bedding in the field is thought to be due primarily to the low susceptibility of the sandstones to differential weathering, in all the exposures examined. Thin section examination of the massive coarse grained beds in this Lithofacies, reveals a quartz rich sandstone composed of angular to sub-rounded grains, enclosed in a secondary silica cement. The porosity of these beds is thought to be very low, since the majority of the void spaces are completely infilled with secondary silica, probably explaining the absence of differential weathering.

Internal biogenic structures commonly occur in the finer grained beds and are represented by simple cylindrical endichnial burrows, terminating on the lower bed boundary as ovate hypichnial casts. Less frequently the burrows display a branching morphology. In some of the finer grained beds these burrow structures traverse the total bed thickness but in the coarser grained beds they terminate within the bed. Horizontal hypichnial burrows are present on some lower bedding planes and are thought to be unroofed sand filled burrows which existed at or near the surface of the lower bed.

Interpretation

The coarse nature of the majority of the beds within this Lithofacies and the presence of cross-bedding and parallel lamination suggests that much of the sediment was initially deposited from a current which possessed upper transitional to lower flow regime characteristics. The apparently massive beds which may show infrequent diffuse traces of internal bed structure are thought to be the product of very rapid deposition from suspension and it is suggested that the phase of traction was practically absent during their formation. This is borne out by the frequent occurrence of bed amalgamation, which commonly occurs in association with these massive beds. In other parts of the succession bedding planes are sharply defined and isolated instances of primary current lineation and channelling indicate that the mechanism of traction was not entirely absent from this Lithofacies.

Parallel lamination is a common feature of the finer grained sandstones in this Lithofacies and it is suggested that these beds were formed by deposition of sediment from a current of lower stream power than that which deposited the coarser sediments although the absence of a ripple phase from the medium grained sandstones indicates that the formative stream flow largely exhibited upper flow regime characteristics with stream power probably in excess of 2000 ergs/cm^2/sec. Mud and silt are practically absent from this Lithofacies and it is suggested that they were maintained in suspension at all times by reason of the high values of stream power which obtained.

Biogenic structures present in the finer grained sandstones, in the form of burrows which completely traverse these beds, are thought to be indicative of a slower rate of sedimentation than that operative during the deposition of the coarser grained sandstones in which the endichnial burrows are confined to the lower sections of the beds. It is suggested that the latter case represents an entombment of the burrowing organism due to a rapid fall-out of sediment from suspension. The varying rates of sedimentation are interpreted as being the product of variable rates of hydraulic discharge and it is suggested that at periods of maximum discharge, current velocities were sufficiently strong to produce the erosive nature of some of the lower bedding plane surfaces present in this Lithofacies.

Massive bedded sandstones are described by Collinson (1969) from the Grindslow Shales and Kinderscout Grit of the Namurian of Northern England, he refers to two facies, Facies 7, which is represented by massive bedded coarse sandstones, and Facies 8, horizontal bedded coarse sandstone. Similarities exist between the Facies 7 and 8 proposed by Collinson and the sediments present in Lithofacies 2, in particular the absence of internal structure and the coarse mud-free nature of the sediments. Collinson suggests that the deposition of his Facies 7 and 8 sediments took place in flat based fluviatile channels of minimum thickness 4-40m and of minimum widths 100-400m. Continuous exposures of this magnitude are not present in Lithofacies 2 and the presence of steep channel walls as noted by Collinson (1969) has not been observed. However the structure present at Loc. 022, is interpreted as a flat based fluviatile channel of circa 50m minimum width.

The absence of channel margins is thought to be due to lack of exposure in the area of outcrop of Lithofacies 2 sediments, which is partly a result of the subdued topography. Alternatively the finer grained sediment occurring at the channel margins (Collinson, 1969) has been locally eroded by small present-day streams, and the channel margins are either covered in debris from hill side soil creep or have been undercut and eroded.

Walker (1966a) describes massive bedded sandstones which he terms Facies C Sandstones, from the Shale Grit and Grindslow Shales of the Namurian of Northern England, these beds which he interpretes as proximal turbidites appear to possess many points of similarity with Lithofacies 2 beds. For the most part the Facies C sandstones are non-graded structureless beds and like the beds in this Lithofacies they commonly display bed amalgamation. However, Walker's Facies C also contains beds of mudstone which he interprets as Bouma E divisions, and despite its many similarities to Lithofacies 2 there is clearly a different origin for this Facies.

In conclusion it is proposed that the environment of deposition of Lithofacies 2 sediments was a high energy environment consistent with the hydrodynamic energy levels occurring in a distributary channel within a deltaic environment or in the broad channel of a braided river system (Allen 1970c). The latter is thought to be more appropriate since there is an absence of fine grained sediment, in particular mud from this Lithofacies, and the coarse grain size of the majority of the beds appears to be more typical of the deposits of a braided river system. There is however insufficient evidence available to be categoric concerning the type of fluvial environment in which Lithofacies 2 sediments were deposited, although their deposition within a constructive delta environment, of the lobate type (Fisher et al., 1969), is a possible alternative origin, which for want of evidence to the contrary cannot be rejected. Whichever of the two river systems is applicable to the genesis of the sediments within this Lithofacies it is apparent from the evidence previously discussed, that within the environment of deposition the rate of accummulation of sediment was rapid and practically continuous. This rapid continuous rate of deposition is thought to indicate a constructive sedimentary structure, which on the basis of palaegeographic evidence appears to have prograded in an easterly direction.

The form of outcrop suggests that the sediment infilled a broad flat based channel, or more probably several adjacent channels, of a similar morphology to those described by Collinson (1969) from the deltaic facies of the Grindslow Shales and Kinderscout Grit.

It is realised that the thickly bedded massive Lithofacies 2 sandstones have many points of similarity with the proximal turbidites described by Walker (1966a) and might in some circumstances be interpreted as such. However the fluvial rather than turbidite origin, which is suggested (ibid) for these sediments is supported by palaeogeographic evidence which is indicative of land proximal deposition on part of a broad shelf which existed in the western part of the North Staffordshire Basin in H_1a - H_1b (inclusive) times.

LITHOFACIES 3

Brief Diagnosis

Thinly to thickly bedded grey siltstone or silty mudstone alternating with thinly bedded to medium bedded fine to rarely medium grained, clean sandstone. Bed contacts between the different lithologies are normally planar and are frequently gradational. Biogenic structures are present in some of the sandstone beds although body fossils are absent.

Distribution

Sediments occurring in this Lithofacies are present in several sections within the area of study. In the Heath Hay Stream Section (SJ 90915932) Lithofacies 3 sediments occur in the succession in both the Lower and Middle Churnet Shales, Siltstones predominate in the lower part of this succession whilst sandstones become increasingly important above the level of H. subglobosum. Lithofacies 3 sediments are also present in the Dingle Brook Section (SJ 92076175) in the Zone of H. subglobosum, here the sandstone beds are subordinate to the siltstones throughout the succession. Beds of Lithofacies 3 aspect are partially exposed in an old quarry at Rough Wood End, Endon (SJ 92105145) within the interval E_2c_2 - H_1a. At this locality the sandstones are the dominant beds in the succession. A weak development of Lithofacies 3 type sediments occurs in the Gun End Stream Section (SJ 96406330) within the interval E_2c_{2iii} - H_1a; and in this section siltstones are dominant in the succession.

Field Characteristics and External Structures

Siltstones and silty mudstones predominate in this Lithofacies, and the sandstones account for less than 10% of the succession. Sandstone bed thicknesses are constant and commonly less than 0.10m but occassionally thicknesses up to 1.0m occur. No irregularities in bed thickness, due to erosion, are present. Grain size is variable within the sandstone beds of this Lithofacies but it is predominantly of fine sand size. The finer grained beds within this Lithofacies are composed predominantly of silt sized particles although silty mudstones and sandy siltstones have been recognised.

The lower bed boundaries of the sandstones are gradational from siltstone, or may be sharp, infrequently with weakly developed load cast structures. Current induced directional structures are absent.

The upper bed boundaries of the sandstones are plane surfaces and may be gradational to the overlying siltstones. Biogenic structures are common in those parts of the succession where sandstones are predominant, the sandstone upper bedding plane surfaces sometimes displaying epichnial burrow pits, whilst the lower bedding plane surfaces exhibit hypichnial casts and irregular branching casts which may be interpreted as unroofed or collapsed exichnial sand filled burrows or as casts of trail marks.

Internal Structures

The fine grained sandstone beds present in this Lithofacies are commonly internally structureless, and thin sandstone beds of this type are present in the succession alternating with siltstone beds. Less frequently the sandstones contain thin parallel laminae composed of slightly coarser grains. Thicker laminae are present in some beds and consist of silt sized particles and finely comminuted organic carbon. An upward increase in the frequency of lamination together with a decrease in grain size is present in some of the sandstones. The siltstones and mudstones are frequently structureless beds although the siltstones may contain fine sand sized particles which are present as thin discontinuous laminae.

Biogenic structures are common within the sandstone beds, they take the form of sub-circular endichnial burrows, commonly of 3-5mm diameter up to a maximum

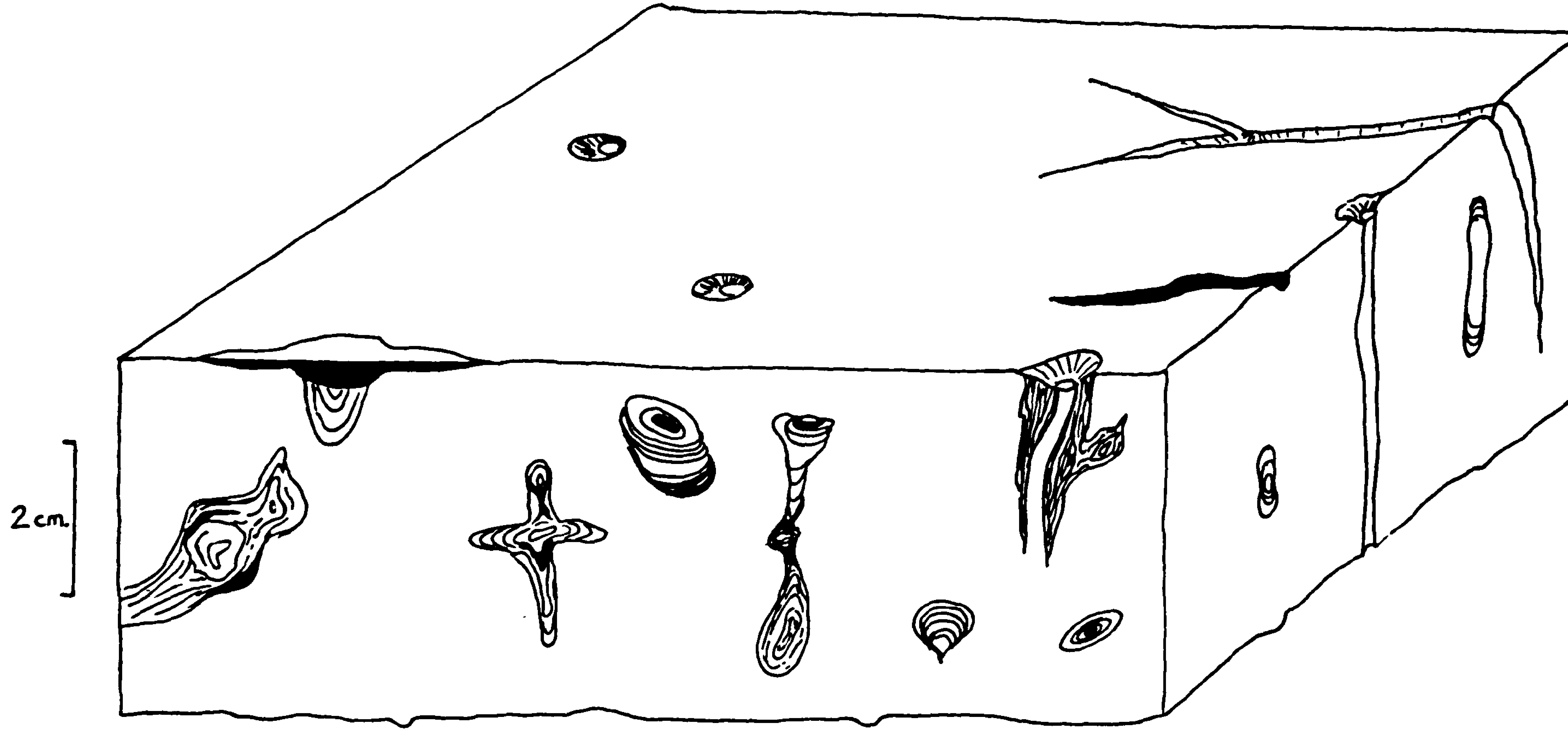


FIG. 2.B Burrows in Lithofacies 3 Sandstones
Rough Wood End above Loc. 023.

of 12mm. In longitudinal section the burrows are straight to slightly curved and subsidiary burrows branching off the main burrow may be present (Fig. 2.B.). The attitude of the burrows shows a complete variation between parallel to and normal to the bedding. Burrows commonly occur completely traversing the bed, whilst others are seen to traverse only the upper parts of the bed. The burrows may be sand-filled mudlined or mudfilled, and within the sand-filled burrows evidence of the internal structure of the burrow may be seen in cross-section in the form of a succession of concentric mud linings. In longitudinal section the sand-filled burrows may exhibit non-parallel walls and successive mud linings separated by sand-fill may be present.

Interpretation

The fine particle size together with the absence of current formed internal structures in this Lithofacies suggests that the sediments were deposited from suspension. The sediments plot in the zone of "No Sediment Movement" on the hydrodynamic diagrams of Simons et al., (1965), and Allen (1968b). One instance of incipient cross-lamination was observed in the upper part of a sandstone above a zone of parallel lamination, which is taken to indicate the onset of traction and is indicative of current strength in the lower part of the lower flow regime. The fine parallel lamination mainly occurring within the sandstone beds in this Lithofacies, is thought to have been formed at current velocities lower than those producing the cross lamination referred to above. Bouma (1962) suggests that a waning turbidity current produces a variety of structures in a bed, including a cross-laminated interval passing upwards, with lowering current velocity, into a finely parallel laminated interval followed by deposition from suspension of a structureless interval consisting of mudsized particles. Present opinion, Bouma (1962), Dzulynski and Saunders (1962) and Walker (1965), is divided as to the origin of the Upper Division of Parallel Lamination, and proposes mechanisms involving slow moving sediment and differential settling or pulsating currents with or without traction at the sediment current interface. Walker (1965), suggests that traction in the Upper Division of Parallel Lamination seems very unlikely, simply because the ripples in the previous division stopped moving when traction ceased. The lamination Walker suggests may be due to the different settling velocities of the various sized grains through the laminar boundary sub-layer. The laminations present in the Lithofacies 3 sandstones which mainly consist of alternating fine sand layers of slightly different grain size, are thought to be analogous, in part, to the structures described by Walker (1965) and it is suggested that variation in supply of sediment and/or differential settling are the formative mechanisms producing this lamination.

Field evidence is insufficient to directly relate the Lithofacies 3 sediments to their source of supply, although it is possible to propose several modes of origin for the sediments. "Laminated sediments" forming in a tidal mudflat environment were studied by Reineck and Wunderlich (1969). They observed that diurnal tidal variations correlated with the deposition of fine and coarse material. Mud layers were deposited at both high and low tides and sand layers during both flood and ebb tides. The repetitive regularity of thin sandstones and thin siltstones/ silty mudstones in some of the sections where Lithofacies 3 beds are exposed also appears to be indicative of regular periodic changes in the supply and type of sediment. However tidal activity is discounted as the primary formative mechanism in the genesis of Lithofacies 3 sediments, since the sediments studied by Reineck and Wunderlich (1969) do not achieve the same individual bed thicknesses or areal distribution as the Lithofacies 3 sediments. It is suggested that tidal forces, although not involved in the deposition of Lithofacies 3 sediments, may have exerted a control on currents bringing sediment into the area of deposition and that variable current strengths could account for the association of the thinly bedded alternating sandstones and siltstones. The isolated thin sandstone beds, in a predominantly siltstone succession, require an initial control which is thought to have a different origin than tidal periodicity. It is suggested that this association is linked to changing current distribution patterns in the source environment and may for example correspond with the change in location of a deltaic distributary, or may be attributed to a climatic variation. The evidence provided by the biogenic structures present within the sandstone beds is thought to indicate a slow rate of deposition. Several types of burrow structure may be recognised and are thought to be indicative of the rate of accumulation of sediment. Endichnial burrows parallel or sub-parallel to the bedding, and vertical endichnial burrows with smaller branching burrows parallel or sub-parallel to the bedding, are frequently mud lined and sand-filled. The numerous mud linings, which occur in a concentric pattern, are interpreted as the burrow linings of successive traverses of the sediment made by the burrowing animal, which followed a route in the sediment already weakened by a previous excavation. Up to seven of these linings have been observed from the same burrow. Burrows of this type are interpreted partly as dwelling burrows and partly as feeding burrows, the Domichnia and Fodichnia of Seilacher (1964), and are thought to indicate a slow rate of accumulation of sediment or even a pause in sedimentation. Another type of burrow slightly larger than the previous type occurring in the sandstone beds of Lithofacies 3 is a vertical burrow present between the upper bedding plane surface and a point within the bed. Internally this burrow type is mud and sand-filled and displays a succession of downwardly convex mud linings. This type of burrow is thought to be the dwelling burrow of an animal that fed at the sediment water interface, and is referable to the form Peleycipodichnus. The depth of this type of burrow 1-4 cms and the interval of sand of less than 1mm between the successive mud linings is again thought to be evidence for a slow rate of accumulation of sediment.

In conclusion it is suggested that the structures displayed by the Lithofacies 3 sediments indicate deposition of sediment from suspension in areas subject to weak current activity. It is proposed that at all times laminar flow conditions existed at the fluid/sediment interface and that settling of particles, carried in suspension in an upper turbulent flow zone, occurred differentially through the laminar boundary. The accumulation of this sediment is thought to have, at times, been slow enough to allow extensive biogenic activity to occur. The environment of deposition is thought to be a shelf or prodelta environment, a conclusion which is supported by the environments of the adjacent Lithofacies and one which is further implied by the proposed palaeogeography.

LITHOFACIES 4

Brief Diagnosis

Thinly bedded to predominantly medium bedded to rarely thickly bedded sandstone, interbedded with medium bedded to rarely thickly bedded siltstones and sandy siltstones. Several sandstone beds may occur in succession without an intercalated siltstone bed. Mudstones are absent. The sandstones are predominantly of fine grain size although medium and more rarely coarse grained sandstones are present in the succession. The sandstones may display sharp, weakly load cast and tool marked bases when marked grain size differential occurs at bed boundaries in other cases bed boundaries are frequently gradational.

Trace fossils occur very infrequently and body fossils are absent. Finely comminuted organic carbon and drifted carbonised plant material may occur as discrete layers and in some instances is present on bedding plane surfaces.

Fig. 2.c.

Succession at Loc. 104 in the Thorncliffe Stream within the interval H1a–H1b (inclusive)

Penecontemparaneous deformation structures taking the form of associations of microfaults may be present in the sandstone beds, whilst distorted lamination commonly occurs.

Distribution

This Lithofacies is present in the Thorncliffe Stream Section (SK 01265848), at Loc. 104, (Fig. 2.C.) circa 7m above the highest H. subglobosum horizon in this section at Loc. 101, and circa 15m below the horizon of Hmct. prereticulatus at Loc. 100.

External Characteristics

The sandstone beds in this Lithofacies display an average thickness of 0.10 to 0.15m, whilst the siltstones although less frequent in the succession possess an average thickness of 0.25m. In the Thorncliffe Stream Section the sandstones form marked ledges in the stream bed when underlain by the softer, more easily eroded siltstones, a circumstance which frequently provides good exposures of the lower bedding plane surfaces of the sandstones. Sharp bedding plane contacts are frequent at sandstone-siltstone boundaries, commonly occurring when marked grain size differential exists at these boundaries. Gradational contacts are present when little variation in grain size exists at the bed boundaries as for example between fine grained sandstone and sandy siltstone.

The sharp lower bedding plane surfaces of the sandstones, may be planar or in some cases weakly load cast. In general the beds are parallel sided and only one instance of a sandstone with non-parallel bed boundaries was observed, in this instance the lower bed boundary displayed a marked erosive nature cutting into the bed below. The upper bed boundaries displayed by the sandstones are frequently gradational although sharp planar upper bedding planes may be present.

P.2.1a.

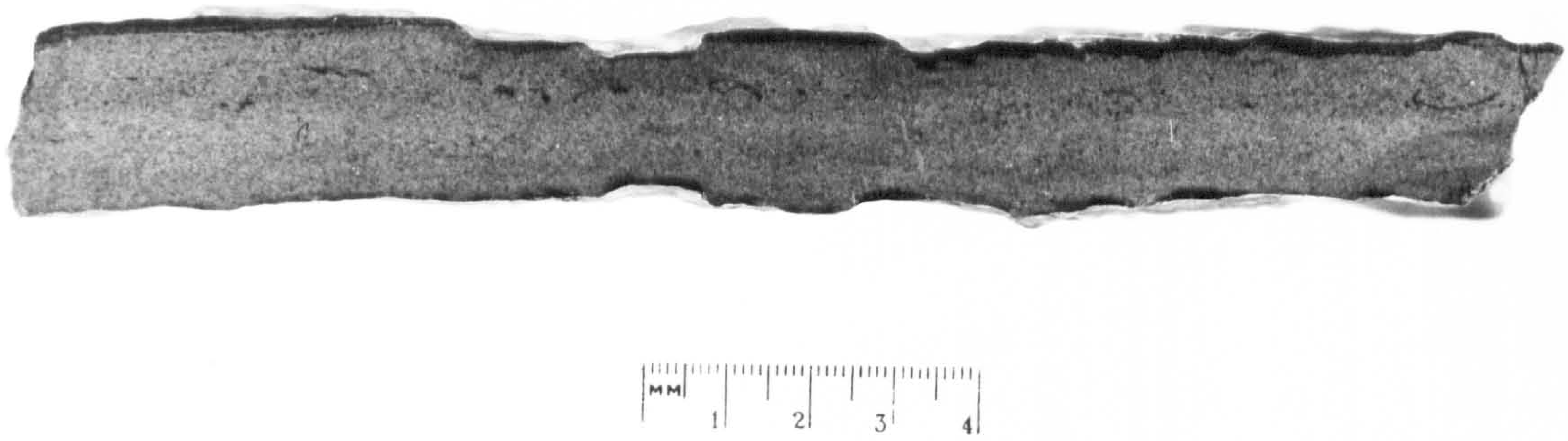
Vertical section through Lithofacies 4 bed 9T/41 displaying stepped relief.

Loc. 104. Thorncliffe Stream.

P.2.1b.

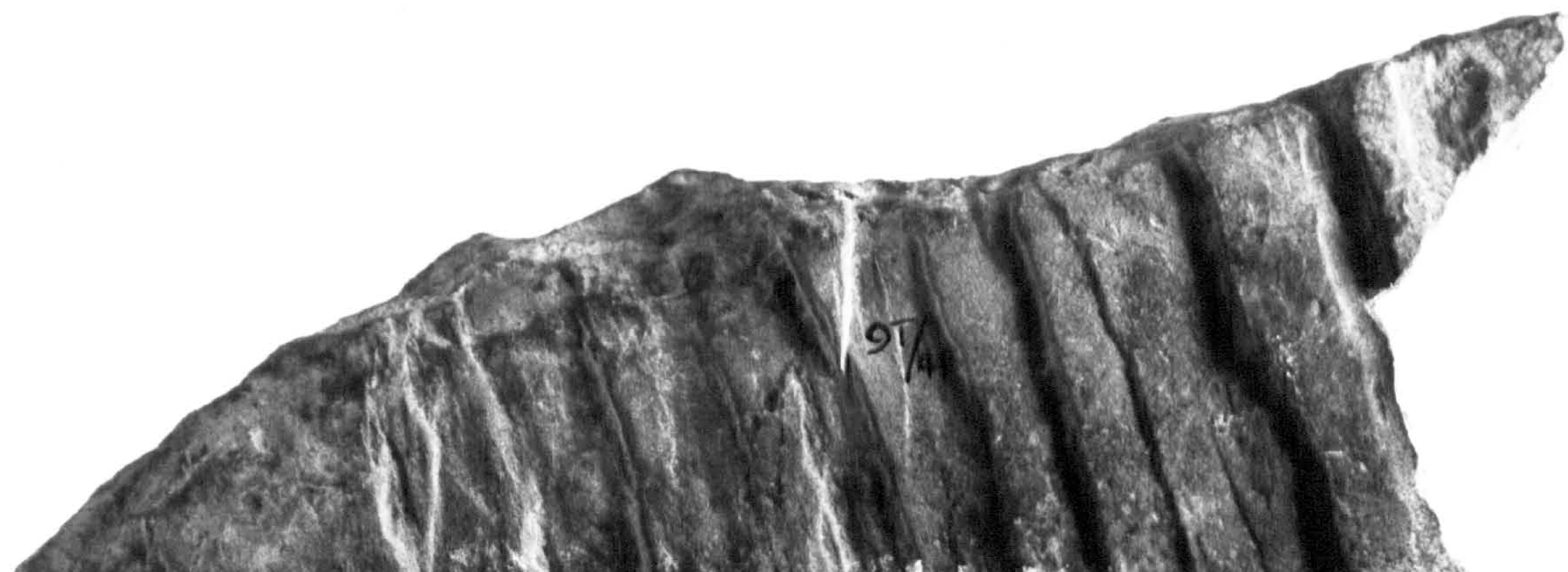
Upper bedding plane surface of Lithofacies 4 bed 9T/41 displaying stepped relief.

Loc. 104. Thorncliffe Stream.



P. 2.1a.

P. 2.1b.



Bedding plane structures present include toolmarks, biogenic marks and deformation structures.

Tool marks are infrequent in this Lithofacies and when present occur on the sharp planar and load cast lower bedding planes of the sandstones. They are weakly incised prod and groove marks and indicate easterly transport for the sediment in a sector between 075^{o} and 120^{o}.

In the upper part of the succession at Thorncliffe a group of sandstones occurs interbedded with siltstones. The sandstones exhibit well defined bed boundaries which present a stepped relief (P.2.1. a and b), the individual steps have heights of less than 0.005m and display a constant strike of 210^{o}. Beds displaying similar features occur in isolation in other parts of the succession. The majority of the upper bedding plane surfaces displayed by the sandstones are planar and only in isolated cases are bed forms present. When developed these structures take the form of weakly developed asymmetrical ripple forms, indicative of formative currents flowing to north east and east.

Biogenic structures are of infrequent occurrence and have mainly been observed on external surfaces in the form of hypichnial casts on the lower bedding planes of some of the thicker sandstones. In isolated cases, layers of carbonised plant debris, consisting mainly of stem segments of Calamites sp., are present on both upper and lower bedding plane surfaces of the sandstone beds. These plant fragments are carbonised impressions and possess dimension of 0.01m long by 0.001 - 0.002m broad.

Internal Structures

The siltstone beds present in this Lithofacies may display weak parallel lamination which may be picked out by thin fine grained sandstone laminae or by

P.2.2.

Internal structure of Lithofacies 4 bed 9T/26. Displaying ripple drift lamination gradational upwards to recumbent lamination which is intersected by a vertical endichnial burrow.

Loc. 104. Thorncliffe Stream.

P.2.2.

micaceous partings or by thin layers of plant debris of the Calamites sp. type. Internally the sandstones may be fine to medium grained structureless beds, but more frequently contain appreciable amounts of silt and finely comminuted organic material which are internally concentrated into laminae. The lamination is present in the sandstones either as undisturbed parallel lamination or may be distorted and all variations exist between sub-parallel laminae to irregular disturbed laminae. The parallel silt-sand laminae occurring in some of the sandstone beds are frequently observed to fine upwards. Distorted laminae associated with biogenic structures are present, but the majority of such laminae are not associated with biogenic structures. Distortion of the parallel laminae in some of the sandstone beds is due to the presence of repetitive microfaulting, the faults have a constant strike of 210^{o} and are of the normal type having a low angle of hade (circa 30^{o} and always less than 45^{o}) and a throw not in excess of 0.005m which is constant towards the south east. Weakly developed and infrequently occurring microfaults striking at 210^{o} and possessing a hade in excess of 45^{o} also occur in these beds. They are of the normal type and hade towards the north east. The microfaulted beds mainly occur selectively in groups in the sequence and less commonly are present in isolation.

Cross-lamination is rarely developed in this Lithofacies and when present may be gradational to and from parallel lamination. The cross-laminae display low angles of inclination to bedding surfaces. Weakly developed stoss side erosion is present. The direction of inclination of the foreset cross-laminae is generally to the west but is variable in the succession within an arc of 180^{o}. The sandstone bed 9T/26, (P.2.2.) displays parallel lamination which passes upwards into ripple drift lamination displaying stoss side erosion, which is gradational upwards to recumbent lamination. A sandfilled vertical endichnial burrow is present intersecting that part of the bed displaying recumbent lamination. Although burrow structures are infrequent in the beds in this Lithofacies vertical, usually sand filled, endichnial burrows of less than 5mm diameter are present in some of the thicker sandstones. The burrows are straight walled and are commonly concentrated in the upper portions of the beds. Less frequent in occurrence are burrows which traverse the beds. In those sandstones displaying parallel lamination the burrow structures may produce a down turning of the laminae marginal to their boundaries.

Interpretation

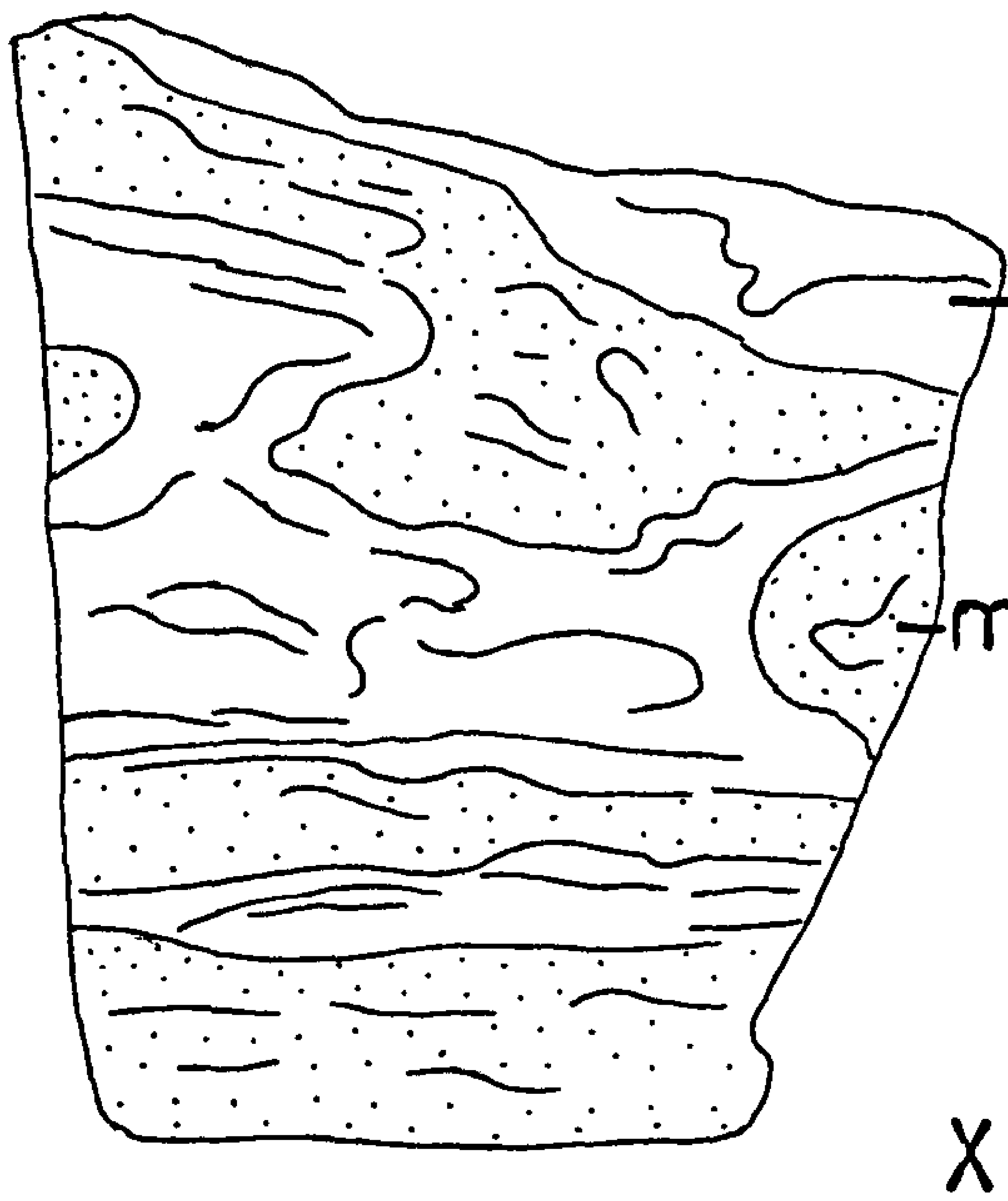
The internal structures exhibited by the sandstone beds in this Lithofacies are particularly diverse although the following account of the interpretation of these structures indicates how such variability may be reconciled to a single formative environment.

