Carboniferous quartz arenites and ganisters of the Northern Pennines.

Percival, C J.

CARBONIFEROUS QUARTZ ARENITES AND GANISTERS OF THE NORTHERN PENNINES

by

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View northwards from Harthope Head, showing the Harthope Ganister and overlying strata up to the base of the Upper Felltop Limestone in Harthope Head Quarry.

Frontispiece

ABSTRACT

The Carboniferous succession of the Northern Pennines contains a wide variety of texturally and mineralogically mature quartz arenites. These occur interbedded with less mature sandstones, shales and limestones and are common in strata of Brigantian to Westphalian A age.

The majority of these quartz arenites appear to have achieved their mature, stable mineralogy by reworking of less mature fluvial and deltaic sands in high energy shallow-marine to shoreline environments. These quartz arenites are up to approximately 18m. thick, and are particularly common in Brigantian and Namurian E_1 and E_2 deposits on the Alston Block. This suggests that during this period sediment supply and subsidence on the Alston Block was often sufficiently low to enable reworking to take place in the shallow-marine to shoreline environments that commonly existed. Preserved sedimentary structures and stratification sequences suggest that the quartz arenites principally formed in barrier island, beach and storm-dominated shallow-marine environments.

The remaining quartz arenites are generally <1 m. thick, irregularly based deposits penetrated by rootlets. They are common in the lowermost Westphalian A strata, and appear to have formed pedogenically by the breakdown of unstable mineral grains and downward mechanical eluviation of clays and other alteration products. These deposits represent the fossilized A_2-horizon of podzols and podzolic soils. Quartz arenites formed in this manner which contain >95% quartz constitute the true ganisters.

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Finally, I would like to express my sincere thanks to my girl friend Kate, who has helped me in innumerable ways during the course of this research, and by now probably knows more about quartz arenites and ganisters than she would like to.

PREFACE

A number of horizons in the Carboniferous succession of the Northern Pennines have been termed 'ganister', due in many cases to their ability to be used as the raw material for the manufacture of refractory bricks. The majority of these horizons are quartz arenites. These have not been the subject of previous research, and as a result a study of them was undertaken during the period September 1978 to October 1981. The original aims were to evaluate the stratigraphic setting, depositional environment and diagenetic histories of the Carboniferous 'ganisters' of the Northern Pennines.

Initially all horizons which had been termed 'ganister' or worked for 'ganister' were examined. From these only those which are sufficiently well exposed to enable detailed analysis were selected for further study; several well exposed quartz arenites which had not been worked for 'ganister' mainly due to their inaccessible location were also included. It became apparent early during the research that a definition of the term ganister was necessary. As a result a limited study was undertaken on the Carboniferous ganisters of the Sheffield region, as it was in this area that the term was first applied.

The bulk of the research has, however, been concentrated on the deposits of the Northern Pennines, particularly those of the Alston Block. The latter area is within easy driving distance of Durham City, which has therefore been the base for most of the fieldwork undertaken. Bad weather in the Northern Pennines has hindered fieldwork, but, nevertheless, a sufficient amount has been done to enable the original aims to be achieved.

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November 1981

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EXPLANATION OF SYMBOLS USED IN TEXT FIGURES

BED CONTACTS

— = Sharp

---- = Transitional

= Erosive/irregular

= Undulating/knobbly"

SEDIMENTARY STRUCTURES

= Trough cross-bedding

/// or = Planar cross-bedding

= Low angle bedding

= Hummocky cross-stratification

= Current ripple cross-lamination

= Wave ripple cross-lamination

= Trough cross-lamination

= Parallel lamination

= Low angle lamination

= Convolute lamination

= Undulating lamination

= Bioturbation

= Star-shaped traces

U = U-shaped burrows

FOSSILS

= Goniatites

= Marine bivalves

= Non-marine bivalves

= Brachiopods

= Ostracods

= Corals

= Bryozoa

= Crinoid ossicles

ɾ = Fish debris

ʎ = Roots and rootlets

= Wood/plant debris

LITHOLOGIES (unless otherwise stated)

■ = Coal

= Sandstone

□ or = Clay/shale

= Limestone

-M- = Marine Band

CLAST LITHOLOGIES

= Intraformational shale clasts

= Vein quartz pebbles

DIAGENETIC AND PEDOGENIC FEATURES

⌒ = Ripple-like structures

● = Siderite nodules

DECLARATION

The content of this thesis is the original work of the author (other people's work where included is acknowledged by reference). It has not been previously submitted for a degree at this or any other university.