Within the sandstone beds various types of distorted lamination are present. Sedimentary structures of a similar type have been observed by Coleman and Gagliano (1965), in sediments accumulating on the Mississippi deltaic plain, and are described by them as distorted or contorted laminations. Coleman and Gagliano (1965) suggest that four distinct types of distorted lamination can be recognised in sediments of fluvial origin. Of the types that theypropose several occur in the Lithofacies 4 sediments and are produced by a variety of mechanisms including gas heave, slumping, differential overloading and current drag. Gas heave structures are thought to occur where sandy sediments accumulate rapidly over organic rich sediments, gasses from decomposing organic material rise or heave upwards through the overlying sediments producing distortion of the internal laminae in transit. Coleman and Gagliano (1965) figure this type of structure (Fig. 3a. p137) which depicts a bulbous mass of silt and organic material intruding upwards through a sandstone unit. Such marked distortion of the laminae was not observed in the Lithofacies 4 sandstones and the proposed ideal sedimentary environment conducive to the formation of this type of structure, that is the presence of an organic rich mud layer below a sandstone bed is also absent. However, the concentration of carbonised organic material present within some of the Lithofacies 4 sandstones is indicative of a source for evolution of gas, but it is thought that such concentrations were insufficient to produce enough gas for the formation of gas heave structures. It is however, possible that gas heave occurred to a limited extent and although it was probably not the prime cause in distortion of the laminae it may have been one of the contributary factors. A second mechanism, proposed by Coleman and Gagliano (1965), thought to be involved in the production of distorted lamination, is that of small scale gravity induced, slumping. In this case distinct blocks of laminated sediment are re-orientated and incorporated in a homogeneous matrix of a different texture. Coleman and Gagliano (1965) figure this type of structure (Fig. 3B p137). The illustration depicts a slumped block of coarser sediment penetrating a finer silty layer below. They suggest that the formative mechanism producing this type of structure incorporated the sliding or slumping of super saturated bank sediment into a river channel during a low water period and that during this large scale slumping the minor internal structures producing the disturbed lamination are formed. The parallel sided beds and for the most part the planar bed boundaries exhibited by Lithofacies 4 sediments are thought to preclude the mechanism of large scale slumping from the genesis of the distorted laminae in the sandstones. However, coarser laminated areas of sandstone occur in some Lithofacies 4 sandstones surrounded by finer sand and silt and accompanied by microfaults of small throw and variable orientation. On this evidence it appears that movement has occurred within the bed, possibly gravity induced, producing some of the distortion of the lamination observed in the sediments in this Lithofacies.

A third type of distorted lamination referred to by McKee et al., (1962) as "intra formational recumbent folding" is also described by Coleman and Gagliano (1965), from the Mississippi deltaic sediments. They suggest that it is one of the most common varieties of distortion found in deltaic sediments and consists of small scale, generally symmetrical folds whose axial planes attain a near horizontal position. Three mechanisms of formation are proposed for these intraformational recumbent folds and include slow mass movement of saturated sediment on inclined slopes, differential overloading and drag on unconsolidated sediment produced by shear initiated by an over riding sediment laden current. A fourth type of distorted lamination, in which overturning of the foreset laminations of current ripple laminations occurs was initially referred to by Dott and Howard (1962) as convolute lamination. Coleman and Gagliano (1965) term this type of structure an intraformational recumbent fold and state that "Regardless of terminology the structure is produced by the drag of strong sediment laden currents....."

The third and fourth types of distorted lamination are present, but only rarely, in the Lithofacies 4 sandstones. When present they are associated with cross-lamination which grades upwards into recumbent lamination which in bed 9T/26 is truncated by coarser sediment. This type of sequence is proposed by Coleman and Gagliano (1965), to represent increasing current velocity, and it is suggested that both lower and upper flow regimes are represented in bed 9T/26. A current direction can also be derived from the recumbent lamination, which in the case of bed 9T/26 is indicative of a westerly flowing current.

Fig. 2. D.



Distorted lamination in
bed 9T/3.

Within Lithofacies 4 the majority of the types of distorted lamination cannot be placed directly into any of the categories suggested by Coleman and Gagliano (1965). The most commonly occurring type is represented by sub-parallel laminae which vary from undulose to folded and may be microfaulted. It is suggested that a combination of several of the mechanism referred to by Coleman and Gagliano (1965), has produced this type of internal structure. In some cases the origins of the internal structures within the Lithofacies 4 sediments are clearly identical with those proposed by Coleman and Gagliano (1965). For example internal structures of type 2 (Coleman and Gagliano, 1965) are present in bed 9T/3, (Fig. 2.D.), here blocks of coarse sandstone are displaced against fine sandstone within the same bed. The fine sandstone containing distorted lamination is in part microfaulted against the coarse sandstone and in other areas of the specimen the fine sediment is observed to flow around the coarse sediment. Within the fine sediment in bed 9T/3 distorted lamination is present and can best be described as microfolded sub-parallel lamination. A second example of distorted lamination is seen in bed 9T/5 (P.2.3.) which clearly exhibits internal structures referable to the second type proposed by Coleman and Gagliano (1965). The origin of the internal structures present in beds 9T/3 and 9T/5 is thought to be similar to that proposed for this type of structure by Coleman and Gagliano (1965) that is the sliding or slumping of super-saturated bank sediment. How much of the distortion of the laminae is due to slumping is unknown, and other mechanisms which may have been involved are gas heave or formative current mechanisms. In the latter case it is suggested that a current exhibiting properties of incipient turbulent flow will produce undulating sub-parallel lamination, and that with increased turbulence the laminae will assume a cross-laminated character. This type of internal structure is seen in bed 9T/17.

P.2.3.

Internal structure of Lithofacies 4
bed 9T/5. Displaying distorted lamination.

Loc. 104. Thorncliffe Stream.

P.2.4.

Internal structure of Lithofacies 4
bed 9T/29b. Displaying distorted lamination.

Loc. 104. Thorncliffe Stream.

P.2.5.

Internal structure of Lithofacies 4
bed 9T/33. Displaying microfaulting.

Loc. 104. Thorncliffe Stream.

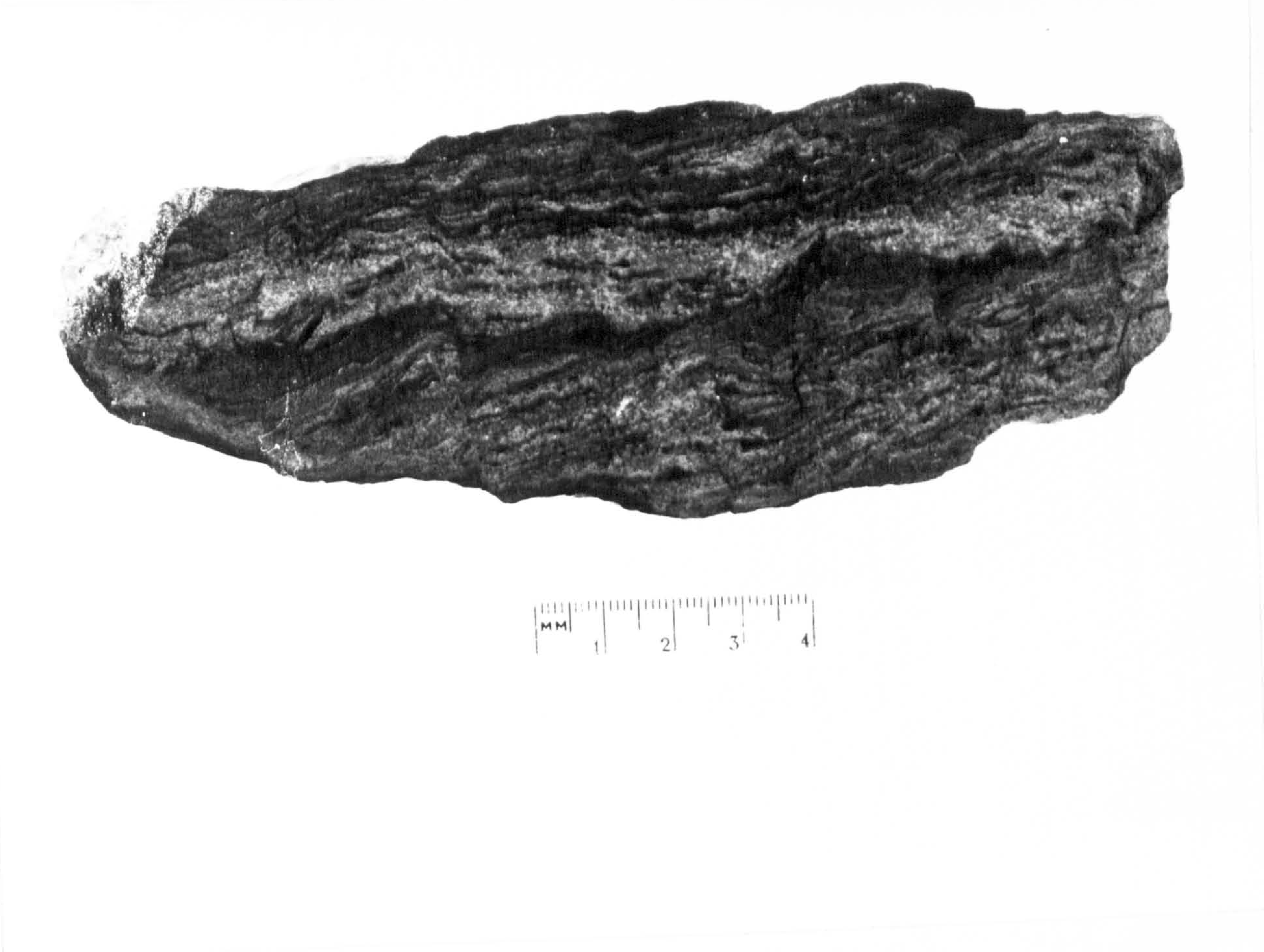
P.2.6a.

Internal structure of Lithofacies 4
bed 9T/37. Displaying microfaulting.

Loc. 104. Thorncliffe Stream.

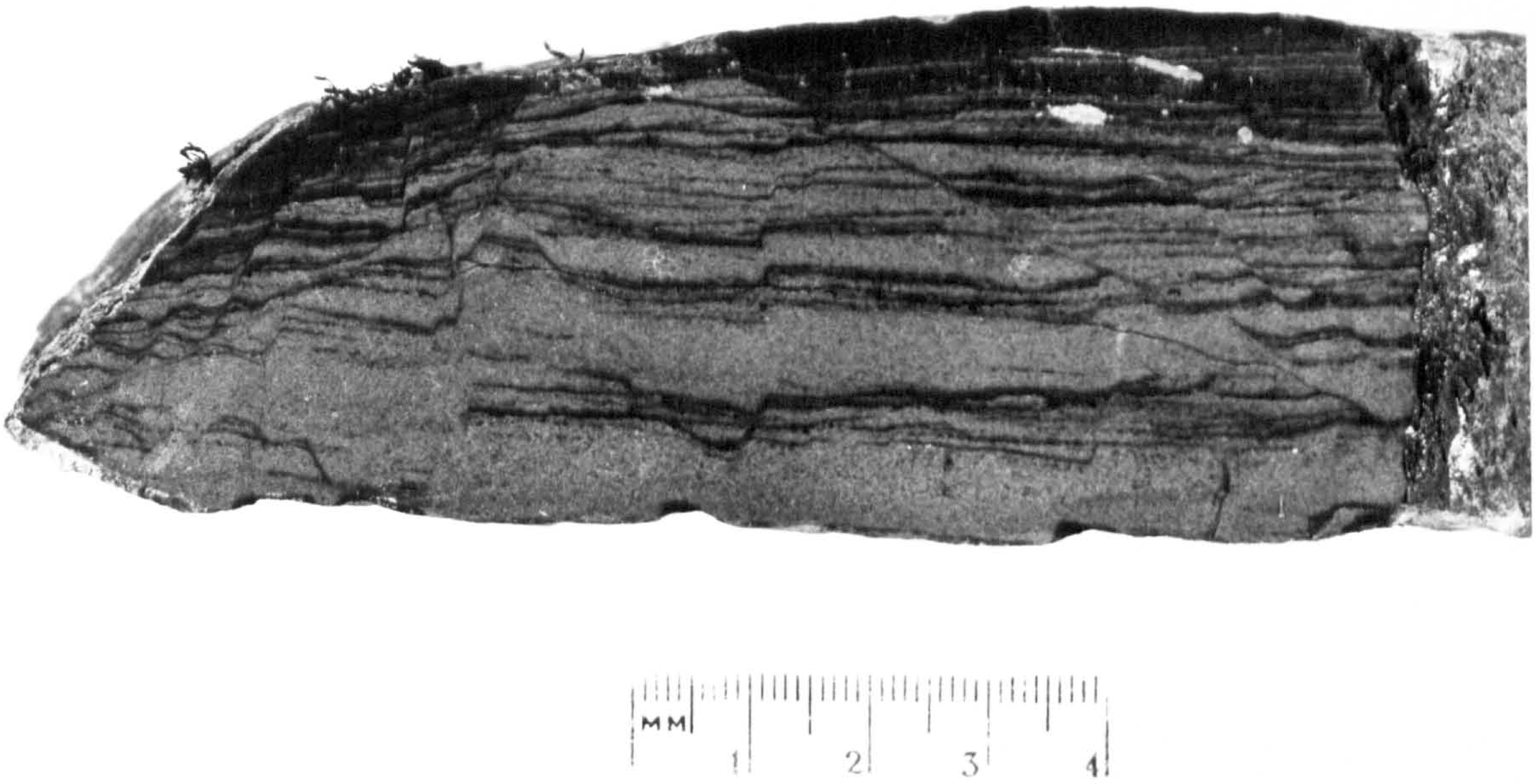
P.2.6b.

Detail of internal structure
at base of bed 9T/37.



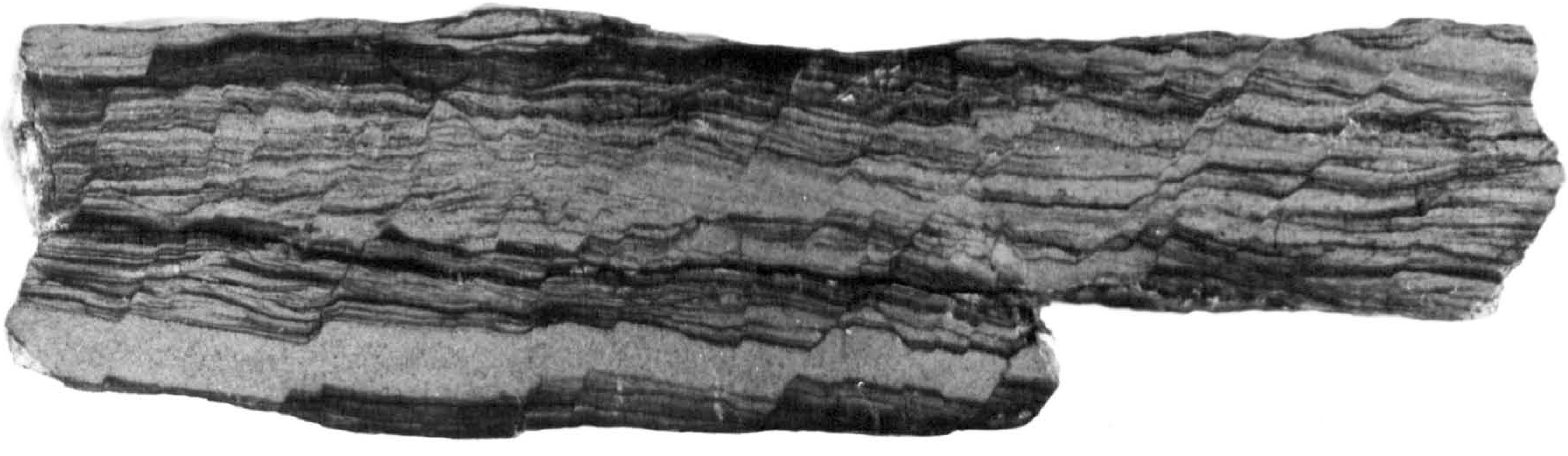
P.2.3.

P.2.4.

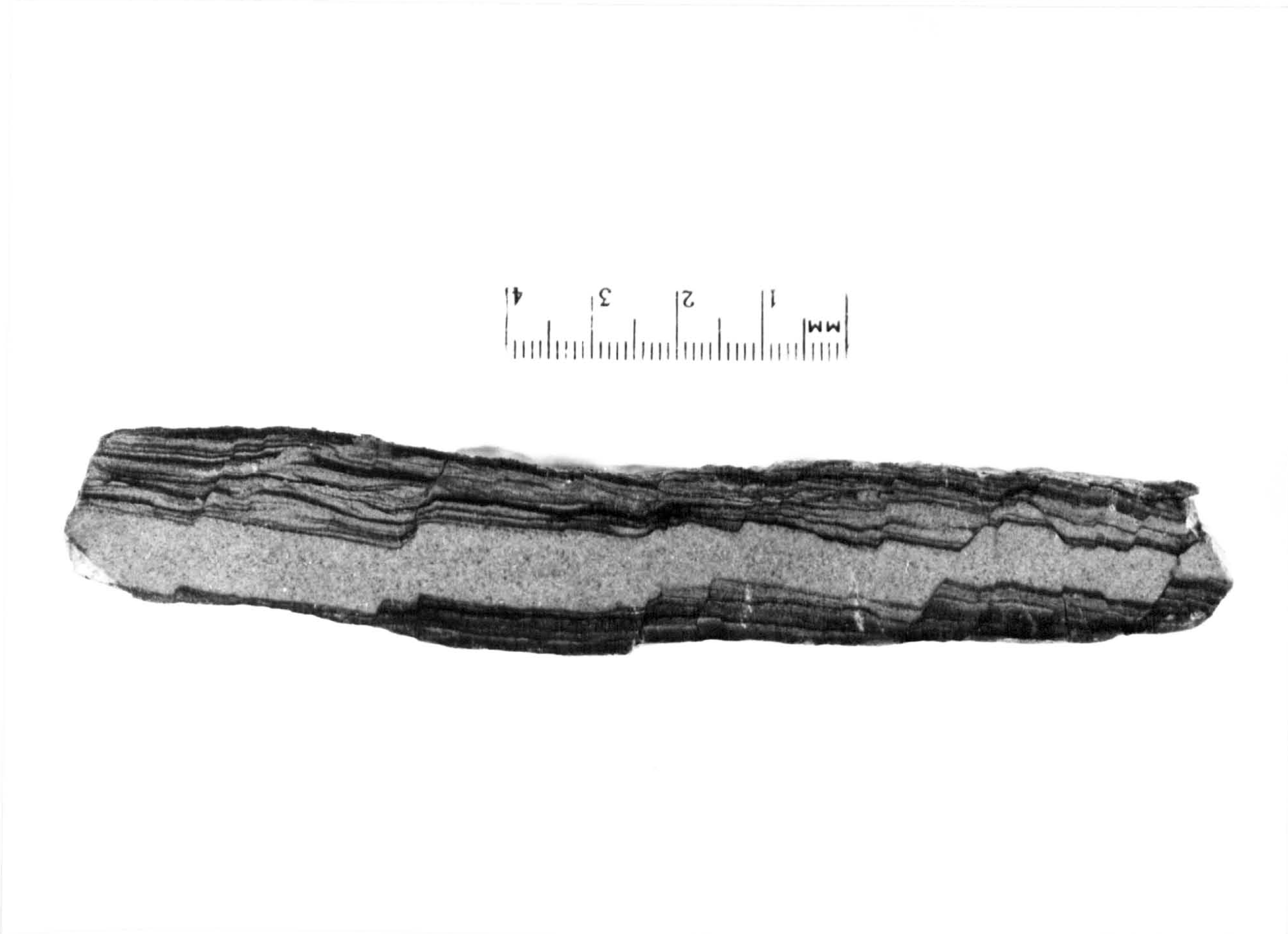


P. 2. 5.

P. 2. 6a.



P. 2.6b.



Chaotic distortion of the laminae is present in bed 9T/29b (P.2.4.). This bed, which contains abundant carbonised plant debris, channels into the bed below. It is thought to have been rapidly deposited by a strong current carrying waterlogged plant debris, mud flakes and medium to coarse grained sandstone in suspension. It is suggested that the collapse of the plant material and the rapid expulsion of water on compaction produced or increased the distortion of the internal structure displayed by bed 9T/29b. However, it is thought that the distorted lamination seen in other beds in Lithofacies 4, although it may be due in part to the expulsion of water from plant debris, is primarily a product of the mechanisms previously discussed.

Several beds display an increase in frequency of parallel lamination as they become progressively finer grained and may pass vertically into cross-lamination as in bed 9T/17, which is a medium to coarse grained upward fining sandstone displaying slightly distorted parallel lamination at the base passing upwards into cross-lamination. Bed 9T/29a is a fine grained inversely graded sandstone which displays cross-lamination at the base gradational upwards to parallel lamination. The internal structures described above are thought to have been produced by currents characteristic of the lower flow regime, which were subject to increases in velocity of sufficient magnitude to allow for the formation of the cross-laminated intervals.

The incidence of cross-lamination in Lithofacies 4 sediments is low and by far the most commonly observed internal structure is parallel lamination, which is present throughout the bed. In contrast to the distorted laminae the parallel laminae are laterally persistent and are only infrequently disturbed by slight irregularities which may be interpreted as primary current lineations (Allen, 1964). It is proposed that the parallel laminated beds were deposited by currents possessing lower flow regime characteristics and that the two types of parallel lamination relate to distinct current velocities. The development of both fine and coarse parallel lamination in association with and grading into cross-lamination is thought to further confirm the lower flow regime origin of these sediments.

The rate of accumulation of sediment in this Lithofacies is partly indicated by the biogenic structures present. Endichnial sand filled burrows are infrequently present in some of the sandstones. They are usually vertical non-branching burrows and commonly occur in the upper part of the bed, although occasionally burrows traversing the width of the bed are present. The absence of branching burrow-systems, previously interpreted as feeding burrows (see Lithofacies 3) together with a lack of bioturbation within the sediments and the overall low incidence of burrow structures suggests that the environment was not particularly suitable for colonisation of the sediments by burrowing organisms. The burrows that are present in the sediments are of two types, the first is infrequently observed and is referable to an eschape burrow, whilst the second type appears to have been a burrow formed by an animal feeding at the sediment - water inferface, and producing a shallow burrow which developed vertically as sediment was deposited. Both types of burrow are thought to represent a rate of deposition of sediment in excess of that occurring in areas where extensive burrowing activity is taking place.

Numerous small scale microfaults possessing a parallel orientation and a frequency of occurrence between 0.005-0.02m are present in some of the sandstone beds in this Lithofacies (P.2.5. and P.2.6. a and b). Apart from the fault structures these beds are internally underformed and it is suggested that the dislocations although not quite penecontemporaneous did however take place at an early stage in the diagenesis of the sediments.

The symmetrical arrangement of the microfaulting suggests some external mechanism producing a constantly orientated stress within the unconsolidated or partly consolidated sediment. Stresses generated by earthquake shocks are a possible mechanism for the origin of the microfaulting although the constant orientation of the strike in different beds and the presence of non-faulted beds in association with faulted beds weighs heavily against this type of origin.

Incipient slumping is suggested as a more likely mechanism capable of producing the microfaulting, it is envisaged that the microfaulting occurred in response to a gradual build-up of lateral tensile stress. It is presumed that this stress accumulated due to the position of deposition of the sediment, either adjacent to or on the margin of a gently sloping channel side. It is thought that fluctuations in water level within the channel or more likely bank erosion created conditions of incipient instability which induced the build-up of tensile stress within the sediments. Slumping of the microfaulted units does not appear to have taken place with the onset of instability, since there are no internal or external evidences of failure of this type. Internally beds within this Lithofacies which are thought to have been affected by slumping display a marked distortion of the internal laminae and this is not a feature of the laminated portions of the microfaulted beds. Externally the bed boundaries of slumped sediments may be non-parallel and in extreme cases the beds may be tightly folded or exhibit flow structures and brecciation, in the microfaulted beds in this Lithofacies however, such structures were not observed and the bedding planes with the exception of a slight stepped relief produced by the microfaulting are planar and parallel.

The relief of tensile stress within the microfaulted beds is thought to have been achieved by the extension of bed length consequent on the dislocation associated with the microfaulting. The south easterly downthrow of the microfaults together with their parallel orientation is thought to indicate that the feature producing the instability lay to the south east. It is proposed that this feature is a channel side aligned north east - south west and from the limited directional current data available it is possible to suggest that a channel side of this orientation existed in the area under consideration.

Associated with the normal type microfaults, and within the same sandstone beds, are less frequently occurring microfaults having a hade of more than 45^{o}. These faults are interpreted as being formed by weak compressive stress which was consequent on the removal of tensile stress due to movement along the normal microfaults. The strike of the microfaulting produced by the compressive stress is identical with that of the normal microfaulting which is to be expected if the mechanism of incipient slumping associated with a north easterly flowing channel is invoked. Similar structures to those mentioned above are described by Daley (1972) as deformation structures, presen in an Oligocene lagoonal limestone. The structures described by Daley(1972) comprise small scale folds, microfaults and slumped slabs which have arisen from the contemporary movement of sediment down a gradient, which he suggests as being the sides of small channels. Daley further points out that cracking or small scale faulting took place approximately parallel to the channel margins which led to the formation of slabs of undistorted sediment sliding down slope to accumulate in the channel bottoms. In addition to the slumped slabs of sediment, Daley also describes deformation structures present in argillaceous bands within the Oligocene lagoonal limestone, including folded laminae with micro-joints and distorted folded layers and refers their origin to instability and slumping on channel margins. The structures referred to above are analogous to some of the types of distorted lamination present in Lithofacies 4 sediments and it is proposed that this is further evidence supporting the concept of a channel origin for Lithofacies 4 sediments.

Daley (1972) refers to and figures (Fig. 7 p44) parallel microfaulting of parallel laminated sediment which he suggests may have resulted from the collapse of the sides of a scour hollow or channel. This faulting is of the normal type and is of the same magnitude as the microfaulting in the Lithofacies 4 sandstones. Elsewhere Daley (1972) suggests that, "The origin of the structures by slumping is supported by the bevelled bases of some bands." Disturbance of the bedding by bevelling or by erosion was not observed in the microfaulted Lithofacies 4 sandstones and it is suggested that the incipient instability condition did not progress to a stage where slabs of material moved laterally down a channel margin or palaeoslope, but that stability within the sediment was achieved by the lateral extension of the bed which accompanied the microfaulting. In addition the slumped slabs described by Daley (1972) contain parallel laminae which have been re-orientated and lie at angles of 30^{o} - 40^{o} to the bedding (slump surface). This type of structure is absent from the microfaulted sandstones within Lithofacies 4 and in its absence tends to support the concept that the conditions of incipient instability which existed in these sediments did not progress to an actual slump failure.

In the light of the evidence discussed (ibid) it is suggested that the sediments present in Lithofacies 4 were deposited relatively rapidly by currents possessing lower flow regime characteristics. The incidence of internal distortion and dislocation further suggests that conditions of instability were inherent in the early stages of diagenesis of the sediments and as has previously been suggested this instability is thought to be due to the slumping of bank sediments due possibly to local variations in water level. On the basis of field evidence the sediments in this Lithofacies are limited in their lateral extent and it is suggested that deposition took place within a localised channel, such as a deltaic distributary. The current directional structures present in this Lithofacies indicate an easterly flowing current, thus giving the channel an east-west long axis. The sediments presentto the north and south of the Thorncliffe exposure further suggest that the Lithofacies 4 sediments were confined to a narrow west-east zone.

It is proposed therefore that this zone represents a distributary channel and on the basis of the internal structure, the associated Lithofacies and the proposed palaeogeography it would appear that the sediments present at Loc. 104 were deposited in a distal part of a deltaic distributary of a constructive delta. The association of sediment to the north and south of Loc. 104 is thought to imply that the distributary was building out into deep water and it is thought to be of the type commonly associated with a "birdsfoot" delta.

LITHOFACIES 5

Brief Diagnosis

Very thick beds of coarse grained to pebbly sandstone and conglomerate are present which commonly exhibit internal planar cross-stratification. Foresets are defined by alternations of coarse pebbly layers interspaced by finer layers of sand grade, or by parallel alignment of pebbles, or by isolated thin sand laminae in the conglomerates. The majority of the bedding plane surfaces are non-parallel erosion surfaces, truncating pre-existing structures. Mudstones siltstones and fine sandstones are absent from this Lithofacies.

Distribution

Beds in this Lithofacies outcrop at the northern end of Ipstones Edge as a series of isolated exposures at localities 086, 087 and 089. They are also exposed on the south side of the Combes Valley at Loc. 11 of Morris (1967) and have recently become exposed[1] in the Combes Brook on strike from the above location. The stratigraphical position of Lithofacies 5 sediments is determined, on the basis of palaeontological[2] evidence to be within the "Middle Churnet Shales Division."

External Structures

Bedding plane surfaces are sharply defined and may occur at the junction of pebbly sandstones with sandstones or may be present between beds of similar lithology. The bedding plane surfaces are planar or curved and may be parallel, sub-parallel or markedly discordant. The discordant bedding planes may be inclined in opposite directions and in some cases are seen to intersect, whilst the curved bedding planes may be terminated by the planar bedding surfaces.

Bed thicknesses are frequently in excess of 1.0m and the maximum observed bed thickness occurs in the conglomerates, approaching 5.0m. Those beds bounded by curved bedding planes are frequently observed to thin to zero within the limits of the exposure.

Internal Structures

The beds contained in this Lithofacies comprise two distinct types; planar cross-bedded sandstones and planar cross-bedded conglomerates. The planar cross-bedding present in the sandstones is well defined, due to the presence of

1. Stream erosion 1973.
2. Stream erosion during 1973 exposed a marine horizon circa 15m below Loc.9 of Morris (1967) and circa 15m above the highest exposure of Lithofacies 5 sediments. This horizon is tentatively placed in the upper part of the Middle Churnet Shales.

P.2.7.

Exposure of Lithofacies 5 beds.

Loc. 086. Ipstones Edge.

(See key, Fig.2, on following page)

P.2.7.

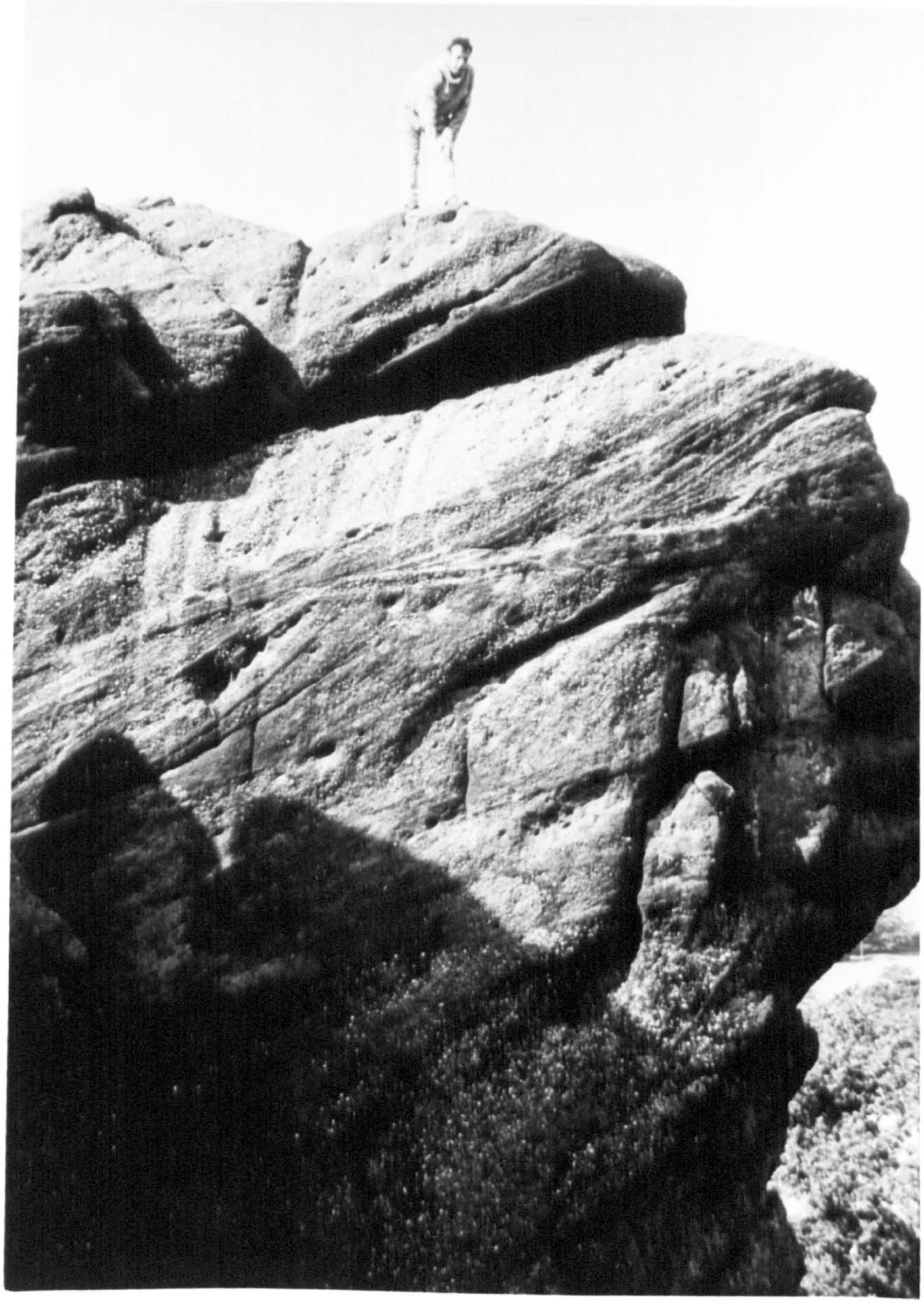
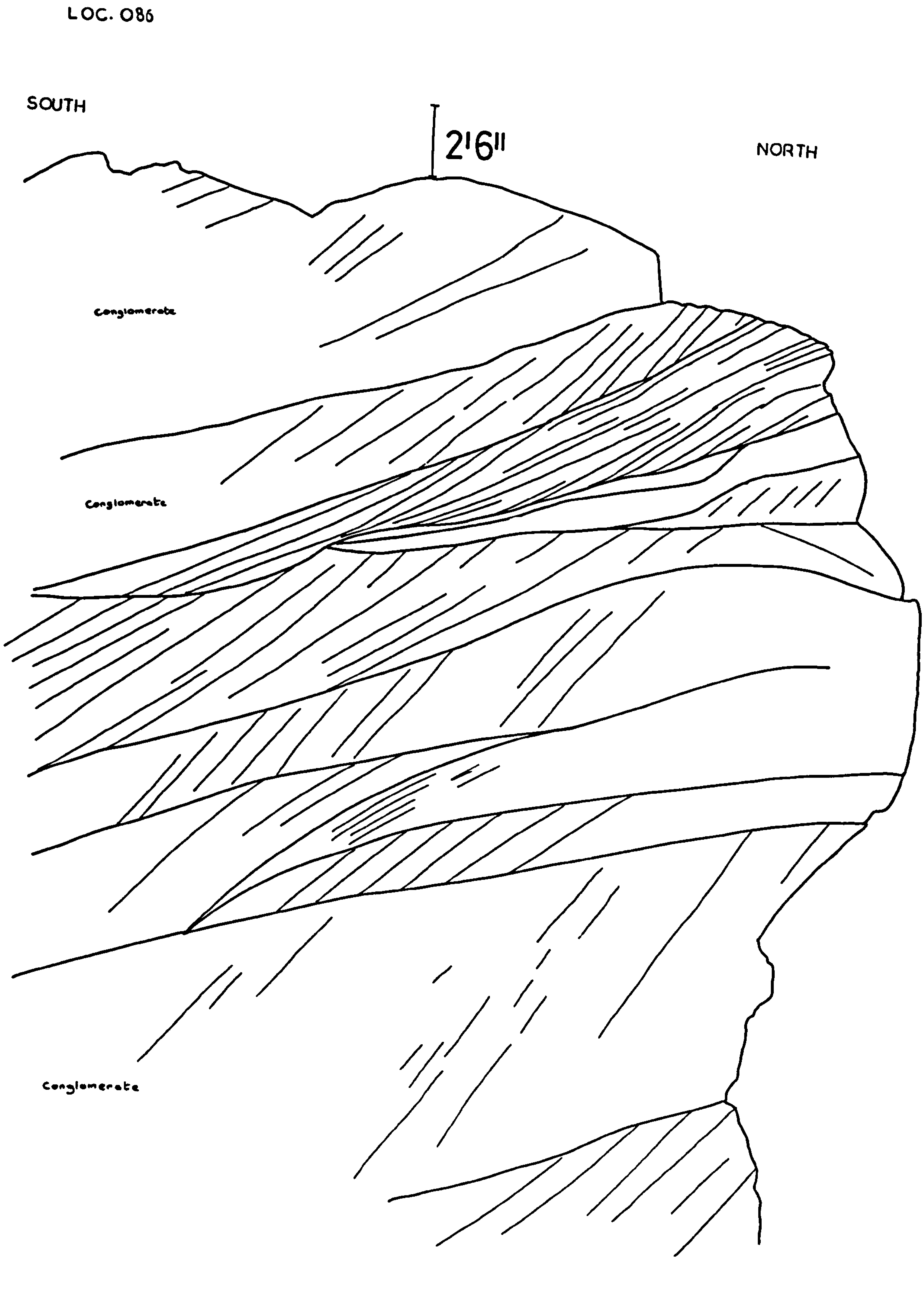


Fig. 2.E.

key to P.2.7.



alternating coarse (pebbly) and fine (sandy) foresets. (P.2.7.) (Fig.2.E.)

The planar cross-bedding present in the conglomerates is less well defined, but is apparent in the parallel alignment of the pebbles and by the occasional presence of thin foreset sand laminae. The lithology of the individual beds is constant in outcrop and neither vertical nor lateral size grading was observed in association with the planar cross-bedded strata. The thickness of the individual foresets varies between 0.02 to 0.30m, the thicker interval being characteristic of the conglomerate beds, although foresets of over 0.25m thickness have been observed in the sandstone beds. The foresets are frequently sharply truncated by the upper bedding plane surfaces, whilst the junction between foresets and lower bedding plane surfaces is observed to be angular in the majority of beds. Tangental bottom-sets were observed only once in a sandstone bed, but were not present in the conglomerate beds. Foreset surfaces are poorly exposed in this Lithofacies, however, the three dimensional form of the outcrops at Locs. 086, 087 and 089 makes it possible to estimate the orientation and inclination of the foresets. At Loc. 086 the angle of inclination of the foresets commonly approximates to 15^{o} - 20^{o} with exceptions up to 40^{o}, the direction of inclination of the foresets at this locality being $200^{o} \pm 10^{o}$. The foresets at Loc. 087 are inclined towards $060^{o} \pm 10^{o}$ at angles of repose between 10^{o} and 15^{o}. At Loc. 089 foreset inclinations have been recorded between 10^{o} and 30^{o} and are inclined towards $180^{o} \pm 10^{o}$. Internal structures, other than the planar cross-bedding described above are absent from this Lithofacies.

More than 95% of the well rounded pebbles present in the conglomerates, and in the coarser foresets of the sandstones, consist of vein quartz, the remaining 5% consist of decayed granitic rocks[1] and fine grained acid rocks, probably

1. Similar granitic rocks occur insitu in the Ercall Hill near Wellington, Shropshire. Ref. British Regional Geology Handbook, THE WELSH BORDERLAND.

rhyolites, which in thin section are extremely fine grained and display a turbid nature similar to that exhibited in thin section by decomposed felspar; oxidised siderite pebbles are also present. The siderite pebbles are flat and elongate and at Loc. 086 they are exposed on a foreset surface with their long axes sub-parallel in the orientation $200^{o} \pm 10^{o}$, which is the direction of dip of the foresets at this location.

A small scale channel structure is present at Loc. 087 directly below a planar bedding surface. The channel, which is exposed in transverse cross-section only, possesses a gentle concave base which is not sharply defined and has a minimum depth of 1.0m and a minimum width of 3.0m. The channel fill consists of a thin veneer of sand partly enclosing a structureless pebbly sand which is coarser than the sediment comprising the bed into which it is incised.

Interpretation

The most noticeable structure displayed by the beds in this Lithofacies is the well developed planar cross-bedding. Bagnold (1941) attributed the cross-bedding developed in desert dunes to sorting of sediment during gravitational sliding of grains down the lee face of a dune, this grain sorting process, Brush (1965) proposes, may be operative during the subaqueous sliding of cohesionless sediment. In a more quantitative approach to the genesis of foreset laminae in desert dunes, Bagnold (1954) demonstrated that in an avalancing situation the grain diameter is inversely proportional to the dispersive stress. Thus the maximum shear, which will occur on the plane of sliding, will be the site where the smaller grains tend to accumulate, whilst the larger particles will tend to migrate to zones of lesser shear at the free surface and the deposit will tend to become inversely graded across the foreset laminae. In addition the larger particles will tend to accumulate at the base of the foreset slope. Graded foreset laminae of this type were not observed in Lithofacies 5 sediments and in particular the coarse pebbly foresets show no grading or concentration of pebbles along the plane of avalanching as described by Bagnold (1954), and Allen (1965, 1968a and 1970b).

Cross-bedding, represented by alternating coarse and finer foresets, of a similar type to that occurring in Lithofacies 5 sediments has been described by several authors, notably Collinson (1970) and Smith (1972), from occurrences in recent fluvial sediments.

The origin of cross-bedding, of a similar type to that displayed by Lithofacies 5 sediments, has been described by several authors including Allen (1963) and Hooke (1968). Such cross-bedding is suggested by Hooke (1968), on the basis of flume sedimentation experiments, to be due to the accumulation of coarse sediment in a scour pocket in the lee of an advancing bed form. The development of such a scour pocket, is suggested by Hooke to be due to the presence of lee side eddies generated by either a migrating ripple or dune, which as the foreset slope is encountered produces an avalanche of sediment down the foreset slope. Thus a layer of coarse sediment builds up as the sediment in the scour pocket avalanches, followed in turn by the avalanching of the finer sediment which previously constituted the migrating bed form. The thickness of the individual foresets in this Lithofacies suggests that the migratory bed forms were dunes, as opposed to ripples which would produce thinner and less coarse foresets (Smith, 1972). In addition the coarse nature of the sediments in Lithofacies 5 tends to support the conclusion that flow regime conditions were applicable to dune formation (Simons et al., 1965).

The absence of fine grained sand, silt or mud from the beds in this Lithofacies suggests that the finer material remained in suspension and that the genesis of the foresets was due solely to avalanching of bed form sediments (Jopling, 1964). Grading within the foresets, as described by Bagnold (1954), is absent from the beds in this Lithofacies. It is suggested that this is due to a high degree of hydraulic sorting of the sediments comprising the migrating dunes and associated lee side scour pockets. The avalanching associated with the migration of the bed forms has produced foresets, which on the basis of field observation appear to be non-graded. An alternative mode of origin is proposed for the genesis of the cross-bedded sediments occurring in Lithofacies 5, in which the coarse sediment is transported in upper flow regime conditions as a traction carpet, producing a continuous avalanching of unsorted sediment at the foreset surface. This type of mechanism, it is thought, would produce a graded foreset of the type described by Bagnold (1954). Graded foresets of this lithology were not observed in Lithofacies 5 sediments, although it is assumed that the process of continuous avalanching of sediment from a traction carpet may be responsible for the internal structure of the conglomerate beds in this Lithofacies. These coarse beds occur as isolated sequences of very thick beds (maximum 5.0m) separated in the succession by sequences of thick sandstone beds from which conglomerate beds are absent. It is suggested that the genesis of the conglomerated beds occurred in higher flow regime conditions than the sandstone beds, possible during periods of increased discharge. At such times it is envisaged that much of the finer sediment was carried in suspension and that only the coarser material was contained in the traction carpet. The crude foreset boundaries observed in the conglomerates are picked out by pebble orientation and by a vague sorting of the larger and smaller pebbles, and by rare coarse sand laminae. Sorting may have occurred due to the avalanching of selectively sorted material (Jopling, 1964., Hooke, 1968), or may have been formed in response to dispersive pressures at the surface of sliding (Bagnold, 1954).

The external morphology of the bed forms present in this Lithofacies is only represented fragmentarily, and for an interpretation of the complete form one has to look to internal evidence. In the exposures examined there is a complete absence of trough cross-bedding, all the foreset laminae occurring in large scale tabular cross-bedded sets. Tangentally based foresets are of rare occurrence in this Lithofacies and have been observed from only one bed, which displays a markedly erosive base. The majority of foresets are angular based, and generally speaking the angle increases with increase in grain size. Collinson (1970) describing the internal structure of bed forms developed in the Tana River, a braided river in northern Norway, indicates that the internal structure developed in the dunes is that of trough cross-bedding with asymptotically based foresets, whilst the internal structure of the lingoid bars consists of alternating coarse and fine angular based planar cross-bedded foresets and occasional less clearly defined foresets with wavy outlines.

Smith (1972), also described the occurrence of tabular sets of planar cross-stratification from bar structures in a modern braided river, the Platte River, Nebraska. He terms the large scale bed forms in which planar cross-bedding occurs, transverse bars. These structures appear to be the equivalent of Collinson's (1970), lingoid bar structures; both existing as large scale bed forms.

Both Collinson (1970), and Smith (1972), indicate the presence of ripple cross-laminae in association with the planar cross-bedding, either at the base or at the top of the cross-stratified division. In the Lithofacies 5 sediments this association was not observed due to the non-development of ripple bed forms on the bar surface or more probably due to their removal by erosion.

Harms and Fanstock (1965), describing modern sediments from the Rio Grande River, Texas, refer to tabular cross-stratification as being a feature developed in bed forms which are best described as bars, they suggest that during high discharge periods bar advance due to avalanching on the down current margin may be as much as 70 feet per day. It is thought that the absence of minor bed forms in the Lithofacies 5 sediments is due to erosion in a similar high energy environment, which was probably associated with rapidly advancing bars. Erosion of the bar surfaces of both the conglomerates and sandstones in this Lithofacies appears to have occurred, since a marked sharp truncation of the top of the foresets is evident in the majority of beds. These erosion surfaces or bedding planes are non-parallel and may be curved and truncated by successive bedding planes, such a discordant relationship is presumed to be evidence of lateral migration of the successive bar deposits, within the main channel.

The orientation of the foresets at Locs. 086, 087 and 089 has previously been described as markedly divergent in a relatively small areaof exposure (approximately 1km), and presents a problem in interpretation of the direction of the palaeo-river course. Smith (1972), indicated that in a modern braided river, the orientation of the maximum slope of the foreset laminae may be markedly divergent from the orientation of the formative current, especially along the side margins of lobe-shaped bars, and bar fronts migrating towards stable banks. Smith (1972) suggested that out of 332 foreset dip measurements, only 30.5% were within 5^{o} of the formative current and that 86.1% showed variations up to 45^{o}, from this evidence he concluded that the orientation of planar cross-stratification was not a true indicator of current direction.[1.] On the basis of the palaeogeography and of the associated

1. Banks and Collinson (1974) suggest, on the basis of a bar model, that a much lower varience of foreset directions is to be expected in ancient deposits, than is proposed by Smith (1972). However, from the limited palaeocurrent data available in the Ipstones area it is not possible to produce a viable statistical analysis.

Lithofacies, it is proposed that the sediments at Locs. 086, 087 and 089, were deposited from a northerly to north easterly flowing river and it is considered that the limited evidence provided by the orientation and dip of the cross-stratification, whilst fitting into such a broad river pattern, is of little value in interpreting the direction of flow.

From the evidence of the lithologies of the beds within this Lithofacies it is proposed that the formative river system was subject to periodic variable discharge. In times of high discharge rates it is thought that the coarser sediments were formed, whilst the finer grained sediments were produced in periods of lower discharge. It is noticeable in the exposures of Lithofacies 5 sediments that the coarse and fine beds are separated into distinct units in the succession a feature which is taken to support the variable discharge theory.

In periods of high discharge it is proposed that the planar cross-bedded conglomerates were formed at the margins of rapidly advancing bars, and that the pebbles forming these beds were moved in traction over the flat bar surface and accumulated by avalanching down the slip face of the bar. The coarse nature of these beds indicates that powerful currents were operative at their time of deposition and it is thought that the currents were powerful enough to maintain the majority of the finer sediment in suspension.

A period of reduced discharge is envisaged in the genesis of the cross-bedded sandstones, when flow conditions were conducive to the development of active small scale bed forms on the bar surface, which as they arrived at the bar margin initiated the alternating coarse and fine foresets. The presence of pebbly foresets, although not as coarse as the conglomerate beds, is thought to indicate that even at the lower discharge rate the stream power was sufficient to transport relatively large particle sizes. A further indication of the high value of stream power is thought to be evidenced by the marked erosive contacts which are present between the successive beds and is taken to indicate that bar migration within the river system was rapid. Upwardly convex bedding surfaces are thought to represent burial of a sector of the bar margin by a more rapidly advancing part of the bar, whilst in other cases erosion of pre-existing bar sediment prior to the deposition of successive migrating bar sediment has produced a concave downwards bedding surface. Bar structures with irregular down-stream margins were recorded by Collinson (1970) from the Tana River. He describes such structures as being modified lingoid bars and side bars. It is proposed that the rapid down-stream migration of similar bed forms could have produced the irregular bedding displayed by Lithofacies 5 sediments.

Channel structures are largely absent from this Lithofacies and only one small channel was observed. This channel is incised into a sandstone bed and the channel fill is coarser than the unit of beds in which it occurs. It is suggested that the channel was formed in a low discharge period and that the coarse fill is locally reworked sediment from which the finer sediment has been removed.

In general it is proposed that discharge rates in that part of the palaeo-river system represented by Lithofacies 5 sediments were high enough to produce sufficient current energy to maintain in suspension all but the coarser sediment, and that the large scale bed forms present were formed in upper flow regime conditions and also in the upper part of the lower flow regime. It is suggested that the environment of deposition of these large scale bed forms is referable to a braided river system and in particular to a major channel in such a system in which erosion combined with rapid migration of the bed forms was operative.

LITHOFACIES 6

The sediments present in this Lithofacies are interpreted as being of turbidity current origin.

Sandstones occur displaying characteristically sharp bases and internally may display all or part of the Bouma sequence (Bouma, 1962).

The Lithofacies 6 sediments are subdivided on the basis of bed thickness, internal structure and lithology into four distinct Sublithofacies.

SUBLITHOFACIES 6a

Brief Diagnosis

Thickly bedded to very thickly bedded medium to coarse grained to rarely pebbly sandstones, which occur in sequence without any intervening argillaceous beds, are characteristic of this Sublithofacies. The majority of the beds persist laterally without any thickness variation, although isolated beds displaying a lenticular form are present. The bases of the beds are sharp and in some beds load cast structures are developed. Deeply incised current induced directional structures of the tool mark and scour mark varieties may be present on the bases of some of the beds.

Distribution

A thick development of Sublithofacies 6a sediments occurs in the Gawsworth Common area (SJ 92406840) (Fig.IA) well exposed in a series of old quarries at Locs. 201, 202 and 203. Palaeontological control is very poor in the area and the succession is placed within the interval E_2b_1 - R_1a on the basis of palaeontological evidence taken from the Macclesfield Memoir, 110, Evans *et al.*, 1968. The *H.beyrichianum* horizon (Loc. 81, Evans *et al.*) is present midway in the succession occurring on a hillside 300 yards East by North of Whitemoor at grid reference (SJ 91576810). Although much time was spent at this locality no palaeontological evidence additional to that provided by the Geological Survey was obtained. The top of the Sublithofacies 6a succession at Gawsworth Common is delimited by a shale mudstone sequence, Loc. 114 of Evans et al., containing a faunal assemblage which has been assigned by the Geological Survey to the R_1a Zone. The base of the Sublithofacies 6a sediments is not exposed but occurs structurally and stratigraphically higher than a succession of mudstones partially exposed in the Rough Hay Quarry (SJ 92126887) which is attributed by the Geological Survey to the "Lower or Middle Churnet Shales" (Evans et al., 1968, p35.). The former is thought by the author to be the most likely since the mudstone succession exposed at Rough Hay Quarry (SJ 92126887) lies structurally above an horizon of Ct. edalensis exposed in Sutton Stream (SJ 92246964) Loc. 34 of Evans et al. The "Middle Churnet Shales" are also exposed one mile to the east of the Rough Hay Quarry in the Sutton Stream bed adjacent to Ryle's Arms Inn (SJ 94186939) and here consists of a mudstone succession with ankeritic horizons containing the goniatites N.nuculum (Loc. 35, Evans et al.) and H.subglobosum (Loc. 80, Evans et al.).

Field Characteristics

Thickly bedded (0.30 - 1.0m) to very thickly bedded (plus 1.0m) medium to coarse grained sandstone beds occurring in a continuous sequence are separated by clearly defined parting planes (P.2.8.), which may have a veneer of argillaceous material which in some cases attains a thickness of 0.01 - 0.02m. The parting planes between some of the sandstone beds (circa 10%) are not laterally persistent and bed amalgamation occurs. The number of sandstone beds occurring in sequence varies between two to ten successive beds and is preceded and succeeded by mudstone intervals.

The bases of the sandstone units are sharp, frequently the first bed in any sequence which overlies a mudstone interval exhibits well developed load cast structures, although load cast structures have been observed between adjacent sandstone beds.

Tool and scour marks are very evident in field exposures in this Sublithofacies and are particularly well developed on the bases of sandstones overlying a pelitic interval. The majority of the sandstone beds are parallel sided. Lateral variation in bed thickness occurs infrequently and when present is seen to be due to the erosive nature of a single bed channeling into one or more beds below.

The upper bedding plane surfaces of the sandstone beds are planar, although rarely non-planar undulating surfaces are present. Nine isolated instances of ripple marked upper bedding plane surfaces occur (less than 5% of the total) and may be overlain in the succession by either an argillaceous or arenaceous bed. Specimen 18T/146 was collected from a large exposed quarry face displaying on the upper bedding plane surface an extensive development of parallel sinuous ripples (Allen, 1968c). Biogenic structures are extremely rare in this Sublithofacies and were only observed in three beds out of a total of 250 beds.[1.] In each case they consisted of endogenetic burrow structures. Evidence of exogenetic trace fossil structures was not found despite close examination of extensive exposures of planar and ripple marked bedding planes. Also apparently absent in the Gawsworth exposures, from the 115m of strata which were examined, are the goniatite index horizons which are characteristic of the succession in other localities.

1. A burrow structure referable to Rhizocorallum was identified by J. Collinson from bed 18T/146. (This was subsequent to fieldwork done in this area by the writer)

External Structures

Sharp lower bed boundaries are exhibited by 75% of the sandstones in this Sublithofacies, and the sandstone beds which overlie mudstone are frequently strongly load cast e.g. beds 18T/167, 18T/154, 18T/120 (P.2.9.). The bases of the sandstone beds overlying sandstone beds are frequently sharp and planar, although load casting may be developed. In the latter instance the development of load cast structures may take place at the base of a thick bed superimposed on a thinner bed (18T/176), or where beds of approximately equal thickness occur in sequence (18T/162 - 161, 18T/178 - 177), and even when a thinner bed overlies a thicker bed (18T/170 - 169), in all these cases there is no apparent grain size difference between adjacent beds. Primary bedding plane structures of the tool mark type are very common in this Sublithofacies and are strongly developed at sandstone/mudstone interfaces and are also commonly present at sandstone/ sandstone interfaces. The structures present include strongly developed prod and groove marks, whilst skip or bounce marks have also been observed. The deeply incised prod marks have a parallel orientation, and this orientation is identical with that given by well developed groove casts which are commonly present on the same bedding plane (P.2.10 a and b).

Bedding plane structures resulting from current scour have been most frequently observed at sandstone/mudstone interfaces and include deep bulbous flute casts and rarely scour channels. The base of bed 18T/159, a thick sandstone, displays the development of a scour channel 30 cms deep which cuts through thin sandstones comprising beds 18T/158, 18T/157, 18T/156 and terminates in bed 18T/155.

The orientation of the long axes of the scour marks corresponds closely with that derived from measurements of the tool marks, and the current directional sense implied by these structures is identical. The orientation of all structures within the sediments of this Sublithofacies which display a preferred orientation due to current flow lies within a 45^{o} sector.

Ripple marked upper bedding plane surfaces occur very rarely in this Sublithofacies but when present display an extensive lateral development (P.2.11a.). The ripples are parallel sinuous to catenary in form (Allen, 1968c) and possess a gentle stoss side and steeper lee side (P.2.11b.). The geometry of the ripple bed forms, based on the nomenclature of Allen (1968) is as follows: ripple length 10-12cms, stoss side circa 6.5cms lee side circa 5cms, height 1-1.5cms (data taken from bed 18T/146). The current directional sense displayed by the ripple bed forms corresponds closely with that suggested by the tool and scour marks on the base of this bed.

Internal Structures

In the field, the majority of the sandstone beds in this Sublithofacies appear to be internally structureless and can be described as massive beds. Laboratory examination of the sediments confirms this and in only a few beds (18T/169, 18T/146, and 18T/23) can size grading (Birkenmajer, 1959) be observed, taking the form of an upward fining of the total grain content, this type of grading has been described and referred to by Middleton (1967) as distribution grading.

Coarse parallel lamination is present in the upper portions of some of the sandstone beds, the total thickness of the laminated zone is usually of the order of 0.02m and rarely exceeds 0.05m. In the field this parallel lamination is enhanced by slight colour changes which if absent would make the recognition of a parallel laminated zone very difficult. On cut and polished surfaces the colour contrast is absent and the laminae are seen to be comprised of thick laminae consisting of sheets of coarse grains intercalated with thin laminae of a finer grain size. Flat ovate mudstone clasts with rounded edges are present in the upper parts of some of the sandstone beds, they have variable dimensions, the majority are less than 0.01m thick and possess a long axis of circa 0.05m although exceptions are present in which the long axis dimension attains 0.10m. Fine parallel lamination was observed in some of these mudstone clasts. The clast generally lie parallel to the bedding and in some cases are present on the upper bedding plane surface, there appears to be no preferred orientation of the long axis.

In some beds the interval of parallel lamination passes upwards into a thin cross-laminated interval terminating in a ripple marked upper bedding plane surface (18T/180, 18T/160), the individual laminae consisting of successive layers of sediment of slightly different grain size. In other beds the massive interval passes upwards into a thin interval of cross-lamination without an intervening parallel laminated zone (18T/146, 18T/147A) (P.2.12.). Both these associations produce a ripple marked upper bedding plane and vertical sections cut normal to the crestal axis display only a minor degree of stoss side erosion, ripple drift cross-lamination as described by Walker (1963) has not been observed to occur in any of the cross-laminated portions of the beds in this Sublithofacies.

Interpretation

The lithology and internal structure of the Sublithofacies 6a sediments indicates that upper flow regime conditions were in existence throughout much of the period of deposition of these beds. Whilst the presence in some beds of an upper zone of parallel lamination or an upper zone of parallel lamination succeeded by a zone of ripple cross-lamination, suggests a waning current transitional to lower flow regime conditions. The presence in this Sublithofacies of repetitive mud free units, each the product of a waning current which was initially characteristic of upper flow regime conditions require for their genesis an environment subject to repeated pulses of current energy. Kuenen and Migliorini (1950) proposed that submarine turbidity currents could produce a sequence of graded beds, similar in some respects to those occurring in this Sublithofacies, whilst Bouma's work (1962) on the Piera-Cava Flysch Deposits confirmed the findings of Kuenen and Migliorini. Bouma (1962) proposed that the ideal turbidity current would produce a sequence of internal sedimentary structures within a bed, which he placed in the following groups: (Now referred to as the Bouma Divisions) A.Graded division. B. Lower division of parallel lamination. C. Division of current ripple lamination. D. Upper division of parallel lamination. E. Pelitic division. These divisions have since been widely recognised and interpreted in the light of the hydrodynamics of their formation, notably by Walker (1965), Walton (1967) and Middleton (1967).

Some of the internal structures described by Bouma (1962) can be recognised in the Sublithofacies 6a sediments although a complete A.B.C.D.E. sequence was never observed in the beds studied.

The most frequently occurring Bouma Division within this Sublithofacies is the A.Graded division, commonly this division accounts for the whole of the individual bed, and is presumed to be the product of a single turbidity current which maintained upper flow regime conditions throughout the period of deposition in that locality. The clean nature of the sandstones as evidenced by the absence of mud or silt sized particles, together with the structureless nature of the beds tends to support the above proposal. The absence of grading within these beds requires explanation. Walker (1965) suggests that ungraded Bouma A.divisions have several modes of origin and that their genesis can be the product of both mature and immature turbidity currents. The initial deposits of very immature turbidity currents are, Walker proposes, unlikely to be graded, since by definition the current has not effected any significant grain segregation. Deposits of this genesis will be poorly sorted possessing a high percentage of fine sediment and as such are not represented in Sublithofacies 6a sediments.

Sandstone beds consisting solely of Bouma A.intervals may however, be formed by deposition from mature currents, in which neither autosuspension nor a traction carpet are developed. Walker (1965) suggests that some of the structureless ungraded sandstones commonly found in the Namurian of the Central Pennines including beds in the Mam Tor Sandstones (R_1c) present at Mam Tor (SK 127836) Derbyshire, and also beds in the Shale Grit at Alport Castles (SK 140916) Derbyshire, may be the deposits of turbidity currents of this type, whilst McBride (1962) proposes that this type of current may in some cases produce less well graded deposits. Both authors however indicate that a considerable amount of mud is present in this type of turbidite, and thus the absence of a mud fraction in the clean structureless A.division turbidites exposed at Gawsworth Common (Locs. 201/202/203), suggests an origin for these beds, other than the one discussed above. It seems likely however that the genesis of these sediments was due to deposition from a current having some degree of maturity as is evidenced by the absence of argillaceous sediment in these beds.

The development of a saltation layer (Gilbert, 1914) or traction carpet (Dzulynski and Saunders, 1962) at the base of a mature current could be involved in the genesis of the Sublithofacies 6a sediments. The grains within this layer or carpet will constitute the coarser fractions of the current, whilst the finer sediment is maintained in turbulent suspension. Walker (1965) suggests that with gradual current deceleration a traction carpet would produce a graded sand bed. Bagnold (1955) maintains however, that a sudden "freezing" of the traction carpet could occur due to a drop in the value of the applied shear stress. This freezing would produce a mud free A.division which may or may not be graded, depending on the dispersive forces operative within the traction layer. It is presumed that rapid deceleration of the turbidity current would produce the sharp drop in the applied stress within the traction layer. Deceleration of this type, it is thought, would occur due to a marked flattening of the palaeoslope or could occur when a physically confined current entered a less confined environment as for example at the mouth of a submarine canyon. It is thus possible that the genesis of Sublithofacies 6a sediments was due to the "freezing" of a traction layer. However, due to lack of exposure, evidence, other than that provided by the internal bed structure, to suggest that this was the formative mechanism is not apparent.

Non-graded "massive" turbidite deposits have been recorded by several authors including Kuenen and Menard (1952), Dzulynski et al. (1959), Walton (1963) and Walker (1967). Non-graded layers equivalent to Bouma A.divisions are described by Horn et al. (1971) from Miocene turbidites of the North East Pacific, and mechanical analysis of these sediments confirmed an absence of grading. These non-graded A.divisions were found to be limited to areas receiving a constant supply of sediment, which were suspected by Horn et al., to be the main routes followed by turbidity currents. Proximity to a "constant" supply of sediment was probably a feature of the area of deposition of Sublithofacies 6a sediments, as is evidenced by the coarse nature and thickness of the beds, and also by their repetition as non-graded A.divisions in the succession. Breaks in the supply of sediment which occurred with the passage of successive turbidity currents are indicated by the sharp bed boundaries which are a feature of this Sublithofacies. The majority of the lower bedding planes are planar, although load cast bases occur when beds in this Sublithofacies overlie argillaceous sediment and in rare instances when beds of sandstone are in juxtaposition, a similar development of load casting is described by Walker (1966), and is present in the Gawsworth succession in beds 18T/87, 18T/132 and 18T/176.

The instance of load casting between successive sandstone beds probably indicates a much shorter interval of time between successive turbidity currents than that represented by the sharp non-load cast bases. In the case of the sharp planar bases it is assumed that the shear resistance of the underlying strata was sufficiently developed to resist deformation when loaded by the deposits of the succeeding turbidity current. This lack of deformation of the underlying bed is thought to indicate that a period of time had elapsed, prior to the deposition of the overlying bed, during which the initial porosity was reduced by consolidation of the sediment, resulting in a consequent increase in shear strength. The second case, that of the load cast bases, is thought to represent deposition from successive turbidity currents separated by a much shorter time interval than in the case of the non-load cast bases. It is presumed that excess pore pressure developed in the upper part of the initial deposit, and before this pressure was dissipated the succeeding bed was deposited providing sufficient load to produce deformation of the water saturated upper level of the initially deposited bed.

Walker (1966a) noted the occurrence of load casting as described above in his Facies A turbidites from the Shale Grit and lower part of the Grindslow Shales occurring in the Namurian of North Derbyshire, he states, "There is a sharp break between the sandstones, shown up by a horizontal joint. The upper sandstones sometimes appears to have loaded into the lower one." Walker associates loading of this type with bed amalgamation into which he describes it as passing laterally.

It is suggested that such merging of beds indicates an almost continuous supply of sediment from successive turbidity currents, with a very short time interval between each flow.

Bed amalgamation although present in Sublithofacies 6a sediments occurs infrequently, but on the basis of previously described evidence it is probably correct to assume that the majority of the beds constituting the Sublithofacies 6a sediments in the Gawsworth area were the deposits of successive turbidity currents providing an almost continuous supply of sediment into the area. Although the majority of beds within this Sublithofacies can be referred solely to the A.graded interval of Bouma (1962), other beds consisting of A.B. intervals account for approximately 20% of the Sublithofacies sediments. The B.division occurring above the A.division accounts for circa 5% of the bed and rarely exceeds 0.05m total thickness. A.B.C. and A.C. sequences have also been observed though much less frequently than the first two types of sequence described and account for less than 5%, in total, of the beds occurring in this Sublithofacies.