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CHAPTER ONE

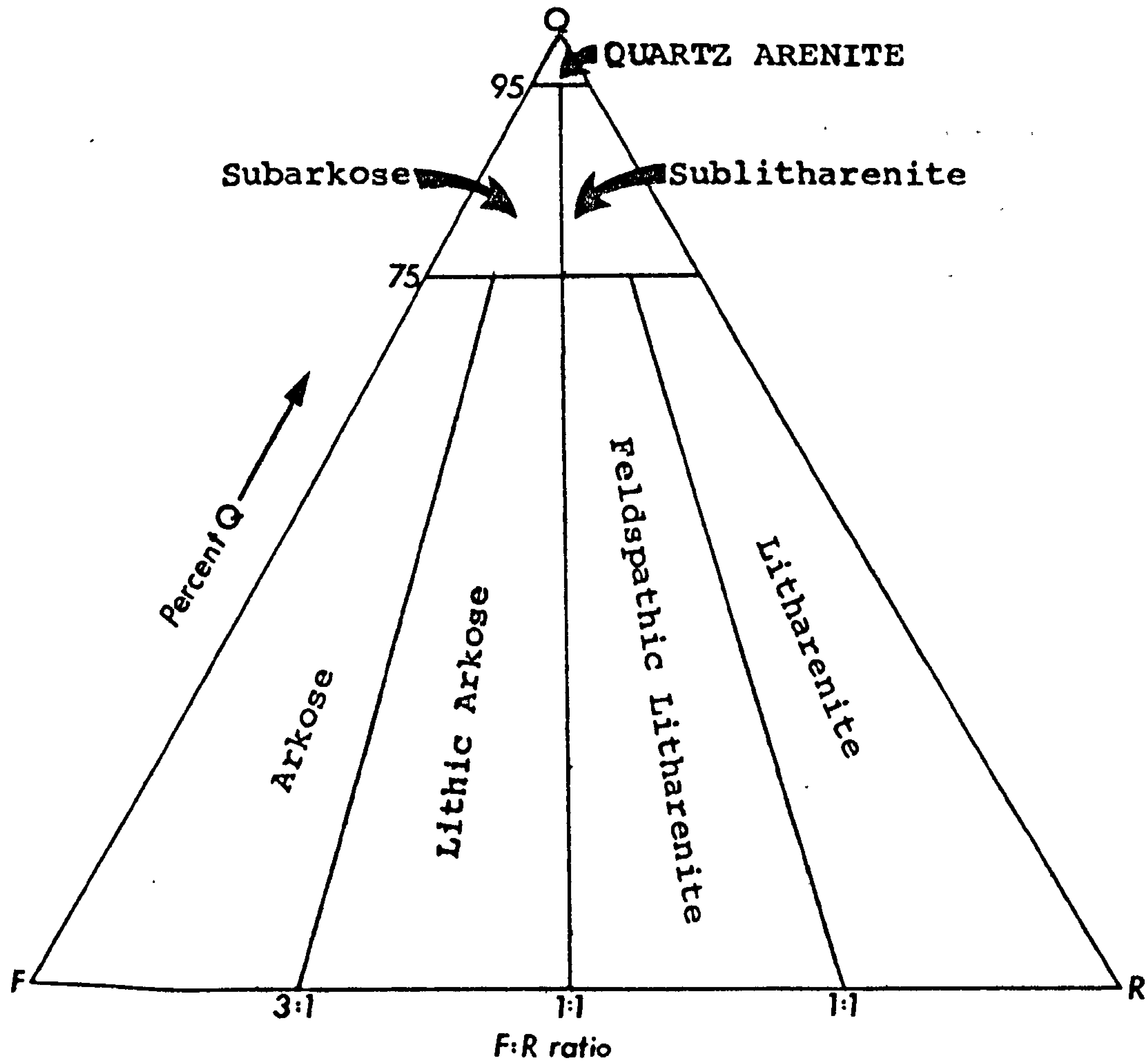
INTRODUCTION

A. Origin and definition of the terms quartz arenite and ganister

The term quartz arenite was first introduced into the geological literature by Gilbert (1954). It replaced the term orthoquartzite (Folk, 1954; Pettijohn, 1954) which was unsatisfactory due to its easy confusion with quartzite (a hard, compact, highly quartzose sedimentary or metamorphic rock which breaks through the grain).

As originally defined by Gilbert (1954) a quartz arenite is a sandstone in which 80% or more of the detrital grains consist of quartz, chert and quartzite. Subsequently several different workers have redefined the term, and as a result a slight variability in its usage exists (McBride, 1963; Chen, 1968; Folk, 1974). Folk's (1974) definition is commonly used where an arenite is a sandstone containing <10% fine grained matrix, and a quartz arenite has a framework grain composition of >95% quartz and quartzite, and <5% feldspar and lithic rock fragments, (Fig.1). Chert grains are no longer incorporated with quartz and quartzite, and are instead treated as rock fragments. Thus, the term quartz arenite is fairly rigidly defined and can be used in a meaningful way.

Contrary to this, the origins of the term ganister are obscure and a clear definition seems never to have existed, resulting in rocks varying widely in character and lithology being called ganister. The term arose in Yorkshire and Derbyshire, particularly in the Sheffield



Classification of the arenites (less than 10% clay matrix) after Folk (1974).

Q Pole: All types of quartz including metaquartzite (but not chert).

F Pole: All single feldspars (K or NaCa), plus granite and gneiss fragments.

R Pole: All other rock fragments: chert, slate, schist, volcanics, limestone, sandstone, shale, etc.

Further subdivision of the Sublitharenite, Litharenite, or Feldspathic Litharenite can be made depending on the proportions of sedimentary, volcanic, or metamorphic rock fragments.