The thin B.division of parallel lamination, which is often only faintly developed and difficult to detect in the field in this Sublithofacies, is thought to be produced during the rapid deceleration of the current. In this situation it is envisaged that traction did not develop, and that the lamination developed simply as a result of deposition from suspension that was rapid enough to prevent the formation of bed forms but not so rapid that segregation of grain sizes was prevented. Current pulsations or separated large scale eddies (Allen, 1964) are a possible mechanism to account for the successive pairs of laminae in this division. The infrequent development of a very thin C.division of ripple cross-lamination is present in this Sublithofacies, in two types of Bouma sequence. In the first instance the division occurs in an A.B.C. sequence and is thought to be the result of traction developed in the final stages of current decay when only a very small amount of sediment fall-out was occurring. In the second case the ripple laminae are present at the top of and merging with an A.division which displays normal distribution grading (Middleton, 1967). Beds of this type are thought to be initially the deposits of immature turbidity currents, and that the top of the sediment deposited by this current was later reworked possibly by the succeeding current into a narrow zone of ripple laminae. The limited vertical development of this C.division suggests that cohesive forces within the greater part of the sediment were sufficiently well developed to resist extensive reworking of the grains. The thinness of the zone also mitigates against the formation of the ripple laminae during the fall-out of sediment from suspension. Palaeocurrent evidence from these A.C. type beds indicates a constant current vector throughout the period of formation of the bed.

In all sequences observed in this Sublithofacies the A.division is always the dominant interval and is never absent from the succession whilst there is a marked absence of the D.division of parallel lamination and of the E.pelitic interval. Walker (1965) proposes that the most obvious cause for the formation of top absent sequences of the following types A.B.C.D., A.B.C., A.B., and A. is erosion, often detectable in outcrop, by the succeeding turbidity current. It is not envisaged that erosion was the main mechanism producing top absent sequences in Sublithofacies 6a sediments, although phenomena associated with erosive junctions are evident in rare cases and include the local removal or thinning of the underlying bed in association with the lenticular shape of the overlying unit. It is thought that if erosion was the dominant cause for top absent sequences in this Sublithofacies that bed thinning and lensing out of the individual units would be usual and not as is the case the exception in the exposures examined. Further discussion by Walker (1965) suggests that another cause for top absent sequences is non-deposition of the upper divisions. He suggests that deposition of the A.graded division could be due to the freezing of the traction carpet, and that if the top of the carpet was too cohesive to be reworked into laminations or ripples that the applied shear would be dissipated within the current. This would result in an increased turbulence and probably an increase in current velocity. Deposition would suddenly cease and a rejuvenated and more turbulent current would transport all the remaining sediment away. During this transportation the abandoned division could if cohesionless be reworked into parallel or ripple laminae, the modified bed would now be A.B., A.B.C., or A.C. Walker's observations on the development of top absent sequences are seen in the light of previous statements to be in general agreement with the author's proposals.

The beds present in Sublithofacies 6a display marked similarities to the Facies C Sandstones of Walker (1966a) which are present in the Shale Grit (Kinderscoutian) of Northern Derbyshire. Summarising Walker's account of the Facies C Sandstones it is seen that the following points of correspondence occur with the Sublithofacies 6a sediments.

1. Individual facies C Sandstone beds up to 10 feet thick and groups of beds reach 100 feet thick. Thin intercalated mudstones are of infrequent occurrence.
2. Horizontal laminations are occasionally developed in the upper one or two inches of a bed.
3. Current ripples occur on a few upper bedding planes.
4. The Bouma divisions observed are A., A.B., A.C., A.B.C., and A.E., A.B.E., A.C.E., A.B.C.E., of these, over 80% of the beds composed of A. or A.E. sequences, A.B., and A.C., sequences make up most of the remaining 20%.
5. Less than 20% of the beds examined displayed graded bedding.

Walker proposes that the origin of the Facies C Sandstones is due to deposition from successive turbidity currents separated by short time intervals and that the very thick sandstone beds together with the absence of silt and mud indicate source proximal deposition. He further suggests that the finer sediment was carried out to more distal areas of deposition, or that between successive currents there was little if any time for the fine sediment to settle out. His final alternative is that successive currents eroded the finer material leaving A. or A.B. intervals. The only significant difference between the Facies C Sandstones and the sediments occurring in Sublithofacies 6a is that of grain size. Walker describes the former as having a mean grain size of fine to very fine sand whilst the mean grain size of the Sublithofacies 6a sediments is appreciably coarser.

In the light of the correspondence of almost all the features except mean grain size between the Facies C Sandstones and the Sublithofacies 6a sediments it is probable that the environments of deposition were very similar. However, due to the coarser grain size it is suggested that the Sublithofacies 6a sediments were more source proximal than the Facies C Sandstones and may have been initially coarser grained or alternatively that higher energy levels obtained in the formative currents possibly due to the presence of a steeper palaeoslope in the Gawsworth Common area.

A massive bedded coarse sandstone facies, Facies 7, described by Collinson (1969) from the Grindslow Shales and Kinderscout Grit of the Namurian of North Derbyshire possesses points of similarity with Sublithofacies 6a. These Facies 7 beds are described by Collinson as being coarse grained structureless beds which may have concentrations of mudstone and siltstone clasts at "erosion sufaces", and in some instances incorporate large blocks of siltstone within the beds. Sublithofacies 6a beds in some cases carry ovate mudstone discs on the upper bedding plane surfaces. These clasts which possess rounded edges are thought to have been transported for some distance within the current and to have been deposited from suspension with a fall in current velocity. The source of the clasts is uncertain but is postulated as being in the area of initiation of the turbidity current. Collinson further states that Facies 7 beds are "broadly lenticular" and confined to channels. Here the correspondence with the Sublithofacies 6a sediments ends, since the latter may be described as possessing a constancy of bed thickness throughout the area of outcrop. Thus it would appear that a closer correspondence exists between Walker's Facies C Sandstones and Sublithofacies 6a sediments, than between the latter and Collinson's Facies 7 sediments.

Sediments similar to the Sublithofacies 6a sediments are described by Horn et al., (1971) from the Miocene of the North East Pacific and are interpreted as channel proximal turbidites. These Miocene sediments are described as consisting of non-graded (not visibly graded) and graded turbidites in close proximity in the succession, and in the case of non-graded beds it is suggested that the finer grained sediment may be absent due to erosion and truncation by later currents. Alternatively it is thought that "poor grading" or "inverse grading" may be due to fluctuating conditions during the introduction of a single pulse of sediment. Within Sublithofacies 6a sediments repetitive grading and inverse grading have been observed and may be attributed to similar fluctuating conditions within a single current. It is suggested that the observations of Horn et al. based on the evidence of cored samples taken within areas considered to lie under the axis or main body of the Miocene turbidity currents, both confirm the current proximal nature of Sublithofacies 6a sediments, and introduce a new facet, that of proximity to submarine channels. The channel systems described by Horn et al., (1971) traverse large sub-marine fans located on the continental rise in the North Pacific, and the sediments described from the source proximal parts of these channels appear to be similar to the Sublithofacies 6a sediments. There is however, insufficient field evidence to confirm that the Sublithofacies 6a sediments were formed in a submarine channel environment, although the possibility of this type of genesis cannot be rejected. It is envisaged that if submarine channels were present in the Gawsworth area, that they were broad based shallow channels in which little erosion occurred. A more source proximal area of deposition than the submarine channel environment of Horn et al., (1971) is the submarine canyon environment. Chipping (1972) describes thick coarse grained and poorly graded sandstones from the late Cretaceous and Palaeocene of Shelter Cove, a locality on the San Francisco Peninsula, which he proposes were formed by high density turbidity currents, grain flows or slurries in a submarine canyon environment. Chipping states that these coarse grained thick sandstones (plus 5 feet) are dominated by Bouma A.divisions, but also comments on the presence of large clasts of granite within the sandstones and large numbers of shale fragments, the latter being confined to zones near the base of the beds. Chipping likens the thick sandstones of the Shelter Cover area to those found in the steeper portions of submarine canyons and in the upper portions of channels incised into submarine fans as described by Hanner (1971). It is suggested that the beds described by Chipping have more in common with the Facies 7 sediments of Collinson (1969) than they have with the Sublithofacies 6a sediments, and on this basis and that of previously discussed evidence it is thought unlikely that the genesis of Sublithofacies 6a sediments occurred within a submarine canyon environment.

In conclusion an analysis of the total diagnostic evidence obtained from the Sublithofacies 6a sediments indicates that the sediments were deposited by north to north east flowing source proximal turbidity currents which maintained upper flow regime characteristics for much of their duration in the Gawsworth area.

The source proximal nature of the sediments is indicated by bed thickness, grain size, and the development of the large deeply incised tool marks and well developed scour marks (Allen, 1970c). The absence of lenticular beds and channel margin structures is thought to indicate that these turbidity currents did not possess the facility to deeply erode the previously deposited sediment.

The depositional environment is difficult to determine but it is suggested that the beds in this Sublithofacies were deposited on the proximal part of a submarine fan either as deposits infilling broad submarine fan channels or as successive deposits on the fan surface. It is envisaged that as the turbidity currents encountered the change of slope presented by the submarine fan their velocity was checked and they deposited coarse non-graded sediment rapidly enough to prevent erosion of the fan. The repetitive nature of the thickly bedded, mud free, coarse sandstone beds in this Sublithofacies suggest that the supply of sediment was at periods practically "constant", a feature which suggests proximity to a structure channelling sediment into the area of deposition. It is envisaged that such a structure would be the mouth of a submarine canyon. Although direct evidence for the presence of such a structure in the Gawsworth area is lacking, it is suggested that a canyon system to the south or south west could have supplied sediment to the area. The supply of sediment appears to have been practically continuous as is indicated by the absence of the marine index horizons, which are present within the interval E_2b_1 - R_1a in adjacent areas. It is presumed that the fine marine sediments were swept clear of the area by the successive turbidity currents or alternatively they were eroded shortly after their deposition. A canyon system located in the area proposed would have its input area in the vicinity of the Red Rock Fault Zone (Evans et al., 1968), and tectonic activity along this zone may have periodically initiated a supply of sediment into the canyon system. Such activity could be reflected in the Gawsworth succession where sequences of thickly bedded coarse sediment could be equated with tectonically active periods along the line of the modern Red Rock Fault Zone. Finer sediment intervals represent quiescent periods.

Similar variations in sediment supply could result from the eustatic changes in sea level associated with marine band genesis. Such changes would have the effect in this area of removing the supply of fluvial sediment to a more southerly or south westerly location and would be reflected in the Gawsworth succession by deposition of finer sediment. A north to north easterly prograding fluvial environment would therefore be equated with coarser sediment of Sublithofacies 6a aspect. Taking into consideration the mechanisms discussed above, it is proposed that the environment of deposition in the Gawsworth area is basically a submarine fan environment containing broad fan channels. The periods of tectonic activity or the eustatic lows would provide the right conditions for input of a "continuous" supply of sediment to the canyon system and it is suggested that even in these periods over-bank flow or channel distal flow would produce finer current distal sediment on the submarine fan surface. The presence of several units or groups of beds of Sublithofacies 6a aspect in the vertical sequence in the Gawsworth area suggests that the fan channels did not maintain the same path but migrated to different areas of the submarine fan, a similar migration is suggested by Chipping (1971) from the Shelter Cove deposits.

P.2.8.

A thickly bedded sandstone sequence of Sublithofacies 6a.

Loc. 203. Gawsworth.

P.2.9.

Load cast structures present on the base of Sublithofacies 6a sandstones.

Loc. 201. Gawsworth.

P.2.10a and b.

Magnification x ½.
Tool markings present on the base of Sublithofacies 6a sandstones.

Loc. 203. Gawsworth.

P.2.11a.

Ripple marked upper bedding surface of Sublithofacies 6a bed 18T/146.

Loc. 203. Gawsworth.

P.2.11b.

Detail of ripples on bed 18T/146.
(Note book measures 16 x 5 inches).

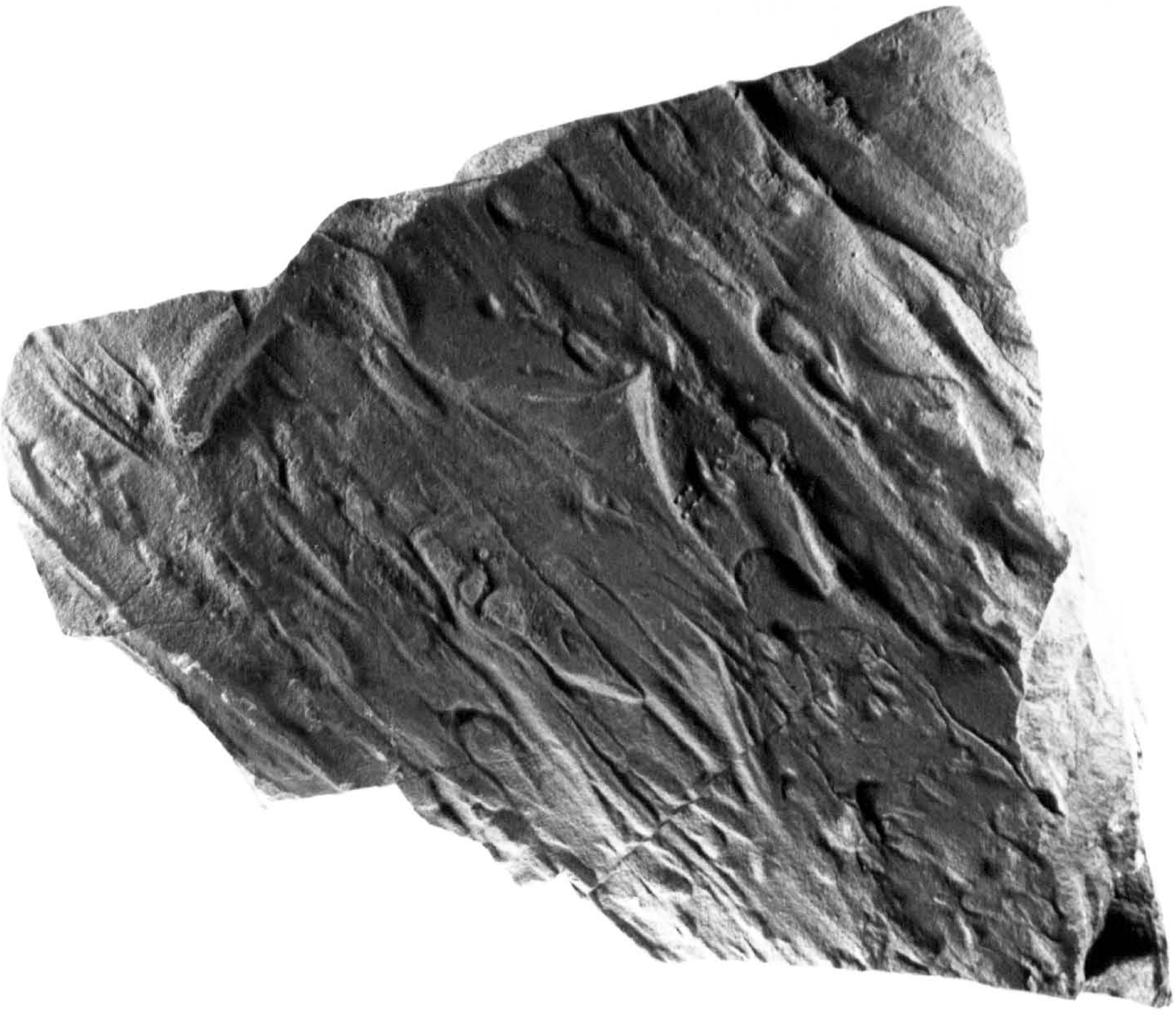
P.2.12.

Magnification x ½.
Internal structure of bed 18T/146.
Displaying a thin interval of cross-lamination above a massive interval. The upper bedding plane surface is ripple marked.

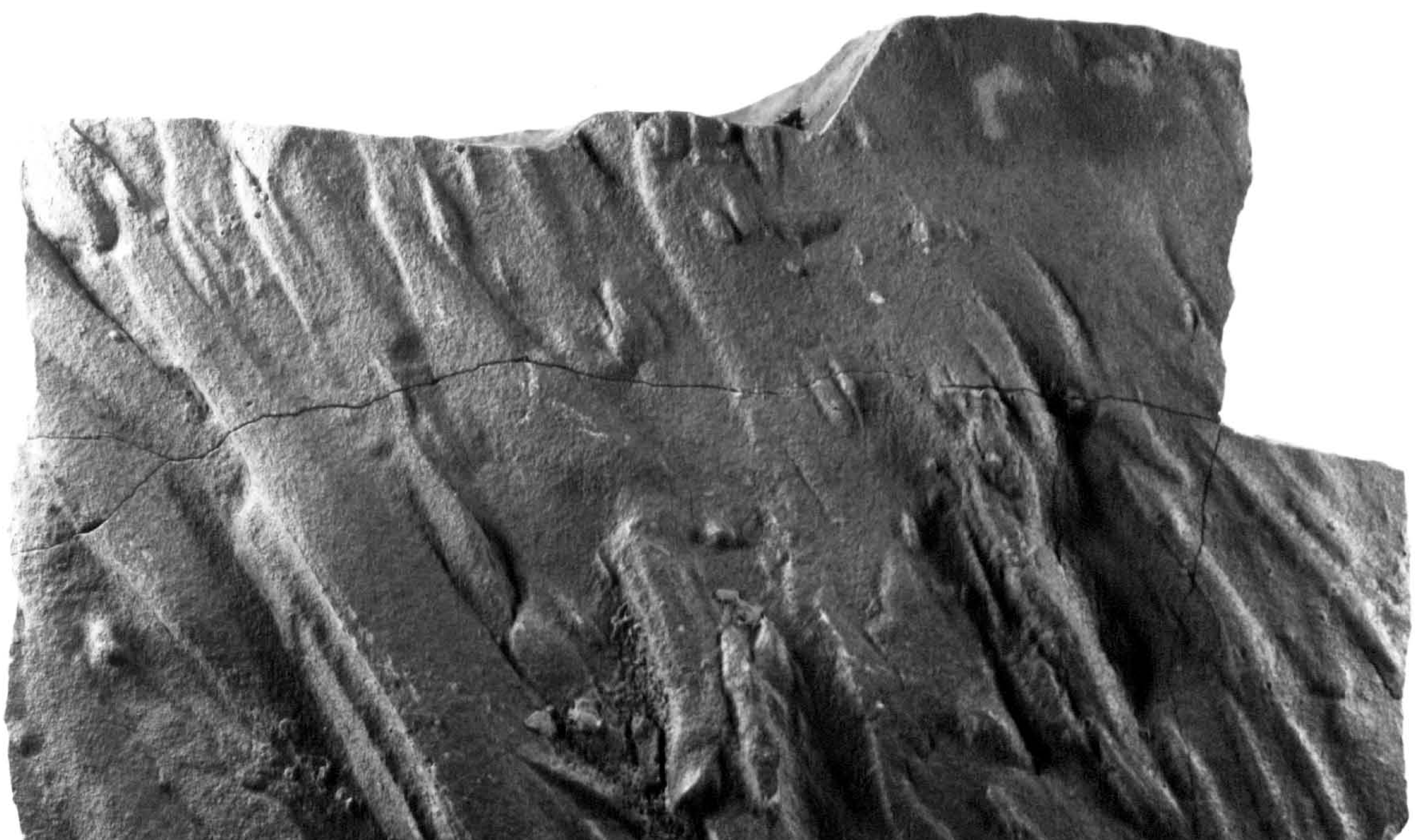
P. 2.8.

P. 2.9.

P. 2.10 a.



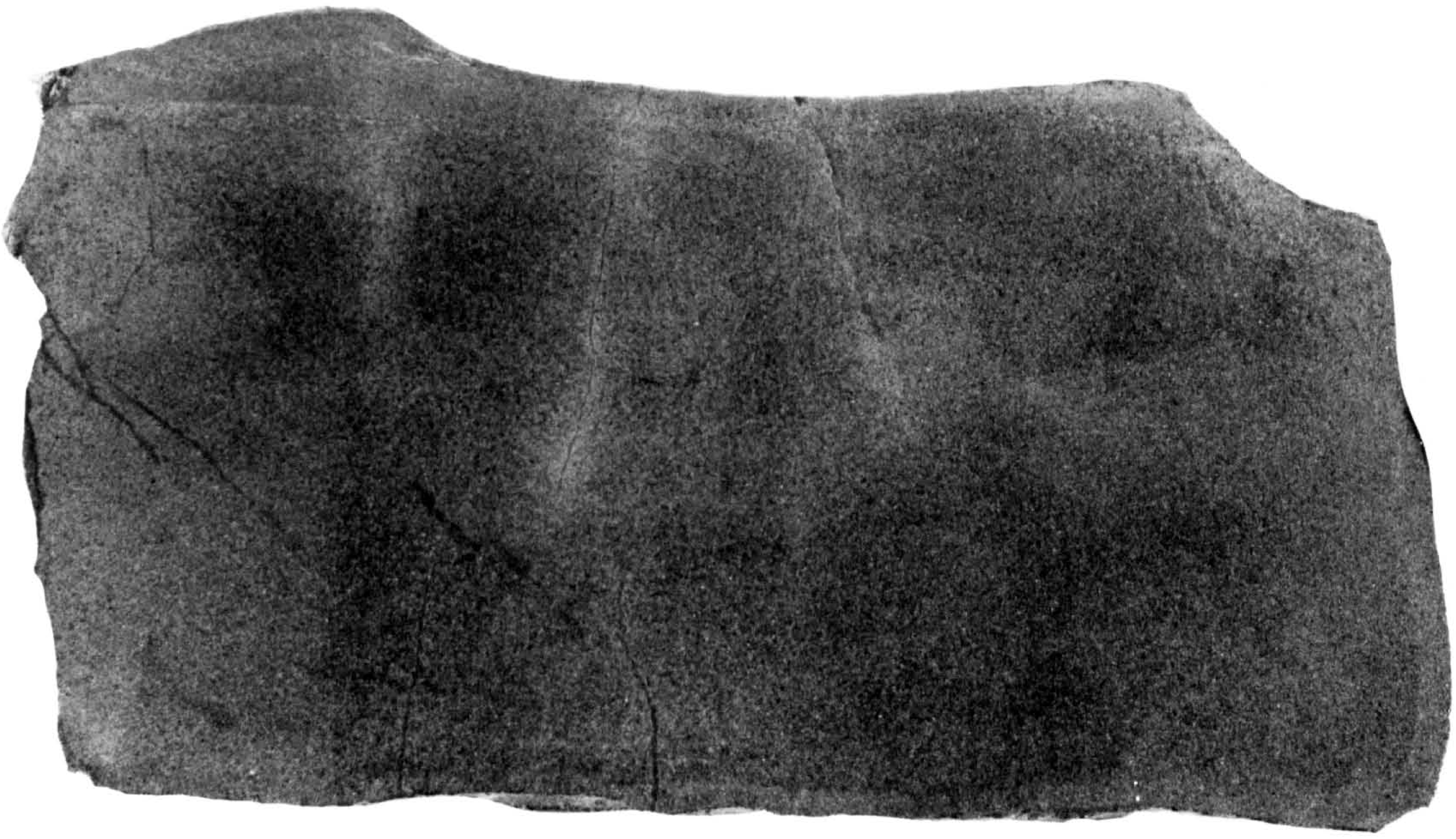
P. 2.10 b.



P. 2.11a.

P. 2.11b.

P. 2.12.



SUBLITHOFACIES 6b

Brief Diagnosis

Very thinly bedded, to thinly bedded to medium bedded, fine to medium grained to coarse sandstones, interbedded with very thinly bedded to thinly bedded mudstones are present in this Sublithofacies. The individual sandstone and mudstone beds alternate in the succession. The sandstone bases are sharp and frequently load cast, tool markings are numerous. The beds are laterally persistant with no evidence of thinning or erosion.

Distribution

Strata occurring in this Sublithofacies are present in the interval H_1a to H_1b (inclusive) in the following sections, 11T Wiggenstall Loc. 121 (Fig.2.F.), 15T Oakenclough Loc. 160, 5T Blake Brook Loc. 142 and in the E_2b_1 - H_2c (inclusive) interval at Locs. 201, 202 and 203 in the Gawsworth (18T) area.

In Sections 11T and 15T the Sublithofacies 6b sediments comprise the whole of the succession at Locs. 121 and 160, whilst in the Blake Brook succession beds characteristic of this Sublithofacies occur extremely rarely in the succession which in the main is represented by Sublithofacies 6c sediments. In Section 18T Sublithofacies 6b sediments are present in association with Sublithofacies 6a sediments, and form a minor part of the succession. Sublithofacies 6b sediments are also present within the interval E_2b_1 - E_2c_2 in the Hurdlow Section, Loc. 069, and in the Thorncliffe Section, Loc. 109.

Field Characteristics

Very thinly bedded to thinly bedded, to medium bedded fine to medium grained sandstones, are present interbedded with very thinly bedded to thinly bedded mudstones. An analysis of the beds in the various exposures is as follows:-

FIG. 2.Fa. Succession at Loc.121 Wiggenstall within the interval H1a-H1b (inclusive)

FIG.2.F6. Succession at Loc.160 Oakenclough within the interval H1a-H1b(inclusive)

Section	Thinly-medium bedded sandstones	Very thinly bedded sandstones	Mudstones
	Average thickness.m	Average thickness.m	Average thickness.m
Wiggenstall 11T	0.09	0.02	0.02
Oakenclough 15T	0.10	0.03	0.06
Gawsworth 18T	0.06	None	
Blake 5T	Circa 0.05	None	Circa 0.05

The very thinly bedded sandstones in Sublithofacies 6b commonly occur in groups in the succession in the 15T and 11T exposures. In the Gawsworth succession (18T) very thinly bedded sandstones occur very rarely, the majority of the beds contained in this Sublithofacies being of the thinly bedded - medium bedded thickness range.

The sandstone beds in Sublithofacies 6b are always separated by beds of mudstone. The percentage of mudstone is variable in the various exposures but is generally less than the percentage of sandstone. Sharp bases are characteristic of the sandstone beds, which are frequently load cast and exhibit well defined tool marks. In all the exposures studied the beds were observed to maintain a constant thickness, large scour marks and channels are absent from the succession.

External Characteristics

Weathered exposures in this Sublithofacies frequently exhibit selectively weathered parallel laminae in the upper portions of the sandstone beds, but are otherwise featureless throughout their thickness. Primary sedimentary structures commonly occur on the sandstone bases, whilst the upper bedding plane surfaces are usually planar and featureless, although ripple marked upper bedding plane surfaces have been infrequently observed (18T/185), exhibiting sinuous ripples displaying stoss side erosion and possessing a ripple length of less than 10 cms.

The bases of the thinly-medium bedded sandstones are commonly load cast, whilst the bases of the very thinly bedded sandstone beds are more commonly planar.

Biogenic sole marks are commonly restricted to the bases of the thinner beds and take the form of irregular nodular structures referable to the Granularia type (Seilacher, 1962; Holdsworth, 1963).

Tool marks are often present in great numbers on the soles of Sublithofacies 6b sandstones and include prod marks, which are the most numerous, groove marks, brush marks and bounce or skip marks. The prod and groove marks on the bases of the thicker sandstones are larger and possess a sharper relief than those on the thinner sandstones. The sector occupied by the current directional structures on the thinner sandstone bases often exceeds 40° whilst the same structures on the thicker beds occur in a sector of less than 40°. Bimodal current directional structures are present on the base of one sandstone bed (18T/185) but have not been observed elsewhere and are thought to be rare in this Sublithofacies.

The casts of flute marks are present on some of the thicker sandstone beds and give a current directional sense which is in accordance with that displayed by the tool markings.

Internal structures

Exposures within this Sublithofacies were extensively sampled in the Wiggenstall and Oakenclough sections, samples were also taken from the Blake and Gawsworth successions. Graded bedding commonly occurs within the sandstones in this Sublithofacies, size - grading being evident in polished section and in thin section, where in addition, the predominently angular character of the grains is visible. The size graded interval, present in most sandstone beds, is present at the base of the beds and in the thicker sandstones it accounts for more than 50% of the bed, but may be absent or less well developed in the thinner beds.

Multiple or recurrent grading (Ksiazkiewicz, 1954) is present infrequently in the thicker coarser beds (11T/17) and inverted symmetrical grading (Ksiazkiewicz 1954) has also been observed. (11T/3 (i) and (ii)). Irregular mudstone clasts are sometimes incorporated in the graded layer (11T/1, 18T/180). These exotic fragments vary from less than 0.005m to plus 0.01m in thickness and frequently are aligned so that their longest axis is sub-parallel to the base of the bed. Sub-rounded clasts of fine grained, parallel laminated sandstone are incorporated in the initial graded interval in bed 11T/9. The laminae are distinguished by thin dark mud layers separating clean sand layers and are parallel to the long axis of the clasts, the attitude of the largest clast 5 cm x 1 cm being parallel to the base of the bed. The remaining smaller clasts display a random orientation.

Several of the thicker sandstone beds contain injection structures (11T/3(2), 11T/8) which consist of coarse sediment injected into fine sediment. These structures are present as internal irregularities wedging upwards with a flame structure type morphology (Kelling and Walton 1957), which may disturb structures in the interval above and produce distorted bedding. One pipe-like injection structure of coarse sediment is seen to pass through finer sediment and reach the upper bedding plane surface where it takes the form of a shallow depression 2.0cms in diameter enclosed by an annular rim of 0.5 cm base and 0.25 cm height, structures of this type are described by W. D. Gill and P. H. Kuenen (1957) and are termed by them, sand volcanoes. These injection structures appear to be post depositional since they cut across primary bed structures in the interval above and in one instance form an excrescence on an upper bedding plane surface which must have been in existence prior to the injection of the coarse material. An interval of coarse parallel lamination is present in the majority of the sandstone beds occurring in this Sublithofacies; within the thicker beds this interval is present above the graded interval, but frequently within the thinner beds an interval of parallel lamination occurs at the base of the bed and the graded interval is absent.

The individual laminae are of two types and are readily observed by their contrasting dark and light shades. The dark laminae are thin, usually less than 1mm thick and in thin section are seen to consist of opaque fine sediment possibly mud or carbon with rare mica flakes embedded in the finer material. The second type of laminae are composed of sheets of grains which may show size grading within the individual laminae and may also be overlain by a succession of laminae in which the grain size becomes progressively finer upwards, as in the gradational laminated bedding of Ksiazkiewicz (1954). The two types of laminae commonly occur in conjunction in Sublithofacies 6b sandstones. Associated with this interval of parallel lamination are horizons of coarse organic debris present in two samples 15T/17 and 15T/15. Cross-sections of the plant material are hollow and infilled with sand and are frequently broken and deformed, presumably during consolidation of the sediment within and around them.

An interval of cross-lamination commonly occurs in the sandstone beds, above the interval of parallel lamination (11T/9, 11T/20, 15T/3, 15T/1, 18T/185, 18T/180, 5Ta N/31) and may account for 30% of the bed thickness. The ripple laminae are usually inclined at less than 40^{0} to the underlying parallel laminae and in the thinner beds are often only gently inclined to the parallel laminae. Stoss-side erosion of the ripples occurs in some instances and the beginnings of ripple drift cross-lamination (Jopling and Walker, 1968) have been observed in isolated examples. An interval of cross-lamination occurs in bed 15T/15 and is subdivided by a horizontal erosion surface, above and below this surface the lee side of the ripple laminae are inclined in opposite directions. Above the interval of cross lamination some beds contain an interval of fine parallel lamination which contains a high percentage of mud and thin laminae of very fine sand. The mudstones in this Sublithofacies are mainly structureless although infrequent examples of mudstone with siltstone or very fine parallel sandstone laminae are present (11T/3a, 11T/12, 15T/10, 15T/16).

Interpretation

The sediments within Sublithofacies 6b display many of the internal structures recognised by Bouma (1962) and are considered to be the results of turbidity current deposition.

The multiple or recurrent grading (Ksiazkiewicz, 1954) observed in the A. graded division of some of the thicker sandstone beds is thought to represent repetitive pulses of current energy within the same turbidity current, whilst the inverted symmetrical grading (Ksiazkiewicz, 1954) is interpreted as a product of an accelerating current. The majority of the A.divisions show normal size grading which is interpreted by Walker (1965) as the product of mature current deposition.

With the exceptions of rare flute casts the absence of primary bedding plane structures of the erosive type is a feature of the beds in this Sublithofacies. However, internal evidence of erosion by successive turbidity currents is present on a limited scale. The majority of this evidence occurs in the A.division of the beds (11T/1, 18T/180) and consists of irregular mudstone clasts roughly aligned with the bedding and incorporated in the graded division. These exotic clasts are thought to have been torn up from the pre-existing semi-consolidated E.

division and almost simultaneously incorporated in the accumulating A.division of the successive sandstone bed. In addition thinner rounded clasts are present above the C.division (18T/180) and are thought to have the same origin as the irregular clasts but to have been transported further and suffered corrosion within the turbidity current. In bed 11T/9, which overlies the pre-existing sandstone 11T/8 without a pelitic interval, several subrounded clasts of fine grained parallel laminated sandstone are present within the A.division, they are interpreted as a pre-existing thin sandstone bed which was excavated by the turbidity current which eventually deposited bed 11T/9. The thin parallel-laminated sandstone clasts are interpreted as a semi-consolidated pre-existing thin bed referable to the B.division which has been subject to erosion, transportation and corrosion within the turbidity current which deposited bed 11T/9, higher divisions and the E pelitic interval are presumed to have been removed to a more distal location by the same current. An indication of the rapid deposition of the coarse sediment is given by the presence of post depositional injection structures. Beds containing these structures are assumed to have had an initial high void ratio which is indicative of a very loose state of packing of the grains (Capper and Cassie, 1963). It is suggested that less rapid fall-out would allow time for closer grain packing via traction and possibly reworking producing a bed less susceptible to the development of excess pore pressure.

Variations in the orientation of current ripple lamination have been observed in the two C.divisions of bed 15T/15. This type of structure is thought to be the product of two non-aligned frontal lobes of the current (Anderson, 1964) depositing successively in the same locality, the second current lobe having similar hydrodynamic characteristic to the first, so that two C. divisions are formed. The association within this Sublithofacies of thinly bedded and medium bedded sandstone beds is presumed to indicate variations in the axial positions of successive currents due to the constantly changing morphology of area of deposition (Bouma, 1962). It is suggested that the areas of depositionwere relatively flat and that as successive currents arrived their paths were slightly diverted by the swell left on the basin floor by the deposits of the previous currents. In this way a succession of current proximal and current distal beds could be deposited in any one locality.

Bouma (1962) suggests a similar mechanism for the filling up of a basin, and points out that the deposition cone formed by a turbidity current will have an upper convex surface which will tend to deflect a succeeding current having the same starting point, and thus produce a succession similar to that described from Sublithofacies 6b. An alternative mechanism which may be capable of producing the same type of succession is that of differential subsidence of the basin floor. In a restricted area of deposition such as is indicated by the geographical extent of Sublithofacies 6b sediments,it seems unlikely that differential subsidence was the factor controlling the vectorial changes in the successive currents and the concept of deflection by the development of a cone of deposition as suggested by Bouma (1962) appears to provide a more satisfactory explanation.

Summary

The sediments within this Sublithofacies are thought to be the deposits of mature turbidity currents which, with minor exceptions, had lost the power to erode the surface over which they were passing. They occupy a median position in the basin between the proximal turbidites of Sublithofacies 6a and 6c and the distal turbidites of Sublithofacies 6d. Their pelitic content accounting for just less than half the thickness of the succession also indicates a position intermediate between source proximal and source distal environments (Walker, 1967 and Vassoevic, 1957).

Comparison with the low pelitic content of the source proximal turbidites of Sublithofacies 6a and the high pelitic content of the source distal turbidites of Sublithofacies 6d provides further support for this statement. The juxtaposition of thin and thicker beds in the succession appears to indicate deposition on a relatively flat floor where successive deposition cones produced current proximal and current distal deposits seen in the vertical succession at any one locality. Field evidence indicates that the exposures in this Sublithofacies at Wiggenstall (11T), Blake Brook (5T) and Oakenclough (15T) form part of the feature known as Lum Edge (SK 06206040) and Lady Edge (SK 05506215). It is suggested that the sandstones forming this area of high ground, which extends for some 15 km along the strike and is lenticular in shape, are the deposits of numerous small scale turbidity currents., generated at several source localities. The palaeocurrent evidence indicates a source area lying in a sector between due west and due south. On the basis of evidence discussed elsewhere in this thesis (see Lithofacies Associations) it is presumed that the source of Sublithofacies 6b sediments was the advancing front of a prograding deltaic area. The sediments deposited by the advancing deltaic area provided a source of supply for the turbidity currents which produced the maximum development of Sublithofacies 6b sediments in the Blake region. The termial points of this ridge of high ground are in the Oakenclough and Wiggenstall areas and at these locations the successions which were further from the proposed delta front exhibit a more distal character than that displayed by the Blake succession.

SUBLITHOFACIES 6c

Brief Diagnosis

Thickly bedded, coarse grained to conglomeratic, massive sandstones, interbedded with thinly to medium bedded, coarse to medium to fine grained sandstones, interbedded with siltstones and mudstones of bed thickness varying from very thinly bedded to very thickly bedded. The thickly bedded sandstones often display a lenticular form and frequently truncate thinner beds in the succession. The thinly to medium bedded sandstones may be laterally persistent but they commonly exhibit a restricted lateral development. The mudstones and siltstones in the succession frequently have a variable lateral thickness and are seen to thin below the thicker sandstone beds.

Distribution

Beds in this Sublithofacies are present at locality 142 in the Blake Brook within the interval H_1a - H_1b (inclusive). They form the thickest exposed development of sediment present along the ridge of high ground known as Lum Edge (SK 06206040) and Lady Edge (SK 05506215). A detailed succession is given in Appendix Fig. IIA.

Field Characteristics

The thickly bedded sandstones appear in the field to be massive structureless beds and when traced laterally are often seen to be formed by the amalgamation of two or sometimes three thin beds. The form of these thick sandstones is often lenticular, the bottom surface being downwardly convex and the upper surface is usually flat although in some instances it is slightly convex upwards. The base of the thickly bedded sandstones may be sharp and planar, or sharp and load cast and frequently contains well developed primary sedimentary structures of the tool mark type, displaying a preferred orientation. The upper bedding planes of the

P.2.13.

Sublithofacies 6c sandstones
forming part of Section $5TaN_{11}$
exposed in the Blake Brook
at Loc. 142.
(Note. See Appendix Fig.II.A.
at the back of the Thesis).

P. 2.13.

thickly bedded sandstones may show amalgamation with the succeeding sandstone bed or may be sharp and contain exotic organic and inorganic material.

The thinly to medium bedded sandstone beds may be parallel sided throughout their outcrop or show rapid termination to zero. The base of the thinly to medium bedded sandstones is frequently sharp and planar, or sharp and load cast.
The upper bedding plane surface is usually sharp and planar or may show amalgamation with the succeeding sandstone.
Primary sedimentary structures of the tool mark type frequently occur on the base of these beds and are especially evident when the bed overlies a thick pelitic interval.

Thickly bedded sandstones or thinly to medium bedded sandstones commonly occur in the succession in separate groups. Pelitic sediment is often absent from these groups or may be present interbedded with the sandstones in the succession.
The finer grained sediments within this Sublithofacies are siltstones, silty mudstones and mudstones. They often form very thick beds and may contain silt or fine sand laminae or thin lenticular bodies of fine sand. These sand and silt laminae may show an abrupt lateral termination when they are intersected by the downwardly convex bases of the thickly bedded sandstones.

External Features

One of the most apparent features in the field is the thinning of the massive sandstone bodies. Such beds often display a downward convex base, and in some cases are observed to thin along the strike from their maximum thickness to zero in only a few metres. For example, bed 5Ta Nii/21 which is constituted by an amalgamation of three sandstones, has a maximum thickness of 0.70m and thins to zero in 5m along the strike to the south (P.2.13.). To the north this bed is less well exposed but is thought to thin out over a similar distance. A further example of this lateral variation in thickness is provided by beds 5Ta Nii/10, 11 and 12 which comprise a unit 0.57m maximum thickness, which thins southwards to 0.05m in 10m and northwards to 0.47m in 10m.

Similar variations in thickness occur throughout the succession and as the beds outcrop on either side of the Blake Brook it is practically impossible to equate the successions on opposite sides of the stream, which is between 5m and 10m wide, unless as can be done in some cases, the individual bed can be traced across the stream bed. This difficulty in achieving a correlation along the strike is therefore attributed to the lenticular nature of the sandstone bodies together with limited exposure. For example, beds 5Tbs/12 and 13 form a lenticular massive sandstone body 0.93m thick which on the north side of the stream, on strike, is represented in the succession by bed 5Ta Nii/28 which consist of 1.94m of silty mudstone. A further difficulty in equating the beds on either bank of the stream was only revealed late in the field examination of the sediments, when stream erosion uncovered dip slope slump structures and associated post slumping erosional features. A west to east variation in thickness was also noted in some beds, although exposures in the dip direction are limited.

The base of the thickly bedded sandstone bodies is always sharp and may be planar or load cast, load cast structures are normally developed when the sandstone bed overlies a mudstone or siltstone bed of appreciable thickness although smaller scale load casting may be present between adjacent sandstone bodies, even though a pelitic interval is absent.

Primary bedding plane structures of the tool mark type are present and are most commonly represented by well defined groove marks and large prod marks which mainly indicate a south westerly derivation for the sediment.

Scour marks are rarely observed, and in particular flute marks have a very limited occurrence within this Sublithofacies.

The outcrops of the thinly to medium bedded sandstone beds, like the thickly bedded sandstone beds, are difficult to equate on the north and south banks of the Blake Brook. In places where it is possible to achieve a correlation these beds are seen to be laterally persistent with little variation in thickness, and in other cases they display a rapid thinning to zero. In other parts of the succession they equate along the strike with thickly bedded massive sandstones and in only one case, at the base of bed 5Ta Nii/21, is the junction between the two observed, and is seen to be discordant, the convex base of a massive sandstone truncating the thinner sandstones and interbedded mudstones. This type of junction although not commonly observed is considered to be operative through the whole of the succession, with the exception of the slump structure previously mentioned.

The bases of the thinly to medium bedded sandstones possess primary bedding plane structures of the tool mark type which commonly consist of prod and groove marks giving a south westerly source for these sediments, similar to that provided by the tool markings on the thickly bedded sandstone bases.

Load cast structures commonly occur on the bases of the thinly to medium bedded sandstones, typically when they overlie a pelitic interval, bases of these sandstones may also be planar. Bed 5Ta Nii/34 exhibits an irregular base which was at first sight taken to be a load cast structure, closer inspection revealed that the base of this bed is armoured with large pebbles which are embedded in the underlying sandstone. This sandstone displaying marked fluctuations in thickness was thought to have accumulated on a scoured surface eroded by the current depositing bed 5Ta Nii/34. It also appears probable that pebbles similar to those occurring in the base of bed 5Ta Nii/34 were the agents producing many of the tool marks displayed by the sandstones in this Sublithofacies.

The upper bedding plane surfaces of the thinly to medium bedded sandstones are usually planar and sharp, in rare cases as in beds 5TN/1 and 5TN/16 the beds display a small scale stepped relief, the steps are mutually parallel and have an east-west orientation.

The finer sediments in this Sublithofacies are very variable in thickness due to erosion by the coarser sediments and are most remarkable for their content of thin sandstone laminae or small lenticular sandstone bodies, some of which have discordant contacts with the thicker sandstone beds.

Internal Structures

The thickly bedded sandstones are predominantly coarse grits to conglomerates, composed of angular to sub-rounded grains. They may be non-graded or exhibit normal size grading of the particles. Exotic clasts of mudstone are commonly present in these beds and may be distributed throughout the bed or they may be confined to an upper zone within the sandstone. Organic debris is also present within the thickly bedded sandstones, being associated with the mudstone clasts and displaying a similar distribution as the exotic pelitic material, occurring both throughout the bed or being confined to an upper zone. Thick beds containing mudstone clasts and plant debris throughout, are frequently not graded, the mudstone clasts they contain are irregular in shape and like the organic debris they occupy random positions within the bed.

The size graded thick beds incorporate exotic material which is confined to an upper zone within the bed, this zone may constitute as much as half the bed thickness although in some cases it forms the top 2 or 3 cms only. Within this upper zone the mudstone clasts occur as rounded discs which are arranged in a layer or layers and lie parallel to the bedding. Organic material, often recognisable as plant stems cf. Calamites sp., may occur intermingled with the mudstone clasts in the size graded beds or may be present in these beds as discrete organic layers within the upper zone, the flattened plant stems lying parallel to the bedding and in bed 5Ta/b. The long axes of the plant stems display a median orientation of 030^{o}.

The thinly to medium bedded sandstones which are usually size graded, also contain exotic material in the form of mudstone clasts and plant debris which in this case is usually present in the upper 2 to 3cms of the bed. The mudstone clasts are of the rounded disc variety and are arranged in a layer or layers parallel to the bedding, in some instances the discs are armoured with sand grains and small pebbles. The organic debris is frequently present as a plant rich layer which may be several cms thick or can occur as a parting plane on which the flattened stems of Calamites sp., are present in large numbers.

The presence of parallel lamination is a feature of the thinly bedded to medium bedded sandstones but is very rarely present in the thickly bedded sandstones. The lamination occurs in the upper part of the bed and may account for up to half the bed thickness, although in some cases it is considerably less, being present in only the upper few cms.

The laminae consist of contrasting thin dark layers and lighter layers. In thin sections the dark layers are very fine grained and opaque, they are considered to be composed of mud and carbon particles, the latter becoming translucent red to orange in thin section, when observed on thinly ground edges. When the beds are split along these dark laminae the exposed surface may be black and powdery and is reminiscent of the maceral fusinite.

The light coloured laminae consist of sheets of sand particles which may show size grading, i.e. the gradational laminated bedding of Ksiazkiewicz (1954).

P.2.14.

Proposed correlation of the Sublithofacies 6c channel - fill sandstones present in the Blake Brook at Loc. 142.

P. 2.14.

In beds 5TN/1 and 5TN/16 the parallel laminae are disturbed by small scale normal faults which have a parallel orientation and a common downthrow side. The amount of throw is usually less than 1 cm and the faults continue to the upper bedding plane surface, which as a consequence exhibits a stepped relief.

Laminae of fine sand are present in some of the mudstones and siltstones and fine lamination has been observed in some of the mudstone clasts which are incorporated in the sandstone beds.

Cross-lamination was observed in only three beds 5Ta Nii/25, 5Ta Nii/31 and 5TN/16, all of these beds are thinly bedded sandstones of fine to medium grain size. The interval of cross-lamination occurs at the top of the bed above the interval of parallel lamination and occupies a narrow zone less than 1 cm thick.

Interpretation

The strata present in this Sublithofacies occur as a complex association of interdigitating beds in which the lateral variations in thickness and the lenticular nature of many of the sandstone bodies together with the internal structures present are important to the interpretation of the genesis of the sediments (P.2.14).

The thickly bedded, coarse grained to conglomeratic sandstones which frequently display a lenticular shape are considered to be deposits occupying small shallow channels which have an average thickness of 1m and are 10-20m wide, the longitudinal extent of the channels cannot be observed since all exposures occur along the strike.

The sediments filling the channels may be the product of single or multiple events, in the latter case the sandstones frequently show amalgamation (Walker, 1964) within the channel structure.

In some cases the contact between the downwardly convex channel bases and the marginal sediments can be observed. The contacts which are discordant indicate erosion of the thinly bedded to medium bedded sandstones or of the pelites, which possess fine sandstone laminae, into which the channels were incised. Beds terminate abruptly at the channel contacts or thin below the maximum development of the thickly bedded sandstones.

Several intervals of the Bouma sequence have been recognised in Sublithofacies 6c sediments. However, the majority of the thickly bedded sandstones are represented by only the A interval in which normal size grading, characteristic of the Bouma A. graded division, is present, non-graded beds also occur. Concentrations of plant debris into distinct layers which are often associated with horizons of rounded mudstone discs occurs in the upper levels of the graded thickly bedded sandstones, they approximate to very coarse laminae and their presence in the upper part of the A. graded division is interpreted in the light of falling current velocity.

The mudstone clasts which are sometimes armoured with sand grains and small pebbles are considered to be sediment, initially in the plastic state, which was derived from the floors and sides of the channels and is thought to have been ripped up by the currents transporting coarse sand pebbles. Similar clasts are named "rip-up" breccias by Dott (1963), who describes them as being laminated siltstones or mudstones which have been torn up by scour or gravity movements very soon after deposition. The rounded edges of the mudstone discs in the Sublithofacies 6c sediments are thought to be due to corrosion of the clasts within the transporting medium and implies that the clasts were transported for some distance.
Natland and Kuenen (1951) suggest that because of the similarity of specific gravity of saturated mud fragments with that of the viscous transporting medium, mud

clasts could be carried and would only settle with falling specific gravity of the medium. The distribution of plant debris within the graded thickly bedded sandstones is similar to the distribution of the mudstone clasts and it must be assumed that the hydrostatic characteristics of the water logged plant material were similar to those of the mudstone clasts incorporated in the same transporting fluid.

Plant material of the type incorporated in the sediments of this Sublithofacies is thought to have been derived from an adjacent paralic or delta plain source. The character of the thickly bedded sandstones so far described from this Sublithofacies is similar to that of sediments deposited by source proximal turbidity currents (Walker, 1967). Chipping (1972) describes an association of beds from a submarine fan environment which are similar in many respects to the sediments occurring in Sublithofacies 6c. He interpretes thick lenticular sandstones, similar in lithology and magnitude to the thickly bedded lenticular sandstones occurring in Sublithofacies 6c, as being the fill of small channels. These channel sediments are described as being the products of high density turbidity currents (Middleton, 1967) which were capable of eroding channels and incorporating the eroded material within the sediment which was deposited in the channel.

A second type of thickly bedded sandstone is present in Sublithofacies 6c. These beds are non-graded, thickly bedded, lenticular, coarse sandstones which typically contain, throughout the bed, randomly distributed irregularly shaped mudstone clasts and plant debris. Such beds are interpreted as the products of grain flows (Stauffer, 1967) which filled up pre-existing small channels cut but not filled by the turbidity currents which deposited the associated proximal turbidites. The presence of the mudstones clasts within these beds suggests that the grain flows had the power to erode the channel floors and margins and to incorporate this exotic material within the flow; although the ability to differentiate the clasts into an upper zone within the bed is not apparent.

The irregular non-rounded form of the clasts indicates that attrition within the grain flow was very limited and that transportation of the eroded material was minimal. This type of deposit which is intermediate in character between a slumped bed and a turbidite has been described by Dzulinski et al. (1959) as a fluxoturbidite. Grain flows of a similar type have been recorded from the upper portions of submarine fans (Dill, 1964), whilst thick poorly graded sands and pebbly sands of a similar aspect to Sublithofacies 6c sediments are mentioned by Haner (1971) as being commonly incised into the upper portions of submarine fans. The absence of diapiric structures within the fluxoturbidites of Sublithofacies 6c suggests however that the flow had closer affinites with a true turbidity current than with a flow of sediment in the quicksand state.

The proximal character of the thickly bedded coarse grained turbidites, in which the A. division predominates, together with the presence of fluxoturbidites suggests that the source area was adjacent to the area of deposition and on palaeocurrent evidence is placed in a westerly to south westerly locality.

The presence of several small channels of differing axial location, is thought to indicate that sediment was being supplied from numerous points, possibly from a delta front, each source initiating localised turbidity currents.

These currents, which on the basis of field evidence do not appear to have formed large channel structures such as those encountered in the Shale Grit by Walker (1966), were probably limited in their development by a low value of slope. Dill (1964), suggests that a slope of plus 10^{o} is required for the movement of particles by the mechanism of grain flow. However, Dekoning (1971) has observed sand flow on slopes of 3^{o} - 6^{o}.

Within the Sublithofacies 6c sedimentary environment it is proposed that grain flows occurred due to instability at several points along the source area, possibly a delta front, which had prograded to a previously land remote edge of the shelf. Each flow developed into a localised turbidity current on a slope of such low angular value that all the sediments possess a proximal character, and that the velocities required by the currents for the erosion of large channels were not attained. In this case the value of slope in the Blake Brook area is probably closer to the figures quoted by Dekoning (1971) than to that indicated by Dill (1964).

Thinly bedded to medium bedded coarse to fine grained sandstones are present in Sublithofacies 6c and have a close spatial association with the thickly bedded sandstones. They are present both as laterally persistent beds occurring in the succession between the thickly bedded sandstones, or they may occur as beds of variable thickness which are laterally equivalent to the thickly bedded sandstones. Both types may be truncated by the thickly bedded lenticular sandstones. These medium to thinly bedded beds are considered to be the deposits of turbidity currents of the type described by Bouma (1962), Walker (1970) and many other authors.

Truncated Bouma sequences are characteristic of these beds, the sequence A.B occurring the most frequently. A., A.E., and A.B.E. sequences have a less common occurrence, whilst the sequence A.B.C. was observed very rarely and was then only present in beds of medium to fine grained thinly bedded sandstone. The evidence of the Bouma divisions present in these medium to thinly bedded turbidites denotes a proximal character for these beds (Walker, 1967).

Two origins are proposed for these medium to thinly bedded proximal turbidites, those beds which possess a variable thickness are seen in some instances to be the lateral equivalent of the thickly bedded lenticular sandstones which occupy the previously mentioned channels, and it is proposed that these thinner beds on the channel margins represent over-spill deposits. The internal structure of these over-spill deposits is less current proximal than that of the thicker sediments within the channels, but this is to be expected if it is considered that the maximum current velocity occurred along the channel axes. The association of thin and thick sandstone beds described by Chipping (1971) shows similar characteristics to the Sublithofacies 6c beds, the thin sandstone beds have a more distal nature than the thick sandstone beds and Chipping interprets them as proximal turbidite deposits which had formed in a submarine fan inter-channel depositional environment.

Further evidence to suggest that some of the sandstone beds were formed in a channel-marginal environment is provided by the presence of parallel micro faults which are present in some of the thin beds. It is proposed that such beds were located on the margins of partially filled channels and that instability developed in the consolidating sediment, possibly due to erosion within the channel, which resulted in repeated slipping of the semi-consolidated sediment, producing a series of parallel normal faults (Daley, 1972) which downthrow towards the channel structure. The successive movement resulting in the re-establishment of equilibrium conditions within the marginal sediments, similar structures are present in channel marginal sediments in Lithofacies 4.

A second mode of origin is suggested for some of the thinly bedded to medium bedded sandstones which maintain a constant thickness of outcrop, these beds possess similar internal structures to the previously described thinly bedded to medium bedded sandstones, but they have not been observed to be the lateral equivalents of the thickly bedded sandstones, and in some instances are present in the succession overlying the channel structures, without any variation in thickness. It is presumed that these beds are the proximal deposits of turbidity currents which lacked the erosive power of the denser currents which transported the coarser material found in the channel fills, and that they possessed a less localised source area than these thicker beds.

The fine grained sediments within this Sublithofacies are represented by mudstones with a high silt content, which frequently contain fine grained sand laminae. Mudstones of this type are not the typical pelitic sediments normally associated with turbidite deposition, and it is thought that much of this finer grained sediment was supplied to the area by delta distributaries being transported in suspension from the adjacent delta. It is assumed that its deposition, via gradual settling from suspension was not wholly connected with turbidity current activity.

The coarser fraction of these fine grained beds is thought to be due to variations in the supply of sediment from the deltaic source area. Reineck and Wunderlick (1969) proposed that tidal variations correlated with the deposition of coarse and fine material from suspension within the tidal zone. Such tidal variations may have affected the supply of sediments which constitutes the finer fractions of Sublithofacies 6c, which is thought to have been introduced into the area of deposition from the adjacent delta front. Alternatively, climatic variations or migration of the distributary channels, in conjunction with differential settling from suspension could produce a similar type of bed. Frequently the fine grained sand laminae have a lenticular shape. In such cases they are presumed to have been formed by the deposition of sand from suspension and its accumulation on an irregular bottom surface, presumably produced by scour associated with turbidity current flow. Renewed current scour is thought to have resulted in the removal of most of the sand except for that contained in shallow depressions which were later covered by pelitic material from suspension.

Material transported by turbidity currents is another source of fine sediment in this Sublithofacies and it is envisaged that this type of material is characteristic of the upper parts of the succession which exhibit a more source distal character than that part of the Sublithofacies containing the thickly bedded sandstones.

Summarising the evidence provided by the Sublithofacies 6c sediments it appears likely that the genesis of the sediments was partly due to turbidity currents depositing turbidites of a proximal character (Walker, 1967) both as the fill of small channels and on the inter-channel zones. It is suggested that the turbidity currents were able to erode the semi-consolidated sediment over which they passed and they are also thought to have eroded the channels within which was deposited the more proximal sediment.

Further sediment genesis was also due to the deposition of material from a semi-slumping, semi-turbulent mass, such a body being described by Dzulynski et al. (1959) as a fluxoturbidite. Sediment deposited by this mechanism is thought to have been concentrated in irregularities on the slope surface, which took the form of small channels which are presumed to have been cut previously by turbidity current action.

Much of the fine sand and pelitic sediment is thought to have been deposited independently of the turbidite or fluxoturbidite mechanisms and is presumed to have been carried into the area from an adjacent source area and to have settled differentially from suspension.

The three processes are thought to have concurrently deposited sediment. Sediment lithology, palaeogeographical reconstruction and stratal thickness considerations suggest that the area of deposition was a slope locality, however, the inclination of the slope is thought to be small since it is envisaged that on steeper slopes fluxoturbidites would accelerate and would rapidly develop into true turbidity currents and that in a steeper slope environment larger and more deeply incised channel structures would be present (Walker, 1966). Chipping (1971) describes an association of sediments from the upper Cretaceous and Palaeocene of the San Francisco Peninsula which are almost identical in lithology and structure to the sediments comprising Sublithofacies 6c. He states that these sediments were deposited on the upper part of a submarine fan which contained migrating fan channels the whole reposing on a slope of 3^{o} - 6^{o}.
Chipping proposes that the submarine fan was connected to a submarine canyon system and that the fan grew in size as a result of the accumulation of sediment which was debouched at the mouth of the canyon. The presence of such a canyon system is not envisaged in the formation of Sublithofacies 6c sediments which are assumed to have been derived directly from several localities in the adjacent prograding source area.
The presence of abundant well preserved plant debris of the Equisitales Family, the occurrence both of fine sediment derived from suspension, and of sediment deposited by fluxoturbidites, are thought to be further indications that the source of the Sublithofacies 6c sediments was adjacent to the area of deposition.

In the Blake Brook locality the onset of the conditions of deposition which produced the Sublithofacies 6c sediments is markedly abrupt. Whilst in the upper part of the succession a gradual transition to the basinalsand free muds of Lithofacies 8 occurs. This gradual transition is evidenced by the thinning and reduction in frequency of occurrence of the sandstone beds as the basinal muds which contain the H_2a marine horizon (Loc. 141) are approached. These features are taken to indicate a gradual regression of the source area of Sublithofacies 6c sediments consequent on the eustatic rise in sea level which accompanied the formation of the H_2a marine band.

The reasons for the rapid onset of conditions favourable to the deposition of Sublithofacies 6c sediments which occur in the succession above the H_1a_{iii} marine horizon (Loc. 143) are not evident in the field and can only be assumed to reflect a sudden change in conditions in the source area. (See palaeontological discussion).

SUBLITHOFACIES 6d

Brief Diagnosis

Very thinly bedded to thinly bedded fine grained sandstones, interbedded with thinly bedded mudstones. The individual sandstone and mudstone beds alternate in the succession. The bases of the sandstones are sharp and planar, some individual sandstones displaying small scale load casting. The upper contact of the sandstone beds is planar and although less sharp than the lower contact is not gradational to the overlying mudstones. Delicate tool marks are present on the bases of individual sandstone beds, scour marks are absent. The beds are laterally persistant, no evidence to suggest channelling, thinning or lensing out of beds is present.

Biogenic structures in the form of hypichnial casts are present on the bases of some of the sandstone beds.

FIG. 2. G. Succession at Loc.144 Blake Brook within the E2b3-E2C1 (inclusive) interval.

Distribution

Strata occurring in this Sublithofacies are present in the interval E_2b_3 - E_2c_1 (inclusive) and are exposed in the following stream sections, 5T Blake Brook Loc. 144, 15T Oakenclough Stream Loc. 164, and in the Wiggenstall Stream Section. Details of the succession in the Blake Brook are given in Fig.2.G.

Field Characteristics

Very thinly bedded to thinly bedded sandstones are seen to alternate in the succession with thinly bedded mudstones.

In the Blake Brook Stream Section the sandstone beds have an average thickness of 0.036m, and a median thickness of 0.03m. In the same succession the mudstone beds average 0.119m and possesses a median thickness of 0.06m.

The bed thicknesses of this Sublithofacies in the Oakenclough Stream Section correspond closely with the above figures, the sandstone beds having an average thickness of 0.045m with a median thickness of 0.025m, whilst the mudstone beds have an average thickness of 0.101m and a median thickness of 0.09m.

In the Wiggenstall Stream Section exposures in this Sublithofacies are restricted by sporadic developments of drift. The sandstones that are exposed have an average thickness 0.029m and the intervening mudstones average 0.032m.

The sandstone beds in this Sublithofacies are predominantly fine grained although exceptions are present, and include medium grain size beds of above average thickness. Beds of very fine grained sandstone gradational to silt occur infrequently and are less than the average thickness of the arenaceous members of this Sublithofacies.

The exposures in this Sublithofacies are not extensive, being restricted to stream banks, but in no exposure studied is there evidence to suggest that bed thinning occurred. Erosive features, such as are seen to occur in Sublithofacies 6a and 6c i.e. channels and large scours, have not been observed in Sublithofacies 6d sediments.

The sandstone beds are all distinctly separated by intervals of mudstone which are on average thicker than the sandstone beds, and there is no evidence to suggest that bed amalgamation occurs in this Sublithofacies. (cf.Sublithofacies 6a).

In the field weathering of some of the sandstones has produced planes of parting parallel to the bedding. Examination of fresh broken surfaces shows that this is due to the selective weathering of planes of lamination within the beds.

The majority of the sandstones in this Sublithofacies have sharp planar bases which frequently contain numerous delicate tool marks, occasionally small scale load casting of the sandstone beds also occurs. Less frequently the sandstone beds display numerous hypichnial casts on the lower bedding plane surfaces.

External Structures

With the exception of the laminations, previously referred to, which have been picked out by selective weathering and frequently comprise the whole of the upper half of the bed, there is no external evidence of the internal bed structure.

The Sublithofacies is characterised by thin, parallel sided, laterally persistent, sharp based, fine grained sandstones, interbedded with mudstones of similar thickness. It is only on the base of the sandstone beds that any variations in the external structures occurs.

Primary sedimentary structures of the tool mark type, are present on the bases of some of the sandstone beds, the majority are delicate prod casts which frequently give a good directional sense, being distributed throughout a sector of approximately 30^{o}. Large deeply incised prod casts are present, but occur infrequently, and commonly display the same directional sense as the more numerous delicate prod casts. One sample from the Blake Brook Stream Section (5T/38) displays prod marks within a 90^0 sector and is considered exceptional in this Sublithofacies. Delicate groove casts are also present on the sandstone bases, these straight linear structures indicate a palaeocurrent direction which agrees closely with that provided by the prod marks. Groove casts often occur intersecting the delicate prod casts which are presumed to have formed prior to them. Bedding plane structures resulting from current scour, have not been observed in this Sublithofacies.

Biogenic marks occur in great profusion on the base of some of the sandstone beds. They take the form of small scale hypichnial casts which are irregular in shape, branching, and possess numerous sub-globular protrusions. These biogenic markings closely resemble Seilacher's (1962) branching sole trails which he named Granularia. Holdsworth (1963) figures (plates 68 and 69) similar biogenic marks from the sole of his Sublithofacies 2a type A-bed and describes them as Granularia-type sole trails. The Granularia are seen to be intersected by later formed primary bedding plane structures including the prod casts and the groove casts.

Small scale load casting occurs on some of the sandstone beds in this Sublithofacies, and may be present in conjunction with beds containing tool mark and biogenic bedding plane structures, the load structures have only slightly disturbed these pre-existing structures.

Internal Structures

Samples of the sandstone beds were taken at random intervals throughout this Sublithofacies, other beds were studied in detail in the field. In the majority of cases it is difficult to determine in the field whether or not the sandstone beds are graded, this being mainly due to the fine grain size of the sediments. In the laboratory thin sections revealed that every bed examined was size graded (Birkenmajer, 1959), consisting of a very gradual decrease in grain size upwards.

Cut and polished sections of the sandstone beds display a variety of internal structures in addition to that of size grading. Lamination is the most commonly occurring structure, frequently accounting for as much as 50% of the sandstone bed (5T/13, 15T/34) whilst some specimens are laminated throughout the greater part of their vertical thickness (5T/6, 15T/21). In hand specimen the individual laminae are picked out by thin dark layers which contrast markedly with the grey of the sandstone, in other cases lamination is denoted by differences in colouration within the sandstone beds; the mudstone beds are not laminated.

Thin section examination of the sandstone beds reveals lamination of two types, the type most frequently observed takes the form of thin dark zones (less than 0.5mm) consisting of dark opaque material of very fine particle size which is presumed to be mud or organic carbon. Mica flakes occur, infrequently, embedded in this layer. Bouma (1962) records laminae from the B.lower division of parallel lamination as consisting of pelite and mica flakes separating layers of coarse grained material. Whilst Walker (1965) describes laminations from the B.division of parallel lamination as being formed by flattish sheets of sand in which the grains may show size grading or are present as ungraded 'sheets'. The second type of lamination observed in thin section within the Sublithofacies 6d sandstones is similar to that described by Walker (1965) and consists of alternating laminae of coarser and finer particles, the particles are all angular quartz grains, there being no difference in grain shape in the coarser and finer laminae.

The structures produced by the lamination are of two types. All the sandstones present in the Sublithofacies exhibit parallel lamination, and cross-lamination occurs quite frequently. (5T/34, 5T/15). The scale of the parallel lamination varies, with relatively broadly spaced laminae at 1-5 mm intervals, and an upper zone of laminae occurring at less than 1 mm intervals. When present the finely spaced laminae always occur above a zone of cross-lamination.
The inclination of the cross-lamination to the lower zone of parallel lamination varies from 0-40^{o} with the majority of the laminae being gently inclined.

Distortions of the parallel laminae are present in some of the sandstones occurring as small scale irregular indulations and very infrequently microfaults, these irregularities are interpreted as distortion structures due to differential loading of the sediment when high pore pressures existed in the unconsolidated sediment (Bouma, 1962, P.E.2).

Irregularities associated with the bases of the sandstone beds are as previously described and have no continuation as internal structures, this includes the biogenic structures, there being no evidence of endichnial burrowed structures.