Fig. 1

region, as a local miners' and quarrymen's term for a rock commonly employed as roadstone (Thomas, Hallimond and Radley, 1918; Strahan, 1920). It was applied with absolute precision to highly siliceous rocks occurring in the Lower Coal Measures which possessed definite physical characteristics of fine grain size, good sorting, angular grains, silica cementation and a splintery to subconchoidal fracture (Thomas *et al*, 1918).

The development of the steel industry in the Sheffield region led to a search for rocks suitable as refractories to line the furnaces and coking ovens. Ganisters were ideal for this purpose due to their physical and chemical properties. A sandstone lying beneath the Halifax Hard Mine or Alton Coal (Westphalian A; Ramsbottom *et al*, 1978) provided particularly excellent material for refractory bricks and was extensively worked. Due to its widespread extraction it became known as the Sheffield Ganister, or Sheffield Blue Ganister, on account of its colouration. This horizon became the 'type' ganister (Searle, 1917; Strahan, 1920).

The growth of the steel industry in other regions of Britain led to a search for sandstones with similar refractory properties to the Sheffield Blue Ganister. Many of these were called ganisters and the term became something of a trade name (Thomas *et al*, 1918).

It seems appropriate that any definition of the term ganister should be based on the properties and origins of the Sheffield Blue Ganister. Many definitions have been proposed (Lebour, 1886; Searle, 1917; Thomas *et al*, 1918;

Strahan, 1920; Williams, Turner and Gilbert, 1954; Williamson, 1967), but none seems sufficiently precise to be universally acceptable. All these authors agree that a ganister is a fine, even grained, highly siliceous sandstone consisting of closely packed, subangular quartz grains cemented by silica. It is also concluded that they occur commonly as the seatearth below a coal seam and often contain abundant carbonaceous traces of rootlets (hence the name pencil ganister).