In one load cast sandstone bed small scale injection structures of coarser grained non-laminated material occur penetrating upwards and distorting the parallel laminated interval above. They are thought to be produced by liquefaction and injection of the sand after shallow burial by the more cohesive finer material forming the parallel laminated zone (Kuenen, 1958; Dzulynski and Walton, 1965). These injections of sand have a 'flame structure' morphology (Kelling and Walton, 1957) and appear in part to be syndepositional structures since the distorted laminae they intrude are overlain by undistorted laminae.

The dark laminae in the zone of parallel lamination usually exhibit featureless planar bases the top surfaces of these laminae may show irregularities which are interpreted as micro-load casts produced in these pelitic or carbon rich layers by the denser sand layer above (Anketell et al., 1970).

Interpretation

The fine grain size of the sediments, the thin to very thin bed thicknesses together with the delicate internal structures and numerous fine tool marks suggests that in the main, lower flow regime conditions (Simons et al., 1965; Allen, 1968) obtained in the currents which deposited Sublithofacies 6d sediments.

The internal structures described by Bouma (1962) have been recognised within the sandstone beds in Sublithofacies 6d, but as previously stated when examining the sediments in the field identification of divisions other than the A. and B.divisions is uncertain. The A.graded division is present in the majority of sandstones within this Sublithofacies and may occupy several centimetres or be only fractions of a centimetre in thickness. In the latter case it is directly overlain by the B. interval of parallel lamination which then occupies the majority of the bed. Thin section examination of the A.graded interval reveals that the coarser grains, without exception occupy the base of the bed and are always size-graded (Birkenmajer, 1959). The thin size graded interval, provided it contains at its base grains of the largest particle size in the bed and occurs at the base of the bed is considered to be the A.graded division of Bouma (1962). Walker (1967) describes thin fine grained sandstone beds which are size graded and suggests such beds could be formed in a distal (land remote) environment, and that deposition could occur from a current which maintained all its sediment in suspension even at low flow regimes.

The A.graded division is succeeded by the B.division of parallel lamination which may occupy as much as 90% of the sandstone bed, although it commonly approximates to one third of the total thickness. Sandstones commencing with the B.division of parallel lamination occur fairly frequently in this Sublithofacies, and constitute the base cut-out sequence, T2, of Bouma (1962) and other authors. The frequency of occurrence of base-absent sequences in beds with an average thickness of 0.03m seems to be a matter of personal interpretation since thin A.divisions may be taken to represent B.division laminae and vice-versa, and due to this factor it would be unrealistic to attempt a statistical analysis of the Bouma divisions with the object of assessing the proximality or distal character of this Sublithofacies. However, Walker (1967) in an analysis of proximality includes all A.-E. beds less than 3 cms thick, in which the sand does not exceed fine grain size, within the T_3 group of Bouma (1967) and refers to such beds as distal turbidites.

Cross-lamination commonly occurs above the B.division and constitutes the C.division of current ripple lamination (Bouma, 1962). This C.division is frequently composed of laminae, inclined at 10-20^o to the B.division, which occupy less than 25% of the bed thickness. The C.division has never been observed in this Sublithofacies to commence at the base of the bed.

The D.division of upper parallel lamination occurs in several sandstone beds in this Sublithofacies and usually takes the form of a thin layer of sediment less than 2.5 mm thick resting on the C.division. Only one instance of the D.division exceeding this thickness was observed in sample 5T/15, here the interval is 0.025m thick and constitutes just less than half of the bed.

The presence of base cut-out sequences of the T4 type (Bouma, 1962) was not recorded from this Sublithofacies and it is thought that their occurrence is unlikely, since sequences of this type are not associated with coarser sediments such as are found occurring in sandstone beds displaying both A. and B.divisions (Walker, 1967; Allen, 1970). In the outer regions of the distal facies of turbidity current deposition in the north east Pacific Horn et al., (1971) recognised a succession of beds consisting of 'thin silt grading to clay', which appear to be equivalent to the D. and E. Bouma Divisions, the presence of sand sized particles was not recorded from this succession, and was confined to more proximal areas of deposition.

The identification of the Bouma Divisions and their distribution within the beds of Sublithofacies 6d indicates, in the absence of bed forms characteristic of other mechanisms of deposition, that the genesis of the sediments in this Sublithofacies was the product of successive turbidity current activity.

The complete Bouma sequence, A.B.C.D.E., which has been observed several times is indicative of deposition by a mature current, Walker (1965). Beds containing very little relatively coarse sediment, that is where the A.division is thin or absent are presumed to represent turbidites forming in a distal environment, the majority of the coarse material having been deposited, possibly by freezing of the traction carpet in a more proximal area of deposition (Bagnold, 1955, and Saunders (196

The slow moving mature currents which are envisaged to have deposited the beds in Sublithofacies 6d, would presumably have transported the coarser fraction, which occurs at the base of the sandstone beds, by rolling and saltation in a zone sometimes only a few grain layers thick, and which now constitutes the narrow

A.division observed in some of the beds. Gradual fall out of sediment would stabilise this layer and produce the B.C.D. and E. intervals characteristic of a mature waning current (Walker, 1965, 1970).

Environments of deposition situated in a more distal zone in relation to the main current vector are presumed to be outside the limit for rolling and saltation of the coarser grains and deposition in these conditions has produced a base cut-out sequence from which the A.division is absent. Alternatively sediment which would normally comprise the A.division was deposited but was sufficiently cohesive to resist re-working into laminations (Walker, 1965).

External evidence of the distal character of this Sublithofacies is also provided by the numerous delicate tool marks, which occur on the base of many of the sandstone beds, and also by the absence of scour marks (Allen, 1970). Bimodal current directions derived from prod mark orientations on the same sole display modes about 90^{o} apart and are interpreted as the products of non-aligned frontal lobes of the same turbidity current, passing in close succession over the same cohesive mud bed (Anderson, 1964). It is not envisaged that such frontal lobes, producing delicate tool markings exhibiting a marked bimodal distribution, would be the product of the steep slopes associated with the proximal environment, but rather that they would be produced when current velocities were slowing down in a basinal area, or even in situations where the direction of slope was reversed.

Bimodal current distributions such as those referred to above are in direct contrast to the unimodal current directional structures observed in the proximal sediments of Sublithofacies 6a and are in the context of Sublithofacies 6d taken to represent turbidity current activity in a distal environment.

Further criteria for determining the proximal or distal nature of beds formed as a result of turbidity current activity, is suggested by Walker (1967) to be related to the presence and type of base cut-out sequences in the succession. Walker uses the percentage of beds beginning with A.division., B.division or C.division., within a turbidite succession to derive an index, the P index, which he suggest is indicative of proximality, the value of P becoming progressively less in distal environments.

Beds commencing with the C.division have not been recorded from Sublithofacies 6d, and although beds beginning with the B.division of parallel lamination have frequently been recorded, the percentage of base cut-out sequences of the type T2 (Bouma, 1962) occurring within the succession is, as previously discussed, a matter of personal interpretation in thin beds such as these and for this reason it would be unrealistic to attempt to derive a P index for Sublithofacies 6d sediments.

The characteristics which indicate the distal nature of some turbidites have been discussed by several authors and have been summarised by Walker (1967) as follows:-

A. Beds thin.
B. Beds fine grained.
C. Individual sandstones rarely amalgamate.
D. Beds parallel - sided, regularly bedded.
E. Few small scours, no channels.
F. Mudstone layers between sandstones well developed. Sand/mud ratio low.
G. Beds well graded.
H. Base of sand always sharp top grades into finer sediment, A. E. sequences rare.
I. Laminations and ripples very common.
J. Tool marks occur more frequently than scour marks.

Taking into account the above points there is a close correlation between the characteristics of distal turbidites as described by Walker (1967), and those of the sediments in Sublithofacies 6d, which are proposed to have had a similar origin.

The analysis of directional sole structures indicates a southerly origin for the transporting currents which in the area of deposition of Sublithofacies 6d sediments are presumed to have possessed hydrodynamic characteritics mainly applicable to lower flow regime conditions (Simons et al., 1965; Allen, 1968) specifically in the plane bed lower phase sector and in the sector of small scale ripples. Much of the finer material accounting for more than half of the sediments in this Sublithofacies is presumed to have been deposited from suspension following the cessation of individual current activity. The time interval between successive turbidity currents is unknown but the presence of numerous unroofed and sandfilled burrows of the Granularia type occurring as casts on the soles of some of the sandstone beds, indicates that the arrival of successive turbidity currents was punctuated by a time interval sufficient to allow the development of extensive biogenic activity. The presence of surface/near surface (exogenetic) burrowing in the consolidating E.division, probably of the Fodichnia group (Seilacher, 1964), is indicative of deep oxygenated waters (Blatt, Middleton and Murry, 1972) an interpretation which is in accordance with the envisaged environment of deposition of Sublithofacies 6d sediments in which the oxygen content of this basinal area of deposition was continually renewed by successive turbidity currents.

POST DEPOSITIONAL STRUCTURES PRESENT WITHIN LITHOFACIES 6 SEDIMENTS

Outcrops of Lithofacies 6 sediments display post depositional structures at several localities within the area studied. In the following account these structures are subdivided into categories on the basis of their morphology and field relationships.

Category I

Brief Description

A fine to coarse grained, conglomeratic, very thickly bedded, structureless bed, composed of coarse angular quartz grains in a matrix of mud and fine quartz grains, the whole containing large irregular shaped exotic clasts of shale and sandstone. The sandstone clasts display A. and B. Bouma divisions, and like the mudstone clasts exhibit a random orientation and distribution.

This bed (15T/1) occurs in the Oakenclough Stream Section, Loc. 160, and is present at the base of the Sublithofacies 6b succession at this locality (Fig.2.Fb.). The bed displays a slightly irregular sharp contact with a mudstone below, like-wise the upper contact is slightly irregular if less sharp.

Interpretation

This bed is presumed to be initially the deposit of a turbidity current carrying coarse sediment into a basinal environment, and abruptly depositing the majority of its load when the topography of the basin produced a rapid decline in current velocity. The sediment deposited by such a mechanism would be derived largely from suspension (Walker, 1967) and if reworking did not occur, which seems unlikely due to the very coarse nature of the large particles, it would possess an initially high void ratio and high water content. A deposit of this type would have a low shear resistance and a high factor of instability. Failure of such a deposit would occur when it was loaded from above by the addition of more sediment, or by the removal of finer sediment from the down slope region, or by steepening of the slope on which the sediment reposed, a combination of the first two mechanisms of failure seems most likely in this case. Failure would either take the form of successive slips each leaving an over-steepened slope which would in turn fail, a phenomenon described as back-sapping in soil mechanics, or would take the form of a larger and more deep seated slip (rotational slip) which would also incorporate the semi-consolidated sediment forming the foundation of the structure. The whole mass would then slump forward and in the process any internal structures such as grading or lamination would be destroyed and the resultant sediment would achieve the non-graded structureless chaotic state it presently exhibits. The latter mechanism appears to be more applicable to this situation, as a large slip would be required to incorporate the exotic clasts referred to in the description of the bed. The degree of mixing of the sediment is thought to have been achieved not only by slip or slumping but also by liquifaction of the bed, a state which probably occurred during the actual slumping when some pore liquid would be expelled consequent on a change in sediment fabric, and pore pressures would tend to become excessive causing the individual grains to float. Liquifaction of the slumping material could only have been a very temporary phenomenon, otherwise a lateral size-grading would have been established, a feature which was not observed during the field examination of this bed.

Bagnold (1956) terms the mass movement of cohesionless grains, grain flow. Submarine grain flows have been proposed by Stauffer (1967) to account for the formation of very thickly bedded structureless sandstones. Grain flows, with excess pore pressure produced by retrogressive flow slides (back sapping) of sands are referred to by Blatt, Middleton and Murray (1972), they suggest that the grain flows are formed by collapse of a locally steep slope, the collapsed sand liquifies and flows away from the base of the slope so that it again becomes over steepened thus continuing the regression of the slides. Blatt, Middleton and Murray (1972) propose that a grain flow deposit possesses the following characteristics:-

(1) Thick beds, ungraded and massive,

(2) large clasts,

(3) absence of lamination or cross-lamination typically formed by traction,

(4) scarcity of sole marks and

(5) presence of dish structures (such structures were not observed in bed 15T/1).

Grain flow as a product of excess pore pressure is thought to have been part of the mechanism which produced bed 15T/1 but in the author's opinion it is difficult to see how grain flow alone could have achieved the incorporation of exotic clasts of sandstone into the bed. These large clasts must have achieved a considerable degree of consolidation to prevent their disintigration within the grain flow. In addition the grain flow which occurred to produce bed 15T/1 is thought to have possessed a very short life since the mud content of the deposit is high.

It is proposed therefore, that bed 15T/1 is the product of subaqueous slump and sliding incorporating rotational slip (category b, Dott, 1963) together with a limited amount of subaqueous grain flow (Stauffer, 1967). Bed 15T/1 is overlain by a mudstone 1.65m thick, the majority of which is assumed to represent the normal accumulation of basinal mud. This pelitic deposit, is thought to have evened out any sea bed irregularities, and has proceeded the deposition of a turbidite facies from which post depositional structures are absent.

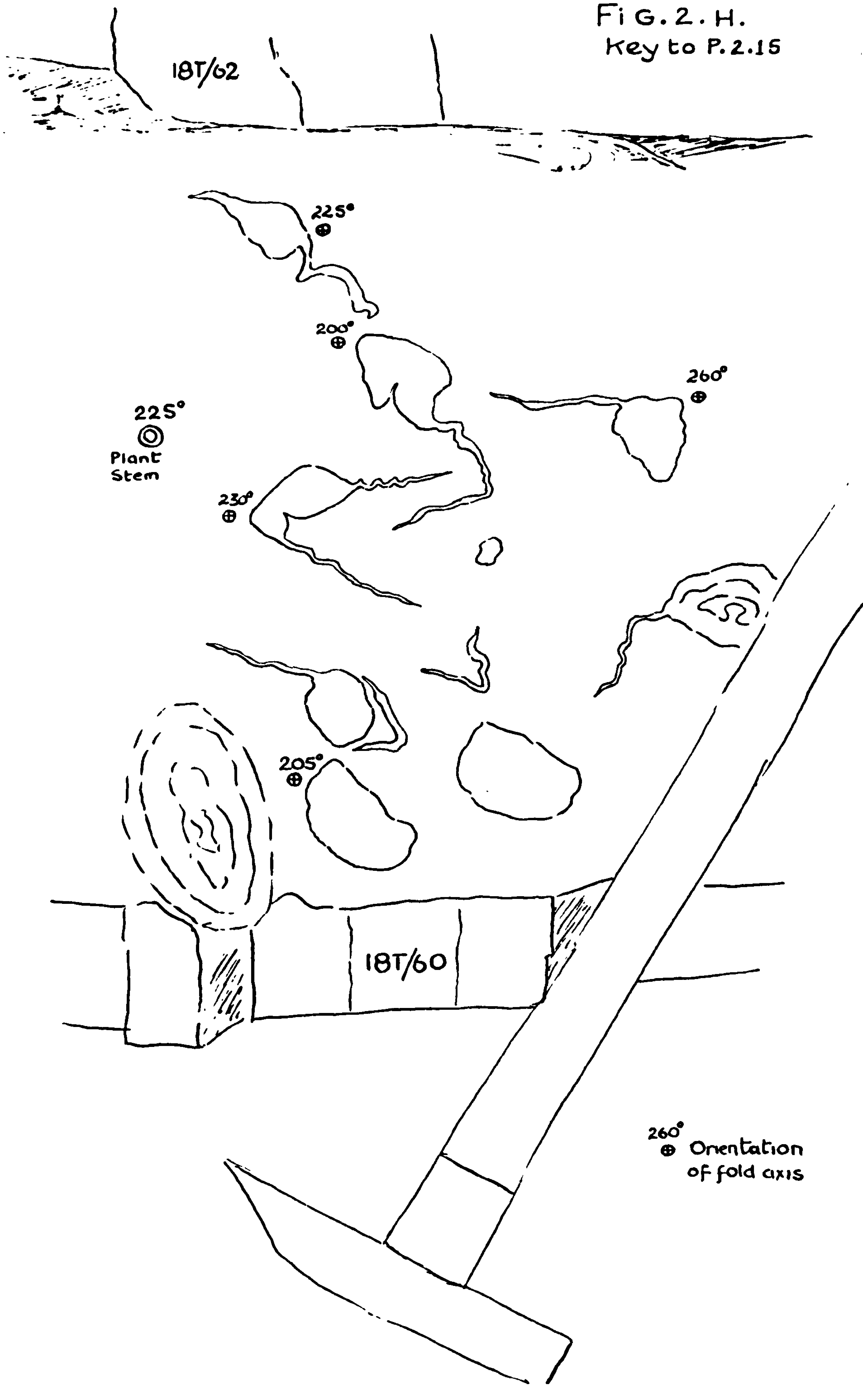
P.2.15.

Category II.
Deformation structures present in bed 18T/61.

Loc. 201. Gawsworth.
(See key, Fig.2.H., over page).

P.2.15.

FiG. 2. H.
Key to P. 2.15



Category II

Introduction

Within the Sublithofacies 6a sediments exposed in the Gawsworth Common area at Loc. 201, bed 18T/61 contains a variety of small scale deformation structures. The enclosing strata are undeformed medium to coarse grained laterally persistant sandstones of a proximal turbidite character (P.2.15. and Fig.2.H.).

Description

Bed 18T/61, containing the deformation structures mentioned above is enclosed by beds 18T/60 and 18T/62.

The lower bed 18T/60 is 0.09m thick and displays a sharp planar base, the upper bedding plane is in part gradational, and in part shows evidence of erosion by the sediments comprising bed 18T/61. Bed 18T/62 is 0.09m thick and possesses a sharp planar base.

Bed 18T/61 varies in thickness from 0.17 to 0.25m and consists of silty to sandy mudstone totally enveloping bodies of very fine to fine grained sandstone which display a variety of deformation structures. These structures take the form of overfolds, recumbent folds and irregular tightly folded bodies. The limbs of the folds which often display crenulations may be streaked out tapering to zero. The greatest thickness of sediment usually occurs in the crestal part of the fold structures and is on average 0.02 - 0.03m thick measured in the position of the axial plane. In the crestal or axial direction the fold structures are discontinuous, the maximum development in this direction being 0.05m. Internally the thicker parts of the deformation structures display very little structure although some bodies display tight internal folding, and evidence of primary parallel lamination is seen in the thinner parts of the structures. In addition to the inorganic sediment present in bed 18T/61, organic debris is present as wisps and discontinuous laminae both in the deformation structures and in the enclosing mudstone, internal undeformed casts of small plant stems, cf. Calamites sp., are present, consisting of fine sand with an external coating of carbon.

The deformation structures have not been observed to connect with any undeformed sand body within bed 18T/61, neither are they in contact with the sharp boundaries of beds 18T/60 and 18T/62.

Current directional evidence in the associated beds indicates that the axial orientation of the deformation structures is frequently normal to the direction of inclination of the proposed palaeoslope however, departures of as much as 70^{o} from this orientation have been observed.

Interpretation

The deformation structures present in bed 18T/61 are very similar in morphology to the deformation structures described by Macar (1948, 1951), Macar and Antun (1950), and termed by them pseudonodules. Kuenen (1958) describing the genesis of pseudonodules proposes that they are an extension of load structures in which distorted fragments of sand or silt become detached from a bed overlying a thixotropic clay and founder into this clay when a change in the physical state of the clay from plastic to liquid occurs. Such a change in the cohesive properties of a sediment could be produced by a shock wave agitating the clay particles and producing the fluid state (Boswell, 1948a, 1948b).

On the basis of evidence elsewhere in the succession (bed 18T/67), it is proposed that bed 18T/61 initially consisted of a bed of mudstone rich in plant fragments enclosing a thin bed/beds of fine laminated sandstone. The originally continuous sand bed/beds has, since deposition, assumed a discontinuous form due to foundering into a thixotropic sediment. The random vertical distribution of the deformation structures within bed 18T/61 suggests that differential settling of the isolated fragments has occurred.

It is presumed that as the detached bodies of sand foundered in the thixotropic mud, they became distorted and assumed downwardly convex bases. Pseudonodules produced experimentally by Kuenen (1958) contain a relatively gently folded internal structure and possess downwardly convex lower boundaries. Boundaries of this type are present in some of the deformation structures occurring in bed 18T/61, on the other hand many of the structures present in this bed have marked concave and convex lateral boundaries, suggesting a lateral movement in addition to a vertical foundering. Internal evidence shows that the deformation structures present in bed 18T/61 possess, in several cases, tightly folded structures which cannot be explained simply by the foundering of a detached body of sand, although it is envisaged that this mechanism is partly responsible for the genesis of the structures. It is suggested that the thixotropic state of the mud in bed 18T/61 existed for only a relatively short period of time and was terminated when the mud passed into the plastic state. Loading of bed 18T/61 by bed 18T/62 which possess a sharp planar base, now occurred, plastic deformation of bed 18T/61 is thought to have occurred at this stage. It is suggested that prior to plastic deformation the plasticity of the mud content of bed 18T/61 was increased, thus lowering the shear resistance and producing a situation where the bed would deform plastically with increased loading. The plasticity of a sediment increases in a linear manner with increase in water content (Capper and Cassie, 1963) and it is suggested that an increase in water content in bed 18T/61 was due to compaction of the abundant water saturated plant debris present in the bed, the expelled water increasing the plasticity of the mud to a point where plastic deformation could occur.

The structures present within bed 18T/61 indicate by their morphology that lateral movement took place during the stage of plastic deformation. The impetus for such lateral movement could have been due to loading of sediment situated on a palaeoslope as described by Shepard (1955) and Williams (1960). Plastic deformation of sediment in such a situation is referred to by Dzulynski and Walton (1965) as plastic glide and induces the formation of slide folds (Dzulynski 1963a) within the deforming mass. The axial orientation of deformation structures in bed 18T/61 is in some cases normal to the direction of dip of the proposed palaeoslope, whilst departures of up to 70^{o} from this orientation have been recorded, this variation in fold axis orientation is assumed to be due to local variations in the plasticity of the mud. Dzulynski and Walton (1965) suggest that as a result of plastic gliding the orientation of the fold axes can vary from parallel to the direction of lateral movement to an orientation normal to this direction.

The majority of plastic deformation which occurred in bed 18T/61 is thought to have taken place in a central zone or envelope, since it is in this zone that the majority of deformation structures occur. The amount of lateral movement is thought to have been small but sufficient to allow slide fold structures to develop.

Dott (1963) suggests that liquifaction of silt and very fine sand may occur during loading, and is produced by the forcible migration of the pore fluid inducing excess pore pressure within the sediment. The individual grains are subject to a buoying effect, so that the sediment is capable of behaving as a liquid. A migration of the liquified sediment to zones of relief of pressure such as those afforded by the crestal parts of the slide folds is envisaged in the genesis of the deformation

P.2.16.

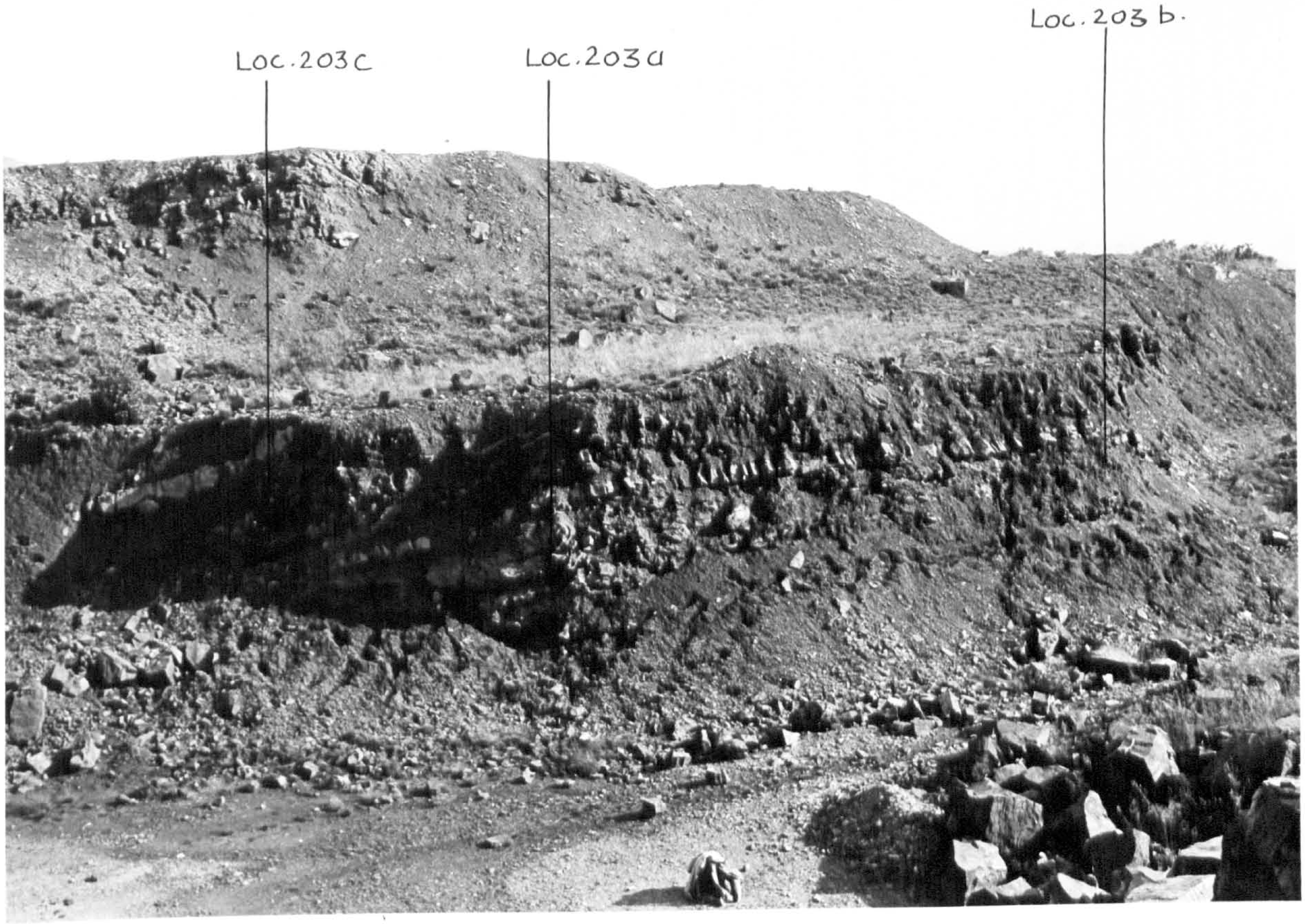
Locs. 203A, B and C of Category III deformation structures present in Sublithofacies 6a beds at Gawsworth.

P.2.17.

Deformation structures in bed 18T/199, at Loc. 203A. (See key, Fig.2.I., over page).

P.2.18.

Deformation structures in bed 18T/199 at Loc. 203B. (See key, Fig.2.J., over page).



P. 2.16.

P. 2.17.

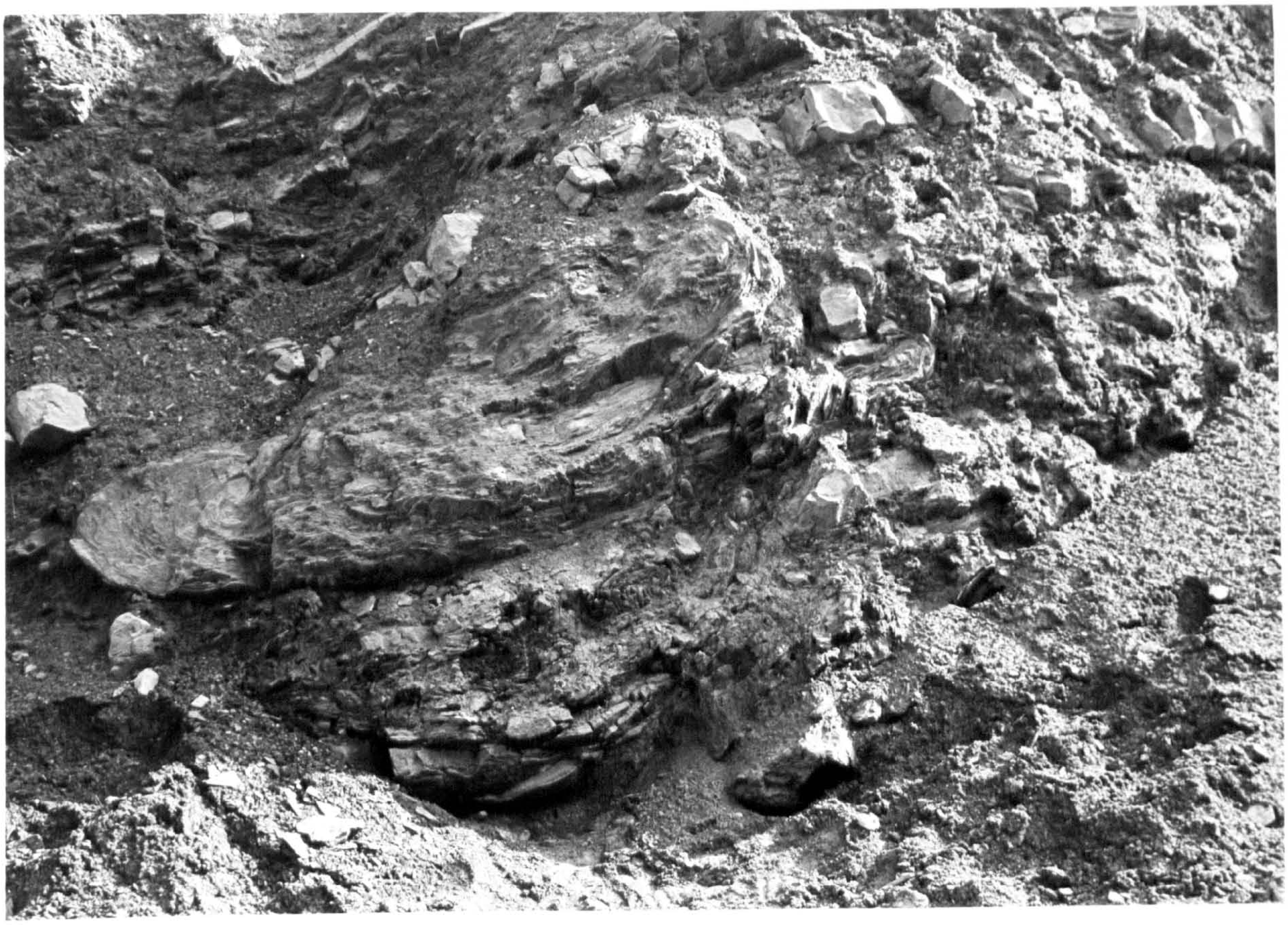
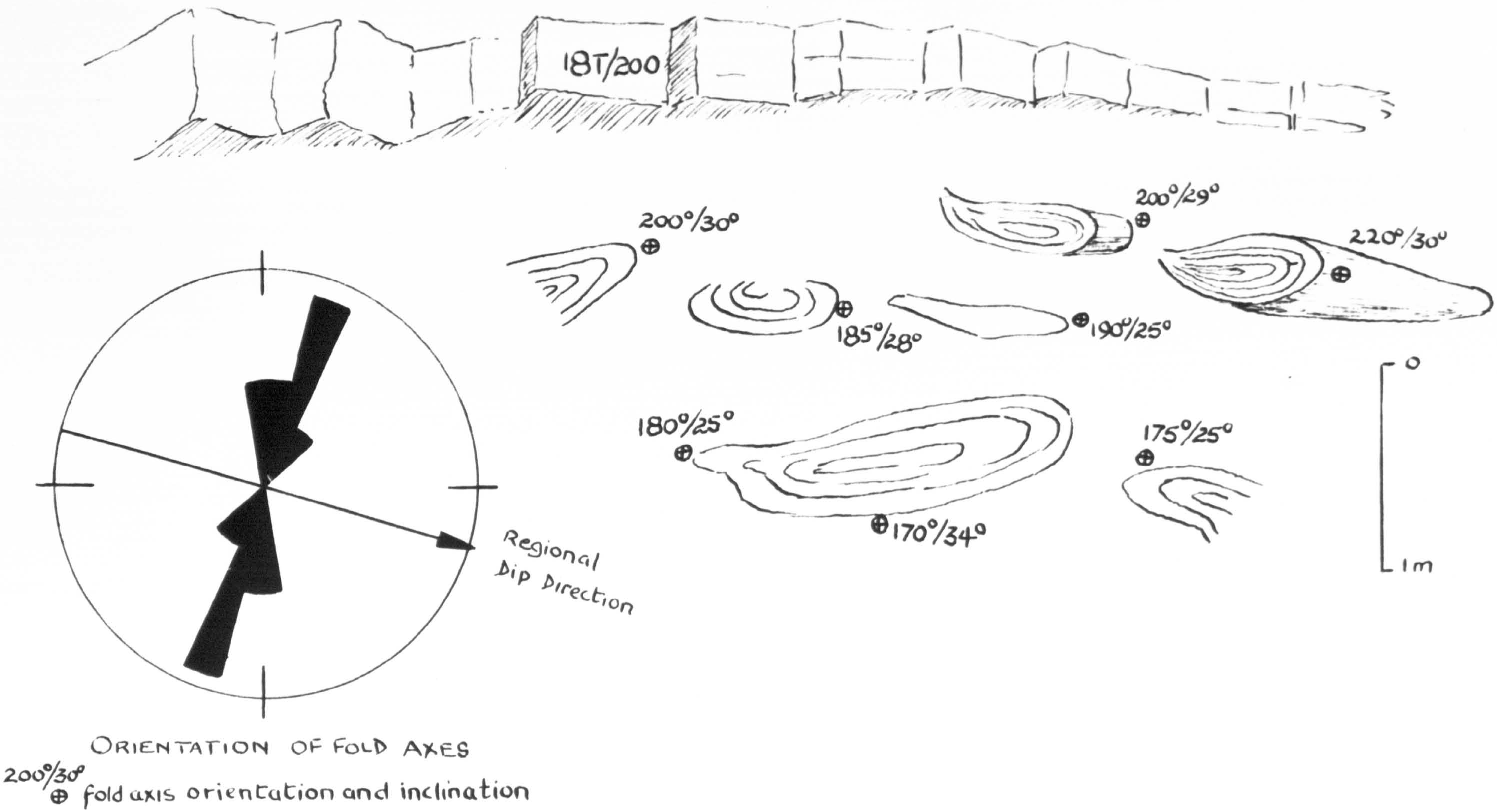


Fig: 2.I.
Key to P.2.17.

DEFORMATION STRUCTURES IN BED 18T/199 AT LOC.203A.

P. 2.18.

FIG: 2. J
Key to part of P. 2.18



DEFORMATION STRUCTURES IN BED 18T/199 AT LOC. 203B structures present within bed 18T/61, such structures consist of a core of fine sand or silt and internally are either structureless or at most show only fragmentary traces of the original lamination. It is proposed that the sediment concentrated in the cores of the folds has migrated from the limbs, which as a consequence are attenuated.

Summarising the above information is is considered that the deformation structures present in bed 18T/61 may have originated as load structures of the pseudonodule type (Kuenen, 1958), which were derived initially from a bed or beds of fine sand occurring within a predominently mud rich bed. Loading induced plastic flow of the mud fraction together with associated liquifaction of the fine sand and migration to points of relief of pressure producing hook-like overfolds.

The amount of slope required for the generation of plastic glide is problematical varying between 15 - 20^{o} Rettger (1935), Moore (1961) and slopes of 1^{o} or less, Hills (1953), Shepard (1955). In the case of bed 18T/61 it is suggested that the angle of slope was near the lower limit since the amount of lateral movement involved is presumed to be relatively small.

Category III

Brief Description

Deformation structures occurring in Sublithofacies 6a sediments are present in the Gawsworth Common area at Loc. 203, (A, B and C) (P.2.16), the structures which mainly take the form of recumbent folds frequently have axial dimensions in excess of 1.0m. The beds containing the deformation structures occur in one part of the succession only and are numbered 18T/199, 18T/201 and 18T/204, intercalated with these beds are beds 18T/200 and 18T/202 which are undeformed.

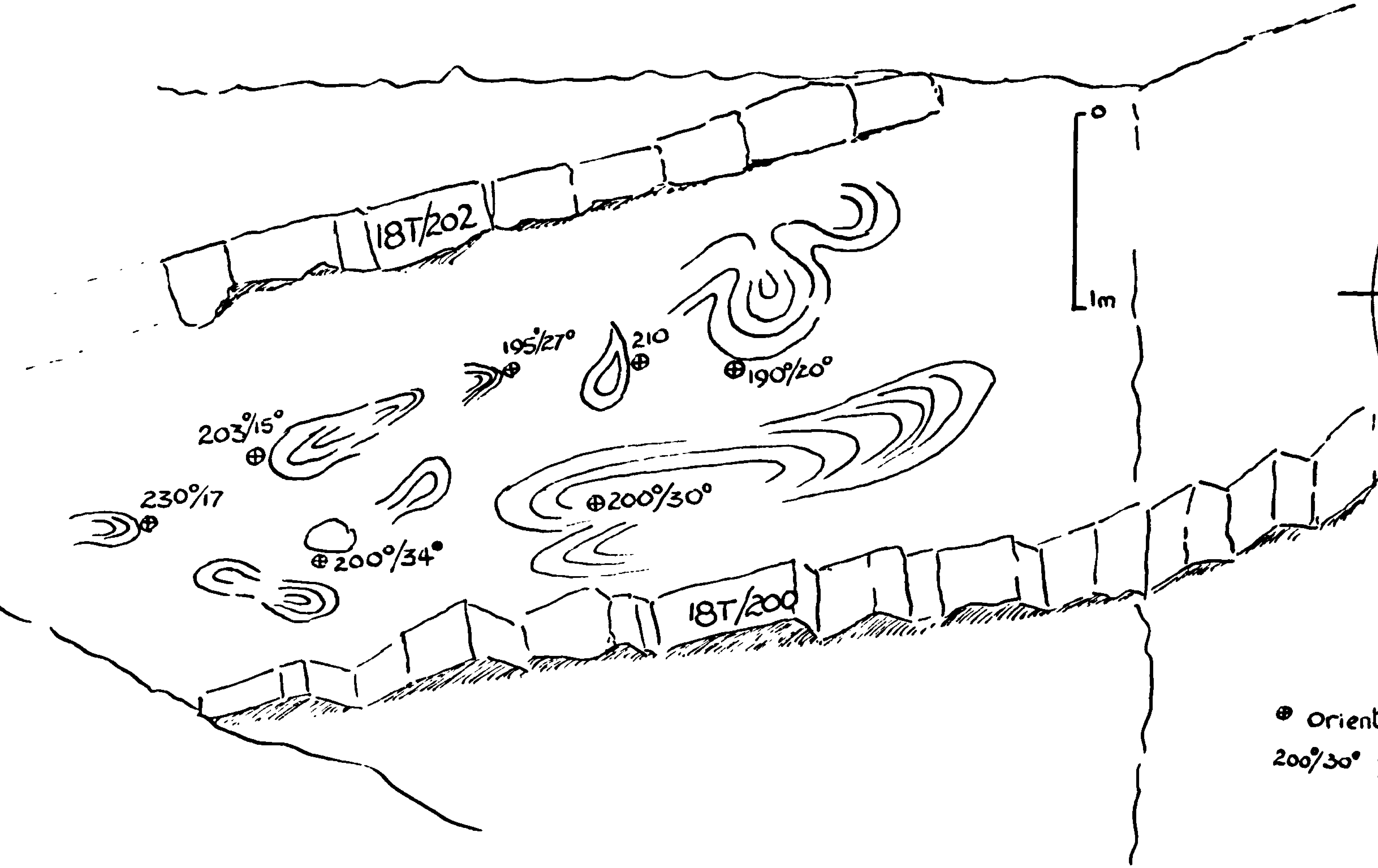
Bed 18T/199 of minimum thickness 2.0m is only partly exposed, the lower boundary being concealed by quarry debris (P.2.17 and Fig.2.I). The bed, as exposed, consists predominantly of mudstone which envelopes deformation structures consisting of fine sand and silt. These structures mainly take the form of recumbent corrugated folds in which the original lamination is still evident. The laminae are composed of alternations of fine sand, silt and mud, the coarser laminations may be dislocated by small faults, microfaults, which terminate in the adjacent finer laminations. Thickening up of the sand and silt laminae occurs infrequently in the cores of some of the folds.

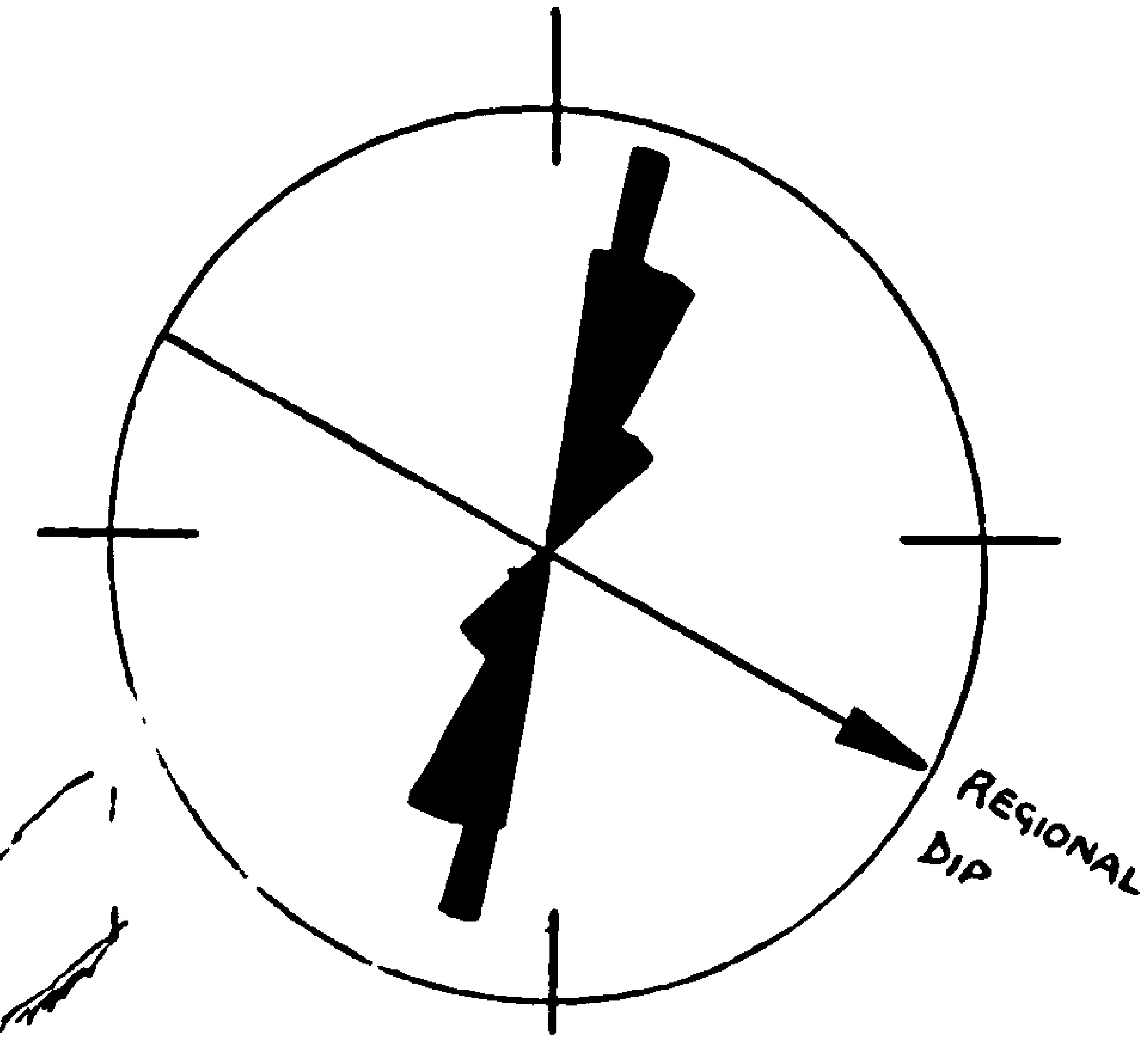
The fold structures present in bed 18T/199 occupy random vertical positions in the bed and the axes of the folds display a common orientation (P.2.17 and 2.18) (Fig.2.I and 2.J.). The attitude of the axial planes of the folds is subparallel to the enclosing strata although exceptions within an angular range of 90^{o} occur. The pitch of folds measured in the field is between 20 - 40^{o} and when corrections are made for the tectonic dip of the beds the pitch is slight and is seen to vary between 0^{o} - 10^{o}. The orientation of the microfaulting is parallel to the axial direction of folding, and the faults themselves are arranged radially about the fold structures. Externally the limbs of the folds may be ridged, these small ridges have an orientation parallel to the main fold axis, and in structures which have been sectioned the ridges are seen to be expressions of the internal corrugation. The external surfaces of the folds also display traces of primary bedding plane structures, which although of infrequent occurrence include fine prod marks.

Bed 18T/200 occurs directly above bed 18T/199 and is a laterally persistant, medium to coarse grained sandstone bed with a constant thickness of 0.19m. The base of the bed is sharp and displays well developed load cast structures, the top

DEFORMATION STRUCTURES IN BED 18T/201 AT LOC. 203 C.

FIG: 2. K.





ORIENTATION OF FOLD AXES

⊕ orientation of fold axis

200°/30° fold axis orientation and inclination is planar. Internally the bed displays a size graded A.division overlain by 0.05m of parallel laminated sediment of the B.division, this bed has previously been interpreted as a source proximal turbidite.

Bed 18T/201 is 2.42m thick and consists predominantly of mudstone enclosing deformation structures which are identical in lithology and structure to the deformation structures presen in bed 18T/199 (Fig.2.K.).

Bed 18T/202 is a laterally persistent medium to coarse grained sandstone having a constant thickness of 0.35m, this bed possesses a sharp load cast base, and a sharp upper bedding plane surface. Internally the bed displays a size graded A.division overlain by the B.division of parallel lamination, 0.03m thick, this bed has previously been interpreted as being a source proximal turbidite.

Interpretation

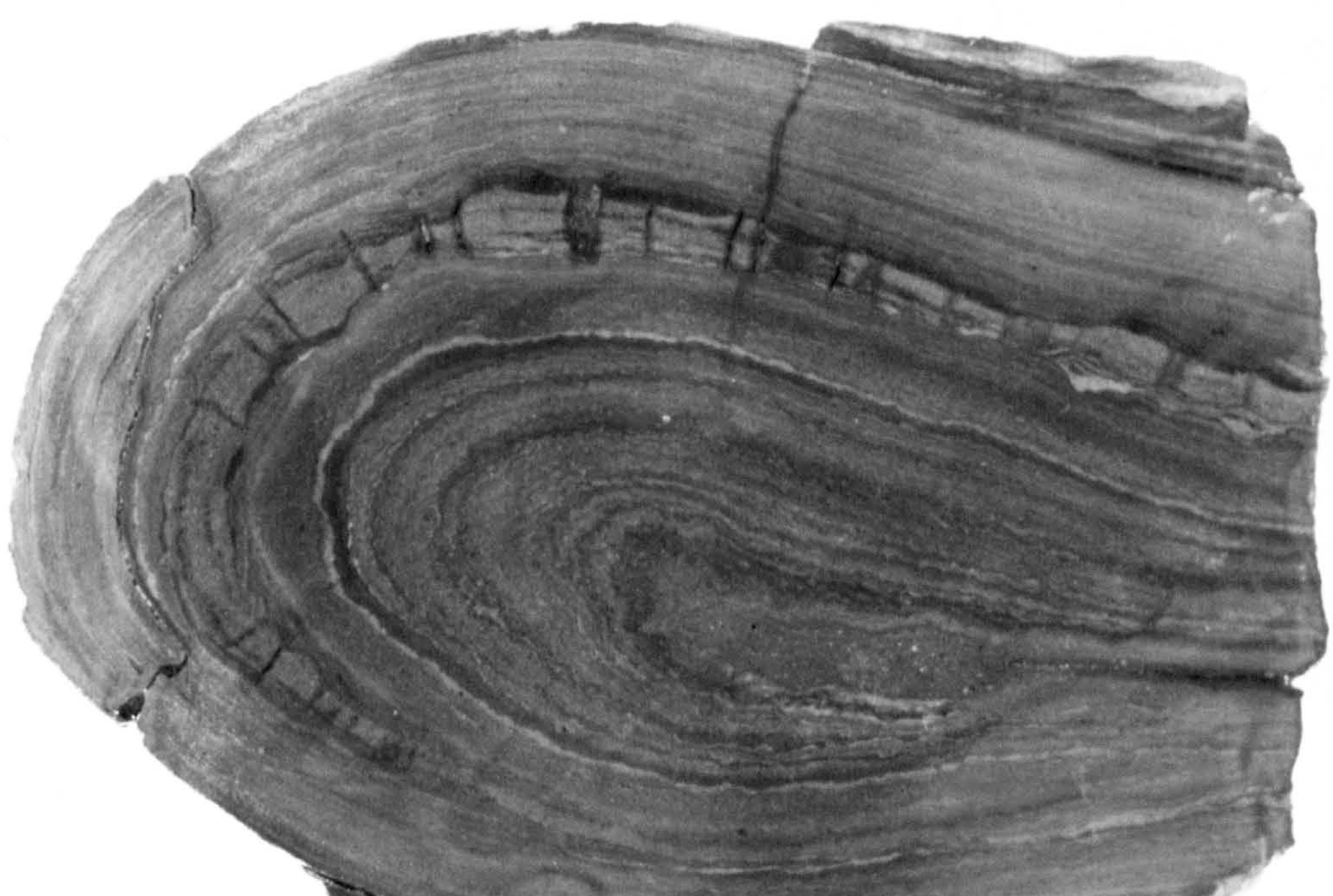
The original character of the beds containing the deformation structures is thought to be similar to that of bed 18T/197 which has a minimum thickness of 1.20m and consists of mudstone intercalated with fine sandstone and siltstone and has previously been interpreted as being a distal turbidite. Deformation of beds 18T/199 and 18T/201 is thought to be due in part to loading of the sediment whilst still in the plastic state (Dott, 1963) by the overlying proximal turbidite beds 18T/200 and 18T/202. Such an occurrence implies lateral migration of the main turbidity current vector and is in keeping with the author's previously discussed interpretation of the genesis of Sublithofacies 6a sediments. It is also suggested that the deformation of beds 18T/199, 18T/201 and 18T/204 is in part due to lateral movement, whilst the beds were still in the plastic state, a mechanism termed plastic glide by Dzulynski and Walton (1965). The occurrence of pull-apart structures (Dott, 1963) and the infrequent thickening of some of the coarser sand

P.2.19a and b.

Internal structure of the Category III deformation structures present in bed 18T/199.

P. 2.19 a.

P. 2.19 b.



laminae suggests that pore pressures increased within the sand fraction to a point where a limited amount of liquid flow developed. However, the retention of the original laminae within the deformation structures supports the proposal; that deformation occurred in the plastic state and also indicates that the majority of the fine sand and silt fraction did not pass into the liquid state during deformation. It is suggested that the stress producing the plastic deformation was applied slowly enough for the pore fluid pressure in the majority of the sand and silt fraction to adjust to the increasing stress field by migration of the pore fluid, without in the main destruction of the internal cohesive structure of the sediments (Terzaghi and Peck, 1948).

The presence of microfaulting within the sandstone laminae indicates that the shear strength of the less cohesive sediment was exceeded during deformation whilst the more cohesive mud fraction resisted shear failure by behaving in a plastic manner (P.2.19a and b.).

A preferred orientation of between 180° and 200° is displayed by the fold axes of the majority of the deformation structures and is presumed to indicate a lateral control during the development of the deformation structures. It is proposed that such control would occur if sediment deformation took place on a palaeoslope, which in this case is thought to have an easterly inclination. Deformation in such a situation is attributed to plastic glide (Dzulynski and Walton 1965) a process in which slide folds (Dzulynski 1963a) develop within an individual bed. The variation in the pitch of the folds observed and the orientation of the fold axes at Loc. 203, is presumed to be due to localised variations in the resultant stresses producing the deformation consequent on the development of the slide folds, and possibly also due to locallised variations in the plasticity of the mud fraction.

Allen (1960) describes and figures (Fig.9, P.203) crumpled bedding structures from the turbidites of Mam Tor, these structures appear to be identical to the deformation structures present at Loc. 203 in the Gawsworth Common area. The structures described by Allen are limited to the thinner sandstone-shale beds, they take the form of recumbent folds whose axes display a preferred E-W orientation. Allen suggests that the parallel orientation of the fold axes together with the direction of overfolding of the structures indicates that lateral movement has occurred normal to this direction, he refers to the movement as gliding which is presumably the equivalent of the plastic gliding of Dzulynski and Walton (1965). The crumpled bedding structures described by Allen are he suggests the product of lateral movement in a slope environment and their occurrence within a turbidite succession provides independent evidence of the presence of a submarine palaeoslope.

The deposition of sediment in a slope environment is, as has been indicated in the formation of category I deformation structures, a potentially unstable situation where instability and slumping may occur. Slump failure is thought not to be involved in the genesis of the deformation structures at Loc. 203, since the deformed beds have a constant thickness and are laterally persistant. It is proposed that the possession of such qualities indicates a minimal lateral movement and mitigates against the mechanism of large scale slumping (Dott, 1963) as being involved in the production of the deformation structures present at Loc. 203.

All the available evidence concerning the genesis of the deformation structures present in beds 18T/199, 18T/201 and 18T/204 indicates that the bulk of the sediments deformed plastically during the development of the slide folds. Similar structures, to these present at Loc. 203, all formed by the deformation of sediment in the plastic state have been described by various authors: Dott (1963) describes "Contorted stratification structures in Sandstone" which he states have been produced by plastic flow. Structures of a similar type but of less axial persistance are described as "Flow Rolls" by Sorauf (1965), the genesis of which he attributes to the plastic deformation of fine grained channel sandstones resulting from vertical loading of sediment on a slope. The amount of slope required to produce penecontemporaneous deformation in unconsolidated sediments has been suggested by several authors to lie between 1^{o} and 20^{o} (see interpretation of Category II structures). The angular value of the palaeoslope obtaining in the Gawsworth Common area is unknown but it is thought, on the evidence provided by the associated sediments, that this area presented the steepest slope in existance on the Western margins of the North Staffordshire Basin during Chokerian and Alportian times.

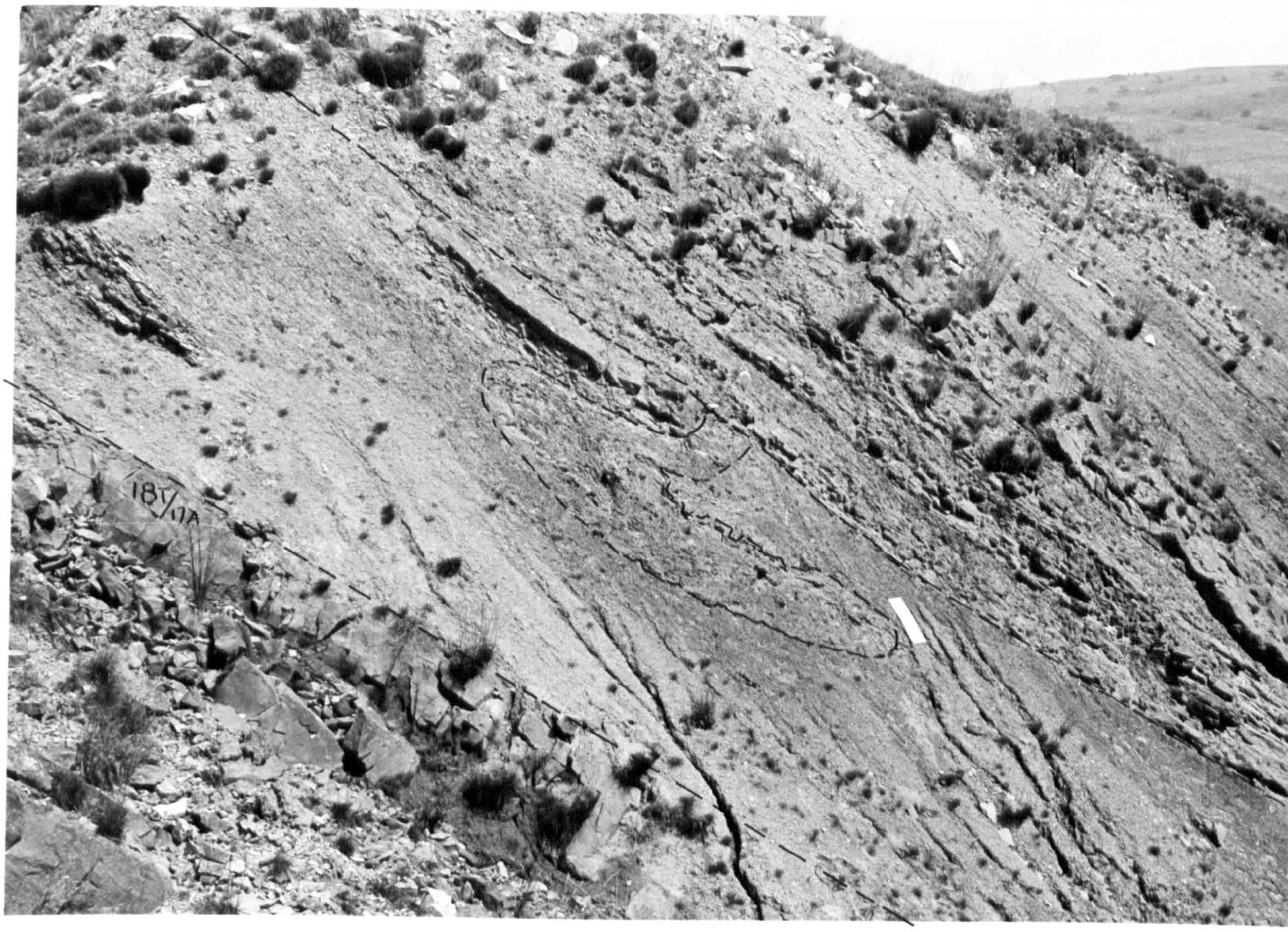
Evidence to suggest that the angular value of the palaeoslope steepened periodically in the Gawsworth area is thought to be indicated by the presence of Category III deformation structures. These structures, which were formed, in part by lateral movement, are present at at least two levels in the Gawsworth succession. The proximity of the Red Rock Fault Zone (Evans et al., 1968, pp.175-177) which delimits the western boundary of the area studied, may indicate that this feature was active during the deposition of Sublithofacies 6a sediments. It is suggested that the deformation structures present at Loc. 203 may have resulted from the establishment of conditions of instability which may have correlated with periods of tectonic activity affecting the adjacent Red Rock Fault Zone.

P.2.20.

Category IV deformation structures present at Loc. 204. Gawsworth. (Note book is 16 x 5 inches).

(See key, Fig.2.L., overpage).

P. 2. 20.



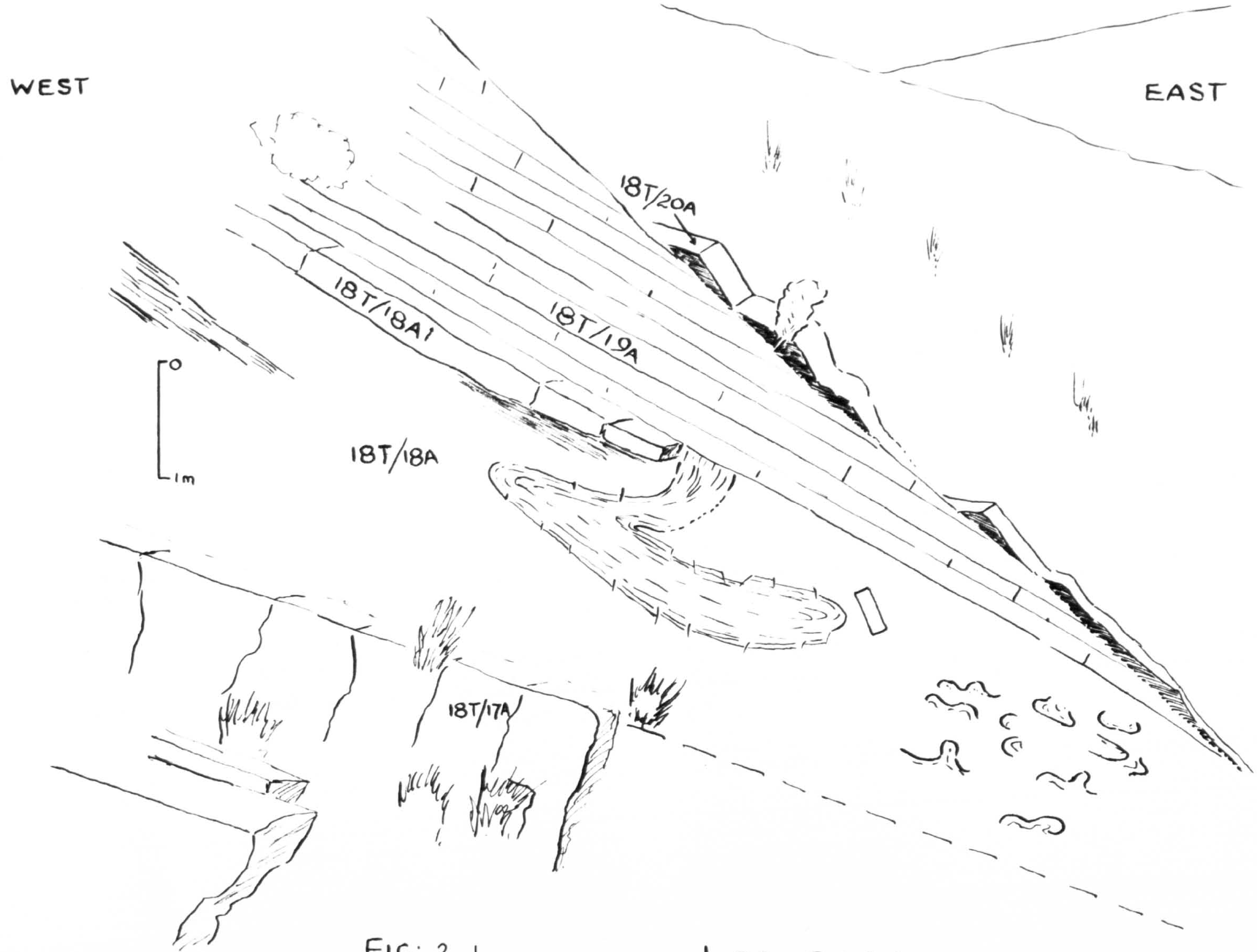


FIG: 2. L.

LOC. 204A

Key to P. 2.20.

Category IV

Description

A deformation structure in the form of a large recumbent fold is present in Sublithofacies 6a sediments at Loc. 204 in the Gawsworth Common succession, the structure is present in an interval designated 18T/18A (P.2.20, Fig.2.L.).

Bed 18T/17A occurs immediately below the deformed interval and is a laterally persistant medium coarse grained sandstone having a constant thickness of 0.90m. This bed has a sharp planar base and a sharp planar upper bedding plane surface. Internally the bed displays a size graded A.division and has previously been interpreted as a source proximal turbidite. The beds contained in the interval 18T/18A are only partly exposed, but are thought to have a predeformation character similar to the interval 18T/19A which is composed of a succession of thinly bedded fine grained sandstones and mudstones.

The maximum thickness of the interval 18T/18A is 1.40m, thinning down dip to circa 1.0m. Internally this interval contains evidence of a recumbent fold which can be traced for a minimum of 3m in the direction of the axial plane normal to the axis, and varies in thickness from 0.30 - 0.50m. The remnants of a second fold of a similar type are present above the recumbent fold, the limbs of this fold are truncated by bed 18T/19A. The fine grained thinly bedded sandstones present in the deformation structure within the interval 18T/18A are dislocated by small normal faults of throw less than 10 cms. The faults are present on the limbs of the fold and have a frequency of occurrence of one per 10-15 cms.

Bed 18T/18Ai is a coarse to medium grained sandstone the base of this bed is sharp and planar, the upper bedding plane is also sharp and planar, this bed which has previously been interpreted as a proximal turbidite, is truncated, on the down dip side, by a planar surface.

The interval 18T/19A is composed of a succession of thinly bedded fine grained sandstones intercalated with mudstones, this interval varies in thickness from 2.00m to 0.60m and is thought to thin further on the down dip side, the upper surface of this succession is truncated by bed 18T/20A. Bed 18T/20A is a medium to coarse grained sandstone which is laterally persistant and has a constant thickness of 0.60m. This bed has been previously interpreted as a proximal turbidite. The base of this bed is sharp and load cast and has a discordant relationship with the beds in the interval 18T/19A.

Interpretation

It is suggested that bed 18T/17A was deposited by a source proximal turbidity current and that the beds within the interval 18T/18A were deposited conformably on this bed.

Bed 18T/18Ai in part overlies the interval 18T/18A and it is suggested that this bed was once laterally persistant and that its abrupt lateral truncation has occurred post depositionally. The recumbent fold structure present in the interval 18T/18A is thought to be the product of plastic deformation of unconsolidated sediment, it is suggested that the deformation was initiated by the loading of the bed by the formerly continuous bed 18T/18Ai. The deformation is thought to have taken place on a palaeoslope and it is suggested that the present structure represents a large slide fold. The fold axis of the deformation structure is parallel to the upper bedding plane surface of the bed below and it is thought that movement took place along this surface which constituted a slope inclined to the south east. During this lateral movement a part of bed 18T/18Ai is thought to have been incorporated in the deforming sediment and has been removed down slope, and is now not exposed. The deformation appears to have been achieved when the majority of the beds were in a plastic state, since there is no evidence of liquid flow having occurred. The small faults present on the limbs of the folds are, it is suggested, the expression of the stress field that existed during the period of deformation, when the shear stress exceeded the cohesive strength of the unconsolidated sand in the structure.

Dott (1963) describes and figures deformational structures from the Green River Formation (Eocene) of Wyoming, which he terms, large-scale contorted stratification. These structures, which are similar in lithology and dimensions to those present at Loc. 204 are proposed by Dott to be the product of plastic flow on a palaeoslope.

In the case of the beds within the interval 18T/18A it appears most likely that the majority of deformation is due to the development of slide folds in a subaqueous environment, however the incoporation and transportation of a large portion of the overlying bed 18T/18Ai is thought to indicate that slumping played a part in the genesis of the deformation structure. The term slumping is employed here to indicate a movement along discrete shear planes which produces marked dislocations in unconsolidated sediments. It is suggested that such a dislocation occurred within beds 18T/18A and 18T/18Ai and preceded the development of the structures formed by plastic deformation. The truncated surface of bed 18T/18Ai is thought to represent the contact of this bed with a plane of slump failure.