Strahan (1920), having defined the term, does not include all rocks with the necessary characteristics as ganisters, but implies that only those siliceous sandstones formed as palaeosols are true ganisters. Subsequently several workers (Searle, 1940; Huddle and Patterson, 1961; Hemingway, 1968; Retallack, 1976, 1977) have concluded that ganisters form by silica enrichment during pedogenesis, and the term has attained genetic significance.

Recent studies of the Sheffield Blue Ganister have shown this horizon also has a pedogenic origin (Chapter Two, p. 38; Pearson, 1973, 1979; Ashby and Pearson, 1979; Curtis, Lipshie, Oertel and Pearson, 1980). Thus a new definition of ganister is proposed which takes into account physical properties, mode of origin and economic use. This is based mainly upon the fundamental characteristics of the 'type' Sheffield Blue Ganister.

"A ganister is a hard, compact very fine to medium grained quartz arenite, cemented by authigenic silica dominantly as overgrowths, formed by silica enrichment of a less mature parent material[1] in a palaeosol. Such horizons contain the necessary physical and chemical characteristics[2] to be used as the raw material in the production of siliceous refractories".

The lack of abundant cherty, cryptocrystalline or opaline silica cement, the fine to medium grain size and moderately well sorted, grain supported fabric, and the lack of evidence of near surface cementation differentiates ganisters from most types of silcrete (Williamson, 1957; Smale, 1973; Watts, 1978; Summerfield, 1979; Summerfield and Whalley, 1980). Silcretes are silicified surficial sediments (Lamplugh, 1902, 1907; Taylor and Smith, 1975) which are divisible into 5 distinct groups on the basis of texture (Smale, 1973):

(1) Terrazzo type

This is the commonest type and consists of a framework of quartz grains of widely varying shape and roundness which form about 60% of the rock. Many grains are irregular in

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1. The parent material should contain $<$ 95% quartz.

2. This requires a minimum of 97.5% SiO_2 (excluding carbonaceous material from the total percentage), (K. Pirt, pers.comm.). In thin section the rock should therefore contain at least 95% quartz (see footnote above).

shape due to solution cavities and are set in a cement of cherty, cryptocrystalline or opaline silica.

(2) Conglomeratic type

This consists of abundant pebbles of the terrazzo type in a siliceous matrix. Many of the pebbles are very irregular in outline and appear not have been transported far.

(3) Albertinia type

This type of silcrete lacks virtually any detrital components and consists almost entirely of the matrix material of the terrazzo type.

(4) Opaline and fine grained massive forms

These consist of layers of opaline, chalcedonic or cryptocrystalline silica which are essentially homogeneous with no detrital components.

(5) Quartzitic type

This form is petrographically identical with sedimentary quartz arenites in which cementation has been effected by authigenic overgrowths on detrital quartz grains.

Of these 5 types only the quartzitic type both texturally and mineralogically resembles a ganister. However, recognition of this variety of silcrete is dependant on its occurrence as a surficially cemented horizon.

Thus unless diagnostic criteria are present which indicate near surface silicification any pedogenically formed quartz arenite should be termed a ganister rather than a silcrete.

B. Previous research

(i) Quartz arenites

Previous research on quartz arenites (and orthoquartzites) has been fairly extensive due to their abundance within the sedimentary record. On a world wide scale quartz arenites from Precambrian to Recent have been studied.

Although they may form in virtually any depositional environment their supermature nature generally restricts them to certain stable, high energy zones. As a result, they are not evenly distributed throughout the stratigraphic column, but occur preferentially during certain periods when the above conditions were common. This is particularly well seen in the late Precambrian and early Palaeozoic where thick (up to 1000 m. or more) quartz arenite sequences abound (Pettijohn, 1975).

Within the British Isles research on quartz arenites has been less extensive, but includes studies by Klein (1970a), de Raaf and Boersma (1971), Swett, Klein and Smit (1971) and Anderton (1976). All of these quartz arenites were interpreted as having formed in tide-dominated shallow-marine environments.

According to Horne (1979a) 'clean' quartz arenites may form in one of 3 ways:

1. Diagenetically due to intense weathering where leaching of less stable minerals occurs. Quartz grains in these sandstones show extensive overgrowths. This group thus includes the true ganisters. Of the various types of silcrete only the Terrazzo and Quartzitic types are of the

right grain size to classify as quartz arenites. The Terrazzo type is invariably a diagenetically formed quartz arenite and although it lacks overgrowths should be included in this group. The Quartzitic type often results from silicification of a sedimentary quartz arenite, and thus most examples of this type of silcrete cannot be included in this subdivision.

2. By erosion of a quartz rich source area. In this circumstance quartz arenites would be ubiquitous in all depositional environments from fluvial, to barrier island, to submarine fan. Although examples of such quartz arenites are known (e.g. Mizutani and Suwa, 1966; Vos, 1975), they do not appear to be common.

3. The last and most common way in which quartz arenites form is in high energy environments where sands have been cleaned of non-quartz material by winnowing of finer grains, and erosion and dissolution of less stable minerals. Quartz arenites formed in this manner are often interbedded with and laterally equivalent to "dirty" lithic sandstones.

The environments in which such quartz arenites form has been the subject of some debate. Those that have been proposed include fluvial (McDowell, 1957; Kelling, 1968; Stewart, 1981), deltaic (Houseknecht, 1980), beach and barrier island (Hobday, 1974; Horne, 1979a), tidal flat and tidal sand body (Klein, 1970a; de Raaf and Boersma, 1971; Swett *et al*, 1971; Anderton, 1976; Tankard and Hobday, 1977), estuarine (Horne, 1979b), aeolian (Folk, 1968) and shallow-marine storm-dominated sand body (Chapter Six, p.205).

Quartz arenites formed in fluvial or constructional fluvially-dominated deltas must be somewhat rare as these are not ideal sites for abundant reworking. Most previously described fluvial or fluvial-dominated deltaic sandstones tend to be lithic or feldspathic in nature rather than highly quartz rich (Russell, 1937; Potter, 1978). Indeed Pettijohn (1975), based on the experimental work of Kuenen (1959) and studies of modern river sands, suggests that it is improbable that quartz arenites could ever be produced by river action, no matter how prolonged. This, therefore, places quartz arenites previously interpreted as fluvial or fluvial-dominated deltaic in origin in some doubt. It seems likely that quartz arenites deposited in these environments result from erosion of material already enriched in quartz. This may consist of quartz rich source rocks, or deeply weathered soil profiles (Potter, 1978). In the latter case first cycle quartz arenites could develop in fluvial and constructional fluvially-dominated deltaic environments, but occurrences of such deposits seem to be rare.

The aeolian environment is one in which winnowing and reworking of sand can occur to a large degree. However, aeolian sands tend to form mainly in arid regions where chemical weathering is limited due to the absence of water. As a result, chemically unstable mineral grains such as feldspars are often present in appreciable amounts. Nevertheless, aeolian quartz arenites are known, and Kuenen (1960), and Folk (1968) suggest that many supermature, well rounded, bimodal quartz arenites are redeposited aeolian sands.

According to Selley (1976) the majority of quartz arenites were formed in marine sand-shoal environments. Most authors agree, and the shallow-marine to shoreline environments are where quartz arenites reach their maximum development. This is due to waves and tidal currents continually reworking sands, winnowing away finer grained material, and abrading less resistant mineral grains. Transport paths in such environments may be extremely long due to the back and forward motion that many grains undergo in response to passing waves or tidal cycles (Klein, 1977). Consequently, given sufficient time well rounded, well sorted, supermature quartz arenites are produced, and may form thick sequences during periods of slow regional subsidence.

High energy shallow-marine seas, tectonic stability, slow regional subsidence, low sedimentation rates and quartz rich source rocks thus favour the production of quartz arenites. As a result they tend to form on trailing continental margins in areas of low to moderate sand supply.

(ii) Ganisters

Due to their restricted occurrence there has been little study of ganisters. Consequently, the literature tends to be limited and mainly concerns their occurrence and economic uses (e.g. Thomas *et al*, 1918; Strahan, 1920). Elsewhere ganisters tend to be mentioned in passing and except for Retallack (1976, 1977), the author is unfamiliar with any specific studies of ganister occurrence and origin. Conversely, their fine grained equivalents, underclays, have been fairly extensively studied, particularly in the United States (Lovejoy, 1923; Stout, 1923; Grim and Allen, 1938; Weller, 1957; Schultz, 1958; Huddle and Patterson, 1961; Wilson, 1965; Reeves, 1971).