Beds in the interval 18T/19A are the product of turbidity current deposition on the irregular surface which was produced by subaqueous sliding and slumping. The beds in this interval which have previously been described as current distal turbidites, vary in thickness from 2.00m probably to zero and are thought to have occupied an irregular hollow in the palaeo-seabed. The current which deposited these beds has eroded the deformed strata which is truncated by the beds forming the interval 18T/19A.

The beds in the interval 18T/19A are in turn overlain by bed 18T/20A which possesses the character of a source proximal turbidite, the base of this bed displays a sharp discordant contact with bed 18T/19A and is presumed to have eroded the sea bed in an area where the palaeoslope had become locally flattened as a result of subaqueous slumping and sliding.

The occurrence of the deformation structure at Loc. 204 is thought as with Category III deformation structures to indicate that sediments deposited here became periodically unstable. As has previously been suggested this instability may have been associated with tectonic activity along the Red Fault Belt. Morris (1971) describing deformation structures present in the Jackfork Flysch Rocks of the Upper Mississippian age which occur in the Ouachita Mountains of Arkansas suggests that in locations where disturbed bedding comprises the majority of the succession, such areas define the unstable margins of a flysch trough. Portions of the upper part of the succession in the Gawsworth Common area are characterised by the occurrence of beds which display features produced by subaqueous sliding and slumping and it is suggested that this area in upper Alportian times constituted an unstable marginal area of the North Staffordshire Basin.

FIG. 2.M. Lithofacies 7. Succession at Loc. 088 Ferny Hill

LITHOFACIES 7

Brief Diagnosis

Thickly bedded to thinly bedded coarse to fine grained sandstone, are intercalated with thinly bedded siltstones which occur infrequently in the succession. Coarser grained sediments typical of the thicker beds constitute the bulk of this Lithofacies from which mud sized sediment is absent. Burrowed structures and bioturbated beds are frequently present, body fossils are however absent.

Distribution

Beds in this Lithofacies are present on the north side of the Combes Valley at Ferny Hill, Loc. 088, here 11m of sediments are exposed on a cliff face forming the valley side (Fig.2.M.). The beds occur in the succession above the highest N. nuculum horizon, Loc. 081 and are considered to lie stratigraphically within the Middle Churnet Shales .

Field Characteristics

Within the limited exposure at Loc. 088, which is 10-15m wide the Lithofacies 7 beds are laterally persistant and the individual beds maintain a constant thickness throughout the exposure with one exception which is a medium grained sandstone bed of maximum thickness 0.12m which thins to zero in circa 1m. The beds present in the Ferny Hill succession indicate that a gradual upward coarsening of the sediments occurs in the unit representing this Lithofacies. The majority of the bedding planes are not sharply defined, whilst particularly within the coarser grained beds there is a tendancy to bed amalgamation.

External Structures

Load cast bases may be present where coarse grained thickly bedded sandstone overlie siltstones, the load structures are weakly developed, penetrating the finer sediment for only a few centimetres, in other cases planar lower bed boundaries occur. Upper bedding plane surfaces are commonly planar although two thinly bedded medium grained sandstones exhibit marked upper bedding planes, the ripples are small scale structures having a ripple length not exceeding 0.05m and are asymmetrical in shape. The ripple crests are orientated approximately north-south and the lee side is inclined towards the west. Tool marks are present on the base of some of the thickly bedded coarse grained sandstones, they are commonly of the prod mark type and in one instance only a groove mark was observed. The tool marks, which are not deeply incised, are aligned in an east-west to south-west - north east sector. Biogenic structures are of frequent occurrence and in some beds the whole of the lower bedding plane surface displays irregular branching grooves or isolated pits, both in the form of hypichnial casts. In one instance the upper bedding surface of a thick sandstone displays a trellised structure, composed of oxidised siderite, which resembles epichinal biogenic structures.

Internal Structures

Normal size grading of the individual beds was not observed in this Lithofacies, although one instance of inverse grading is present in a very thick bed which grades upwards from grit to conglomerate. Throughout the succession it is however possible to detect a general upward coarsening of the sediments together with a general increase in bed thickness.

The coarse grained sediments are frequently structureless throughout, although some beds display a thin upper zone of parallel lamination which is frequently defined by alternating coarse and finer laminae. In one bed a zone of parallel lamination is developed at the base and the interval above is structureless. Infrequently parallel lamination is developed throughout the whole thickness of the sandstone beds in this Lithofacies. The rare siltstone beds present, without exception, display parallel lamination, the lamination frequently consists of alternating laminae of sand and silt, whilst lenticular parallel laminated sand bodies may be present within the siltstone, similar laminations, termed lenticular laminations are described and figured by Coleman and Gagliano (1965, Fig.2., P.135) from the Mississippi deltaic plain deposits. Wavy lamination (Coleman and Gagliano, 1965, Fig.2., P.135) is present in some thin sandstones and passes upwards in one bed into ripple cross-lamination of the climbing ripple type Walker (1963), McKee (1965). Current ripple lamination is developed in two thinly bedded, medium to fine grained sandstones, these beds display a weak development of cross-lamination of the climbing ripple type. Carbonised plant debris is present in thin discrete layers in some of the medium to thickly bedded coarse grained structureless and parallel laminated beds. The plant layers are usually found at or near the base of the beds and some of the larger fragments can be identified as Calamites sp.

Sand filled endichnial burrows are present, and occur mainly in the thinly bedded sandstones, both vertical and lateral burrows occur, and in some of the thinner beds biogenic structures occur in such proliferation that the beds may be described as bioturbated.

Interpretation

The majority of the beds present in this Lithofacies are sandstones, mudstones are absent although beds of siltstone are present, but account for less than 5% of the succession.

The coarse grained thickly bedded sandstones which occur frequently in the upper parts of the succession at Loc. 088, are massive structureless beds and are interpreted as being deposited by currents possessing upper flow regime characteristics. In one instance a very thickly bedded coarse grained sandstone 16T/28, was observed to coarsen upwards to a conglomerate, and apart from this reversed grading, the bed appears to be structureless. The overlying thickly bedded coarse sandstone displays a load cast base and contains endichnial burrow structures, it is suggested that these two beds in conjunction represent varying rates of deposition and that a period of non-deposition separates the two. Bed 16T/39, a thickly bedded structureless coarse sandstone, displays a load cast base and overlies a siltstone, it is likewise thought that the junction of these two beds also represents a period of non-deposition and that bed 16T/39 was deposited by a more powerful current than bed 16T/38.

Marked variations in stream power are represented by variations in internal structure as illustrated by beds 16T/33, 16T/23, 16T/22, 16T/21 and 16T/13, all these beds are thickly bedded coarse grained sandstones which possess a massive structureless base passing upwards into an interval of parallel lamination. The laminated interval is usually finer grained than the structureless part of the bed, and comprises 20% or less of the total bed thickness. Beds of this type are thought to represent a rapidly waning current and in the case of beds 16T/13 and 16T/33, and their overlying thinly bedded siltstones, current power is thought to have decreased to the point where the finer material in suspension was deposited. The parallel lamination present in the thickly bedded coarse grain sandstones 16T/21 and 16T/22 is much coarser than that previously described, the coarser laminae being represented by grit (granule) sized particles. It is suggested that this structure is due to hydraulic sorting prior to deposition possibly in association with a large scale bed form of which there is now no evidence. It is thought possible that in an extensive exposure this type of parallel lamination could be interpreted as low angled planar cross-bedding and that in this exposure only the intersection of the bottom-sets and the cliff face give rise to a structure which can only be interpreted as lamination lying parallel to the bedding plane surface.

Parallel lamination occurring throughout the bed is a feature of many of the finer grained thinly bedded sandstones and the siltstones, The sandstones show alternating coarser and finer laminae which may be associated with thin layers of plant fragments, the laminae in the siltstones take the form of alternating laminations of silt and fine sand. This second type of parallel lamination is thought to have been formed by settling of sediment from suspension in a low hydrodynamic energy environment which was subject to slight changes in current velocity. Similar laminae are described by Coleman and Gagliano (1965), from the Mississippi Delta, they suggest that parallel lamination of this type was present in all the environments represented in this delta.

The association of parallel lamination passing upwards into wavy lamination which in turn grades upwards into current ripple lamination is seen in beds 16T/5 and 16T/6. The parallel lamination is present in a thinly bedded fine to medium grained sandstone, and in bed 16T/6, which is of similar lithology and thickness, the laminae becomes undulose or wavy. Coleman and Gagliano (1965), suggest that the wavy appearance of such laminae is due to the presence of minor irregularities and obstructions on the depositional surface. However, in bed 16T/6 the wavy lamination passes upwards into a zone of current ripple lamination which suggests that increasing stream power is responsible for the structures present and that the wavy lamination is an intermediate stage between the fine parallel and the current ripple lamination.

Current ripple lamination is also present in beds 16T/9 and 16T/12, both thinly bedded fine to medium grained sandstones, current ripples of this type are characteristic of lower flow regime conditions (Simons and Richardson, 1961), and their occurrence throughout these beds suggests uniform current conditions during their period of deposition. Both the current rippled beds are overlain by medium to thickly bedded beds of coarser lithology which possess an upper zone of parallel lamination of the coarser type. It is thought that these coarser grained beds overlying the current ripple laminated beds are the product of a higher stream power than the current ripple laminated beds and that the two in conjunction indicated raplidly varying current velocities.

A primary sedimentary structure present in some of the siltstone beds is lenticular lamination (Coleman and Gagliano, 1965), which consists of thin laminae of fine laminated sandstone, which taper to zero in circa 10 cms, contained in thinly bedded siltstone. Coleman and Gagliano (1965), interpret beds of this type of lithology as being due to the presence of impoverished current ripples occurring at the silt water interface, into which coarser material was concentrated by the oscillatory motion of waves, and this was then covered by an influx of finer sediment from suspension. In the Lithofacies 7 sediments the lenticular sandstone bodies may show parallel lamination, and it is suggested that these structures are

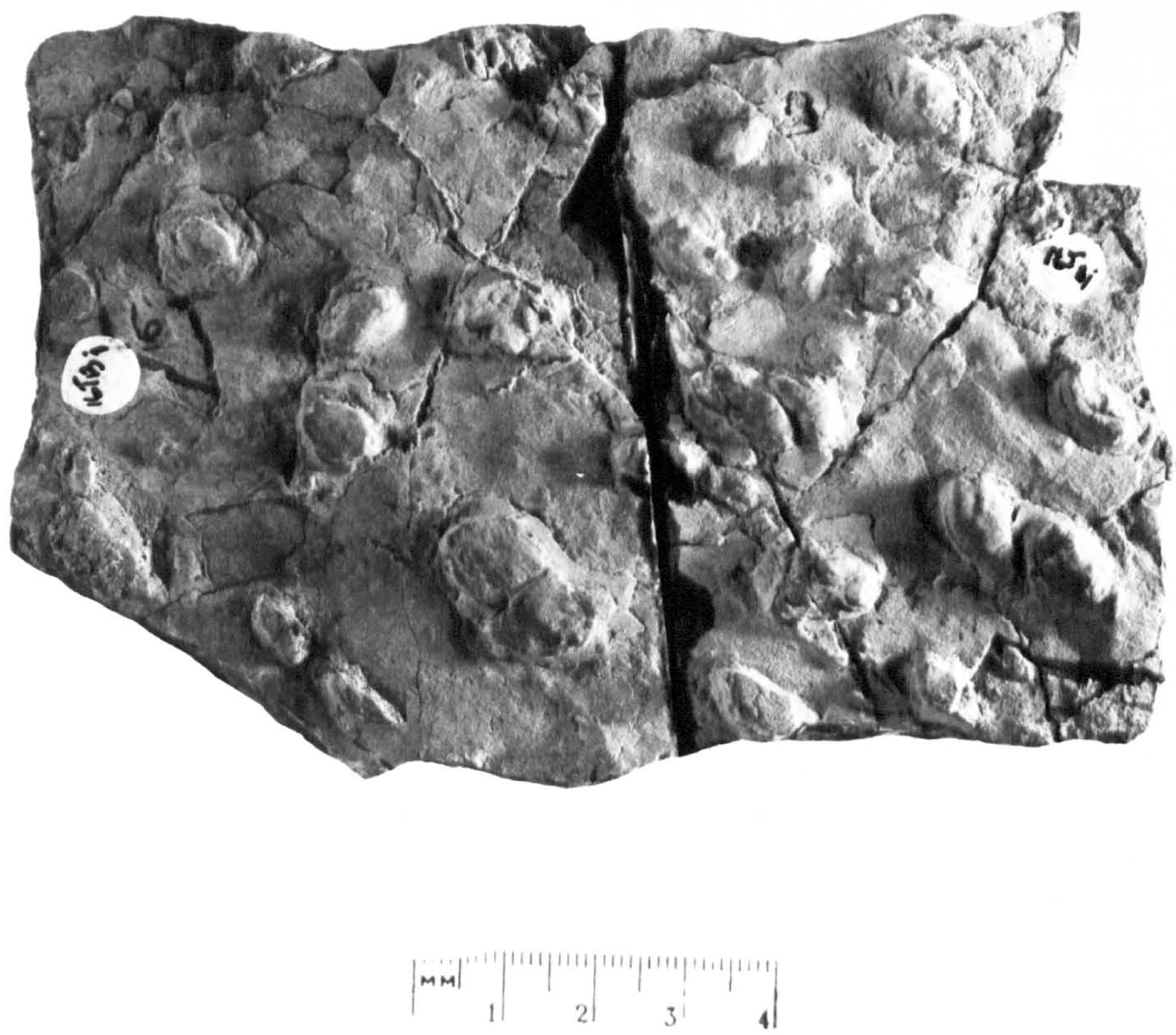
P.2.21a.

Base of a Lithofacies 7 sandstone bed 16T/Bi oval hypichnial casts.

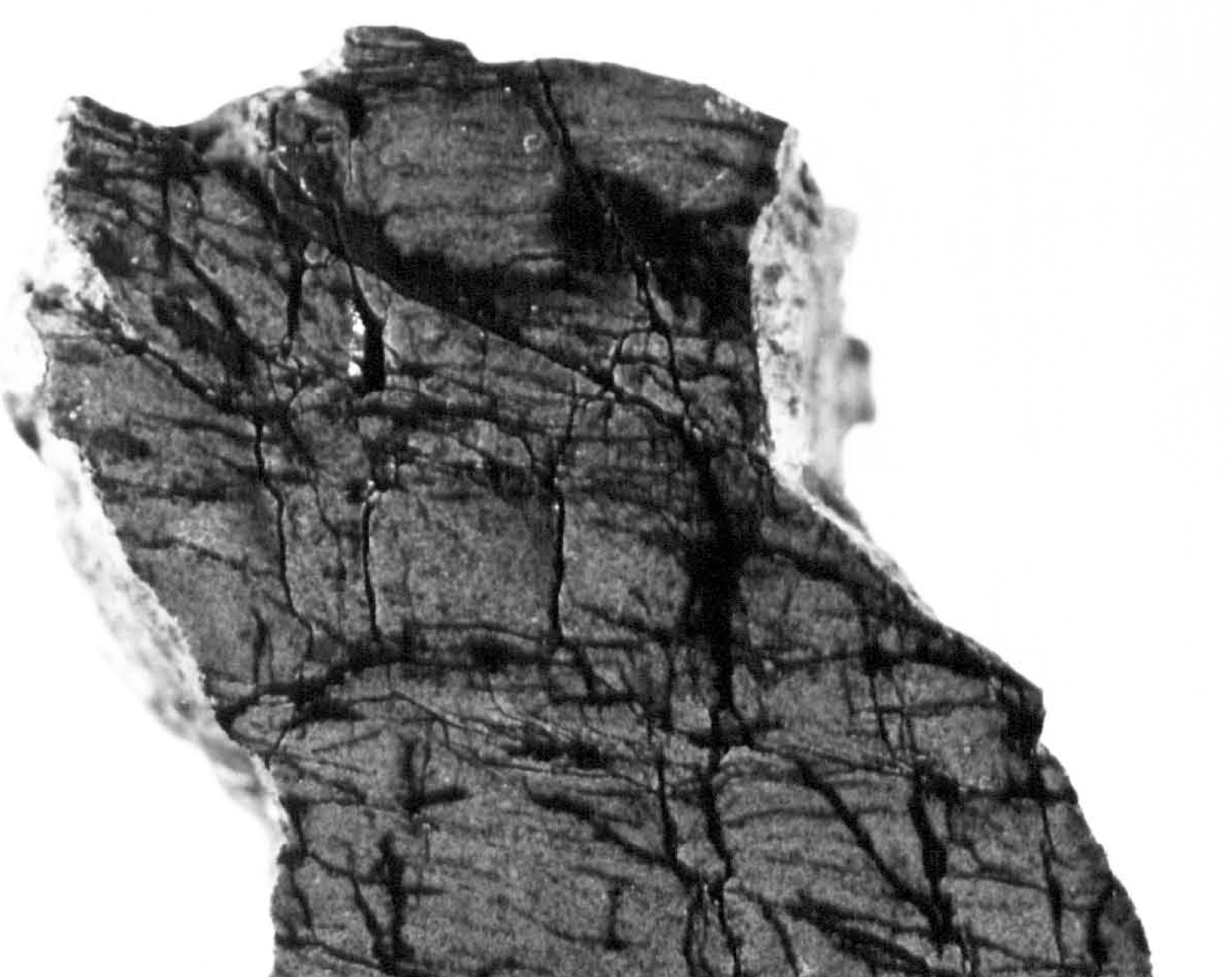
Loc. 088. Ferny Hill.

P.2.21b.

Internal structure of bed 16T/Bi.



P. 2. 21a.



P. 2. 21b.

the relic of a more continuous layer of fine laminated sand which had accumulated on an irregular silt surface, and that erosion by weak bottom currents removed all but the small amount occupying the weakly developed depression, this was later blanketed by silt and preserved in its lenticular form. The presence of such structures must be taken as a further indication of the variable current velocities which obtained during the genesis of the sediments in this Lithofacies.

Thin layers of plant debris are present mainly at the base of the thinly to medium bedded sandstones, the plants are of the Calamite type and are thought to have accumulated in a waterlogged state in relatively still water and were then buried by a sudden influx of sandy sediment. In one bed only 16T/20, a thickly bedded coarse grained sandstone, plant debris is concentrated in a thin layer within the bed, and in this case is thought to have been deposited as water-logged debris from suspension, in favourable hydrodynamic conditions, or to have accumulated in the lee of a large bed form and later formed an avalanche deposit in the manner of foreset laminae.

Trace fossils present in this Lithofacies take the form of endogenetic burrow structures and are restricted in occurrence to the sandstone beds. The burrows are of two broad types, vertical endichnial sand filled burrows which traverse thinly bedded sandstone beds and are commonly represented on the lower bedding plane by oval hypichnial casts. Burrows of this type also occur in some of the thicker sandstone beds but have not been observed to completely traverse the bed, they are confined to the lower part of the bed (P.2.21a and b). The second type of burrow can be termed a horizontal endichnial burrow and lies parallel to the bedding surface, near or at the lower bedding plane. The horizontal type of burrow structure occurs throughout some of the thinly bedded sandstones and produces a bioturbation of the internal structure in these beds, burrows of this type are interpreted as feeding burrows (Seilacher, 1964), and may indicate a period of non-deposition of sediment. A second type of horizontal endogenetic burrow structure was observed at the base of a thickly bedded coarse sandstone, bed 16T/33. This bed, which overlies a siltstone, displays a bioturbated lower bedding plane which appears to have been produced by the extensive development of horizontal burrow structures near or at the upper surface of the underlying siltstone, these burrows are interpreted as being of the Fodichnia type. During the subsequent deposition of the coarse sandstone the burrows were either unroofed or they collapsed and in either case were infilled with sand, thus producing numerous hypichnial casts.

It is proposed that the extensive development of the sand filled burrow structures present on the base of bed 16T/33 are indicative of an environment in which the accumulation of sediment was not a continuous process. Whilst the vertical endichnial burrow structures present in the thicker beds which, unlike those present in the thinner beds, did not completely traverse the bed, are thought to indicate a rate of deposition of sediment which was rapid enough to entomb the burrowing organism and prevented it from reaching its next feeding level.

Reviewing the evidence provided by the beds in this Lithofacies the salient features to emerge concerning their genesis are, that the accumulation of sediment was not a continuous process, the rate of deposition of sediment varied from slow deposition to rapid deposition of the coarser fraction. Whilst the internal structure and particle size indicate that some beds formed in upper flow regime conditions and are present in the succession in juxtaposition with beds which exhibit lower flow regime characteristics. The environment of deposition capable of producing the sequence of beds and structures exhibited by Lithofacies 7 sediments is thought to be a fluvial environment in which periods of low and high hydrodynamic current energy obtained. The periods of low current energy would account for the deposition of the silt and fine sand and the accumulation of waterlogged plant debris, it is also suggested that biogenic activity was at a maximum in these conditions. Whilst the period when higher energy values obtained are represented by the accumulation of sediments in both upper and lower flow regime conditions. Fluctuating condition of this type may reflect periods of variable hydraulic discharge, or may be the product of variations in the main current vector. In either case it is considered that Lithofacies 7 sediments were deposited in an environment marginal to the main stream flow either in an overbank situation or in a part of the river system which periodically was subject to 'slack' water conditions. In the second instance it is proposed that such an environment could be represented by a minor channel in a braided river system, in which coarse sediment was deposited as massive beds in periods when high discharge rates obtained within the river system. Whilst in periods of low discharge fine sediment would be winowed off to be deposited in the 'slack' water of this minor channel, similarly drifted plant material would tend to accumulate in this environment and would eventually become water saturated and sink. The occurrence of plant material, concentrated at the base of the coarse sandstone beds can thus be readily explained as being the product of deposition of coarse sand onto the water saturated plant layer during a period of higher discharge. The absence of internal structure within the sandstone beds, can also be explained in this situation and is thought to be due to a rapid check of current velocity, when the mass of water transporting the sand encountered the body of 'slack' water present in the channel. Under these conditions it is assumed that the sand was deposited too rapidly for any significant grading or internal bed structure to form. A similar mechanism for the formation of structureless non-graded beds has been attributed to the 'freezing' of land proximal turbidity currents (Walker, 1964), and it is suggested that during periods of high discharge that a sediment laden water-mass suddenly encountering a body of 'slack' water would locally produce deposits of a "proximal turbidite type".

The general character of the succession of Lithofacies 7 sediments at Loc. 088, is that of an upward coarsening sequence, together with a general increase in bed thickness in the upper parts of the succession. It is suggested that these characteristics indicate a more frequent occurrence of higher discharge rates, or what is more likely a variation in the flow pattern, within the braided river system such that the area of deposition represented by the sediments at Loc. 088 became increasingly proximal to a major stream path. Blatt, Middleton and Murray (1972), suggest that the infilling of a channel in a braided river system is represented by a coarsening upwards sequence which it is suggested is the response to increasing current activity. Coleman (1969), describing channel processes in the braided course of the Brahmaputra River indicates that channel migration within the main-stream banks occurs frequently and that the position of the main current causes the river course to constantly vary its position. It is thought probable that the deposition and lithological character of Lithofacies 7 beds was controlled by current migration within a braided river system and was also influenced by variable hydraulic discharge. However, in the absence of major bed-form structures from this Lithofacies it is envisaged that the genesis of the beds present at Loc. 088 occurred at all times in an environment distal to the main stream course or major channel location of the proposed braided river system.

The coarse nature of the sediments comprising Lithofacies 7 is thought to indicate that the formative river system possessed those characteristics, particularly that of high current energy, attributed to a braided river system by Allen (1970). In addition the absence of mud from the succession at Loc. 088 is taken as evidence that a high level of current energy obtained throughout the period of deposition of these beds. Allen (1970) suggests that the deposits of a braided river system rarely contain mud or silt and if present occur in thin beds, as is the case in this Lithofacies.

An alternative mode of origin previously proposed for Lithofacies 7 sediments was that they were formed in an over bank environment, that is either as levee or crevasse-splay deposits associated with a meandering river.

Allen (1964, 1970) describes levee deposits as consisting of a vertical alternation of thinly bedded fine sands, silts and clays. He further suggests that a vertical grading from coarse up to fine, combined with a sharp base and a gradational top, is characteristic of the sand layers deposited in levees. Clearly the absence of mud and fine repetitive bedding from Lithofacies 7 sediments precludes their formation from within an overbank environment such as that afforded by a levee structure.

The sediments associated with a crevasse-splay structure have at first sight more in common with Lithofacies 7 sediments than the deposits forming levee structures. Allen (1970), suggests that crevasse-splay deposits are coarser than those of levees and that the sediments commonly consist of sand. Bed thicknesses are also appreciably greater in this type of overbank deposit. Stanley (1968) describes Carboniferous 'flood deposits' from Eastern Massachusetts, which possess many similarities to the crevasse-splay deposits as described by

Allen (1970). Stanley suggests that these 'flood deposits' are the product of a sudden release of sediment laden water from the confines of a river channel, and that following the release of water there is a rapid fall in current energy, this produces sharp based graded sandstone beds, which as with the crevasse-splay deposits described by Allen (1970), possess channelled bases and other scour structures, commonly in the form of flutes. The rapidly waning current produces a fining upwards sequence and silt followed by mud is then deposited, finally plants may colonise the upper surface of such a deposit. The succession as described above is repeated at successive periods of high water,and thus the character of the deposit becomes cyclic provided that the original crevasse in the river bank is taken as the point of release of sediment laden water in successive flood episodes. Significant differences in the character of the crevasse-splay deposits and Lithofacies 7 sediments exist, the main ones being the presence of cyclic upwards fining sequences in the overbank deposits, and the presence of the mud fraction. It is proposed by Allen (1970), that the mud content of a crevasse-splay deposit sequence may not be present in the form of a continuous bed as described by Stanley (1968), but may be present incorporated in the arenaceous part of the sequence as mud pebbles and larger clasts referred to as blocks. In this case it is assumed that the mud layer of the previous cycle has been eroded by the successive rapid release of flood water. The character of this type of overbank deposit now exhibits a closer similarity to the Lithofacies 7 sediments. However, distinct difference still occur in that scour structures and incorporated mud and silt clasts are not a feature of the Lithofacies 7 sediments, and despite erosion, cyclic fining upwards sequences are still considered to be characteristic of crevasse-splay deposits.

Due to the restricted exposure of Lithofacies 7 sediments at Loc. 088, evidence to indicate that they were formed within a fluvial environment is limited and it is acknowledged that the evidence present may be subject to a different interpretation than that suggested. Therefore, in this instance the writer is forced to utilise the field relationship between this Lithofacies and Lithofacies 5. The proximity of the two in the field, Lithofacies 5 sediments pass laterally into Lithofacies 7 sediments (a break of circa 20m is present on strike), is thought to indicate that the Lithofacies 7 sediments are the product of the same fluvial regime that produced the Lithofacies 5 sediments, whose coarse grained cross-bedded sandstones and conglomerates have been interpreted as being deposits formed within the active part of a braided river system.

In conclusion, the weight of evidence appears to indicate that Lithofacies 7 sediments are deposits that were formed within the environment of a braided river system and that in particular they may represent the gradual infilling of a minor channel or partially cut-off channel within this river system.

LITHOFACIES 8

Brief Diagnosis

Thinly bedded grey to black pelitic sediments compose the bulk of this Lithofacies and particles above silt size are characteristically absent from the sediments.

Apart from the frequent bedding or fissility the beds in this Lithofacies appear to be structureless. Biogenic structures are absent and body fossils are extremely rare except in those parts of the succession associated with faunal horizons.

Two Sublithofacies are recognised on the basis of the occurrence of silt sized particles within the pelites.

SUBLITHOFACIES 8a

Distribution

Beds of Sublithofacies 8a type form the bulk of the succession in the following sections; Fairthorn Farm, Thirklow and Swallow Brook, they are also present in the Wiggenstall, Blake and Oakenclough Stream Sections.

Characteristics

The sediments occurring in this Sublithofacies are characteristically black or dark blue grey in colour. They may be fissile, splitting easily into thin layers, or tough and blocky exhibiting no preferred planes of parting. Isolated pyrite cubes or blobs may occur, or pyrite may be finely disseminated in the sediment. Yellow jarosite may be present on parting planes and is commonly associated with the occurrence of body fossils in these sediments.

Interpretation

The fine grain size and the absence of current formed structures are thought to imply that the sediments in this Sublithofacies are the product of the settling of sediment from suspension in areas of minimal current activity. The fissile nature of some of the sediments is probably accentuated by the absence of bioturbation and it is suggested that in the absence of burrowing forms the sediment accumulated in a stagnant environment. The stagnant nature of the area of deposition of the sediments is further attested to by the presence of pyrite, which it is suggested has been formed in a reducing environment by the reaction of hydrogen sulphide, a product of the bacterial decomposition of sulphur compounds (Love, 1958), with iron to produce a hydrotroilite gel which later crystallised as Pyrite, a process which is also known to occur in modern black muds (Berner, 1970).

The black colour of some pelitic sediments may be attributed to a high carbon content (Blatt, Middleton and Murray, 1972) and it suggested that in oxygenated waters complete decomposition of organic material would occur, whilst in waters where the dissolved oxygen content approaches zero organic matter is able to accumulate. In the subsequent diagenesis of this type of sediment, Degens (1967) indicates that complex organic compounds including kerogens and hydrocarbons, which are produced partly by bacterial processes and partly by the physico-chemical processes associated with diagenesis, produce a darkening of the sediment.

It is suggested that the black colour of the Sublithofacies 8a sediments is due to the incorporation of a significant amount of organic carbon into the accumulating mud. Gehman (1962), indicates that the organic residue in mudrocks varies from a minimum of 1% to a maximum of 33.5%. It is also presumed that the accumulation of these sediments took place in an oxygen poor environment in which water circulation was minimal, as is evidenced by the lack of coarse detrital sediment and the absence of current structures in this Sublithofacies.

A blocky, non-fissile nature may be characteristic of Sublithofacies 8a sediments in those parts of the succession associated with faunal bands, and is thought to be due to the presence of a weak carbonate cement which in some cases may react with dilute Hcl producing a non-coherent muddy surface on specimens treated in this manner and in this case calcite would appear to be the dominant carbonate. It is suggested that the carbonate is either an early diagenic product derived from the complete or partial destruction of shells accumulating in the faunal band, or is a product of direct chemical precipitation from sea water.

SUBLITHOFACIES 8b

Distribution

Sediments of this type are characteristic of much of the succession in the Bent End, Hurdlow, Combes Brook, Heath Hay and Dingle Brook sections, they are also recognised in portions of the "Middle Churnet Shales" exposed in the Astbury area.

Characteristics

The beds are grey to blue grey in colour and although commonly thinly bedded they are rarely fissile. Examination with a hand lens reveals the presence of silt sized particles and small mica flakes and the rock has a 'gritty' feel when chewed. Organic material in the form of poorly preserved plant debris is present but of infrequent occurrences. Siderite nodules or thin non-continuous bands of siderite may be present, and may contain organic remains.

Interpretation

The fine grained nature of the sediment and the lack of any current induced structures suggests that the Sublithofacies 8b sediments accumulated by fall out from suspension as slow moving currents gradually decelerated. The slightly coarser nature of these sediments than that of the Sublithofacies 8a sediments may suggest that they are less source distal than the latter.

The absence of black colouration is thought to be due to the decomposition and comminution of organic material in waters containing dissolved oxygen. The presence of oxygen implies circulation of water in which it is suggested that some of the finely comminuted organic material may have been transported in suspension to accumulate later in stagnant areas.

Isolated organic remains are present, these take the form of relatively large carbonised plant fragments which commonly display poor preservation, and are thought to have floated into the area and on becoming waterlogged sank and were incorporated in the accumulating silt and clay sized particles.

Siderite nodules and bands present in this Sublithofacies are thought to be the product of early diagenic chemical reactions, possibly triggered off by bacterial activity associated with the decomposition of organic remains, since both plant and animal remains have been observed forming the nucleus of the siderite nodules. Curtis (1967), discussing the origin of diagenetic minerals in argillaceous sediments of Westphalian age, suggests that siderites are formed in unconsolidated muds partly by the chemical breakdown of the iron bearing clay minerals which combine with the Co_2 in the pore water, and partly by the association of ferric hydroxides and Co_2. The former being either transported and deposited with the clay minerals or occurring as direct precipitates from the depositional waters.

Curtis also suggests that the chemical environment conducive to the formation of diagenetic pyrite is unsuitable for the formation of siderite and further that the two were not found in association in the Westphalian sediments he investigated.

The presence of pyrite implies genesis of sediment in a stagnant environment (see Sublithofacies 8a) and its non-occurrence with siderite suggests that the latter may have formed in more oxygenated waters.

The absence of siderite from the black fissile mudstones, characteristically formed in a stagnant oxygen poor environment, further points to the association of free oxygen with the diagenetic growth of siderite. Trewin and Holdsworth (1973) indicated that the fixation of iron as siderite may be favoured by the suppression of biogenic sulphide activity due to a reduction of salinity. This would probably take place in localities where supplies of fresh oxygenated water were being introduced into the areas of deposition of Sublithofacies 8b sediments. On the basis of the proposed palaegeographical evidence regarding the distribution of siderites in Sublithofacies 8b sediments, the writer concurs with the findings of Trewin and Holdsworth (1973) who indicate that the appearance of siderites in the interval E_1a to E_2b_1 in the North Staffordshire Basin is associated with periodic influxes of oxygenated water from the southern, terrestrial-deltaic terrain.