Within the British Isles research on ganisters has been virtually non existent, except for some recent work on the Sheffield Blue Ganister by Pearson and co-workers (Pearson, 1973, 1979; Ashby and Pearson, 1979; Curtis, Lipshie, Oertel and Pearson 1980). However, this mainly concerned the geochemistry of the surrounding sequence and only briefly mentions the ganister. Consequently, this is a field in which much remains to be done.

Modern pedogenically formed quartz arenites are divisible into 2 main groups. Firstly, there are the silcretes which are unlike ganisters in that they form surfically cemented horizons. Secondly, there are the eluvial horizons of soils of the podzolic group. This group can be divided up into the *podzols* and the *podzolic* soils.

Podzols form by translocation of iron and aluminium compounds down through the soil profile (Cruikshank, 1972). Removal of these compounds results in a 'bleached' eluvial soil horizon enriched in quartz (Muir, 1961). This process occurs most rapidly on freely drained parent materials under a humid climate. Organic solutions from leaf litter aid the podzolisation process (Bloomfield, 1953, 1956) and thus podzols occur most commonly under the coniferous forests of the Boreal zone.

Podzolic soil profiles develop under broadly similar conditions, but are not so strongly acid as podzol soils (Bridges, 1970). Clay is mechanically washed down through the soil profile (lessivage) and deposited in the illuvial horizon. This results in a similar light coloured eluvial horizon enriched in quartz.

Later silica cementation of these eluvial horizons would produce a sandstone very similar to a ganister and it is thus thought that most 'true' ganisters form in this way.

C. Occurrence and economic uses of quartz arenites and ganisters in the British Isles

In the British Isles quartz arenites occur in virtually every geological period from the late Precambrian to Recent. Very thick deposits are confined to the late Precambrian where they locally form successions up to several kms. thick, e.g. Islay and Jura.

Ganisters are much more restricted in occurrence and tend to be confined to the Carboniferous, particularly the Namurian and Westphalian A. This may be due in part to their lack of recognition elsewhere. Economic usage of any quartz arenite or ganister has depended mainly on the distance to markets, quality of the rock and cost of extraction. Refractory products were required mainly by the iron and steel industry, which was dominantly located on the exposed British coalfields. Consequently, many local Carboniferous rocks were quarried for this purpose. At the present time only a few quarries remain which supply material for silica bricks, the principal ones being in the Basal Grits (Namurian) of South Wales.

Friable quartz arenites are important sources of glass sand, and the Lower Cretaceous Woburn Sands have been extensively quarried for this purpose, particularly in the Leighton Buzzard area.

The main properties which make a quartz arenite or ganister useful in the manufacture of refractory bricks are a high percentage of silica, and a low content of aluminium and alkalies, and in addition fine, even angular grains. The chemical composition tends to affect the refractoriness of the brick, whereas the physical properties tend to affect its mechanical behaviour during variations in temperature. Generally the rock should contain at least 97.5% SiO_2, and less than 1% Al_2O_3 to make it useful as a refractory (K.Pirt, pers. comm.).

The manufacture of siliceous refractories has to an extent always been something of an art rather than a science. As a result specifications and procedures vary from one producer to another. On being quarried the rock is crushed, screened, and then ground. Approximately 2-3% of bonding material is then commonly added. The actual amount varies depending on the chemical composition of the original rock.

Bricks are moulded from this mixture and left to dry before being fired. The length of the firing period varies, but is generally no more than 8 days. During firing sudden variations in temperature must be kept to a minimum to avoid cracking the bricks. Temperatures in the firing kiln are of the order of 1500°C, but may reach 1650°C during the finishing period (Searle, 1940). After this the bricks are slowly and carefully cooled.

Firing the bricks serves 2 main purposes. Firstly, to produce a silicate melt by reaction of the bond with the finer grains. This then permeates the remainder of the brick, and acts as a cement binding the brick together. Secondly, to convert as much of the quartz to tridymite and cristobalite. This gives a large permanent expansion to the brick, but a lower subsequent thermal expansion when the brick is in use (Scott, 1917; Thomas *et al*, 1918; Searle, 1940).

The bonding material is very important as it affects the strength of the brick and also the rate at which higher temperature forms of silica are produced. Many different bonds have been tried, but only two, clay and lime, have ever been used on a large scale. This gives rise to the 2 basic types of bricks used, *ganister bricks* with a clay bond, and *silica bricks* with a lime bond.

Ganister bricks developed from the use of the Sheffield Blue Ganister, which contains a few per cent clay, and can be made into bricks without the addition of any other bond (Havard, 1912; Searle, 1940). The origin of *silica bricks* goes back to at least 500 B.C., when they were used by the Persians for mural decoration (Searle, 1940). As a refractory they were first introduced by a Mr. Weston Young from Glamorganshire who produced a brick from Dinas sand (crushed Basal Grits from Craig-y-dinas) mixed with a small amount of lime (Percy, 1875). These became known as Dinas bricks, and due to their highly refractory nature soon began to replace the slightly inferior ganister brick.

Production of silica bricks soon spread worldwide. In America, however, the name ganister was given to these lime bonded bricks, and quartzite brick referred to one with a clay bond (Havard, 1912). According to Johns (1917) the main properties which make these bricks economically useful are:

1. Ability to withstand temperature changes without cracking or disintegration.
2. Refractoriness at the highest temperature employed in the furnace.
3. Resistance to the attack of combustion and reaction products found in the furnace atmosphere.
4. A regular and not excessive coefficient of expansion.

The first and last points depend mainly on the amount of conversion of quartz to tridymite and cristobalite. In British silica bricks this is approximately 30%, but may reach 80% in some American varieties. The remaining points depend to a large extent on the chemical composition of the brick. Refractoriness is a somewhat difficult subject as it depends on a multitude of variable factors. High percentages of impurities such as Al_2O_3 will decrease the refractoriness by lowering the melting point of the brick. The ideal refractory should therefore be low in impurities and consist mainly of high temperature polymorphs of silica, particularly tridymite.

The life of a brick is variable and depends on its quality and the situation in which it is employed. This may be up to 20 years for silica bricks lining coking ovens (K.Pirt, pers. comm.).

With the recent decline in the steel industry there has been a dramatic fall in the extraction of quartz arenites and ganisters for refractory purposes. Originally these beds were worked in many small quarries and mines. Today these are abandoned, and thicker quartz arenites are worked on a larger scale at a few localities.

Research has been carried out on the use of other highly siliceous rocks, notably silcretes, for the manufacture of refractories. Such rocks are employed in South Africa and similar rocks, e.g. Findlings quartzite have been used in Germany for many years (Davies, 1952). As yet, however, bricks made from this material have never been used on a large scale in this country.

CHAPTER TWO

GANISTERS OF THE SHEFFIELD REGION

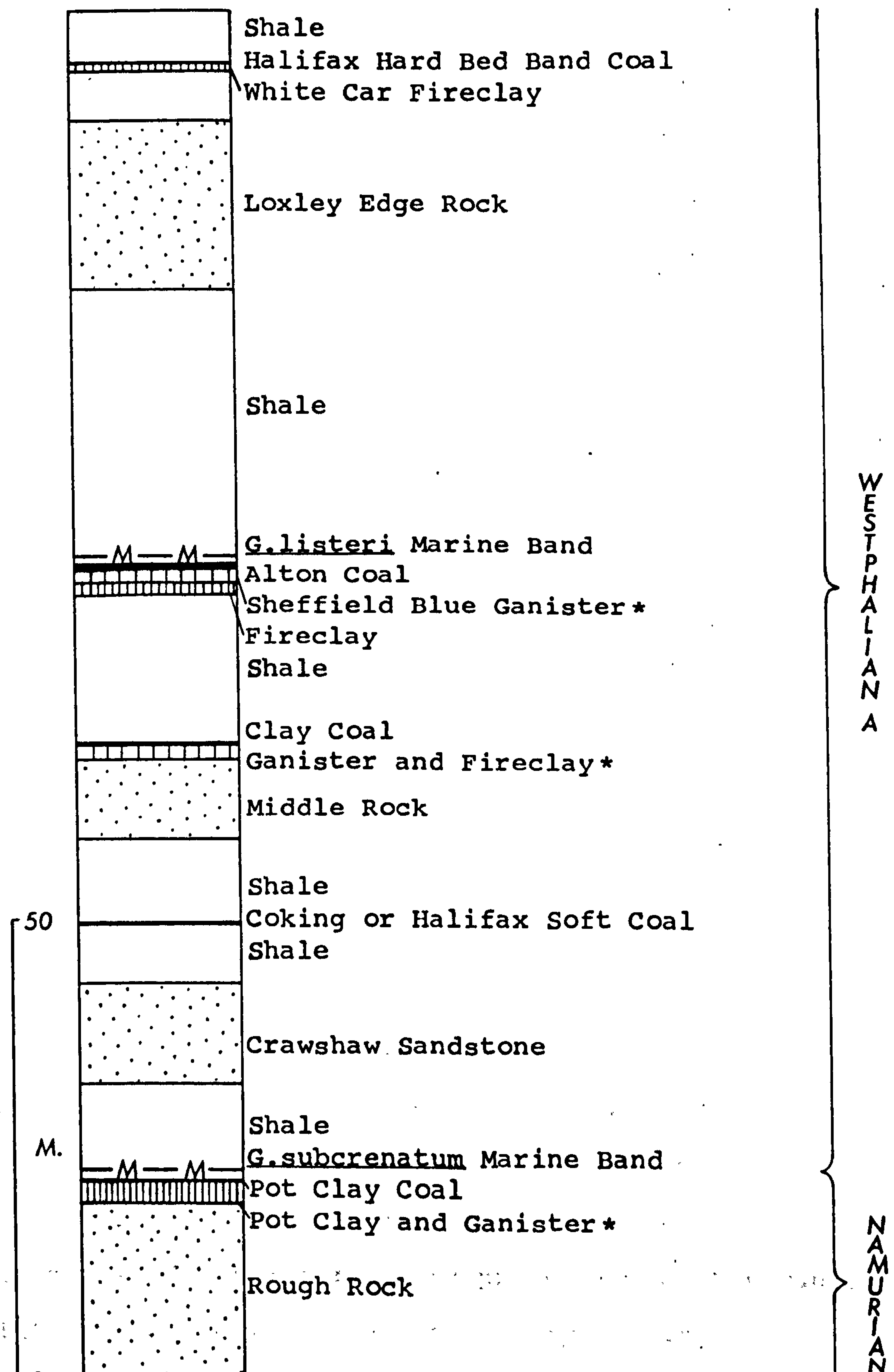
A. Introduction

The city of Sheffield lies on the western limit of the East Midlands coalfield. In this region Namurian and Westphalian strata outcrop extensively and form part of the eastern limb of the Pennine anticline. Due to its position on the coalfield the 2 main industries in the Sheffield region are coal mining and the manufacture of iron and steel. The latter arose during the medieval period (Eden, Stevenson and Edwards, 1957), but underwent its most massive growth during the last 200 years, when it began to outstrip rivals due to the abundant local resources.

Of some importance in this respect has been the occurrence of high grade refractories within the local Carboniferous succession. These include both fireclays and ganisters, which although thin, have been extensively worked. Gradually, however, this has declined due to exhaustion of the more accessible deposits, and at the present time no ganister is being extracted.

A variety of horizons have been utilized, but of these only 3 have been worked extensively throughout the region. These are the Pot Clay fireclay and the Sheffield Blue and Clay ganisters (Fig.2). The latter 2 horizons were both quarried and mined on a large scale, but present day exposures are poor.

SECTION SHOWING THE STRATIGRAPHIC POSITION OF THE MAIN GANISTERS IN THE SHEFFIELD REGION



*=Important ganister occurrences.
Modified from Strahan(1920)

Fig. 2

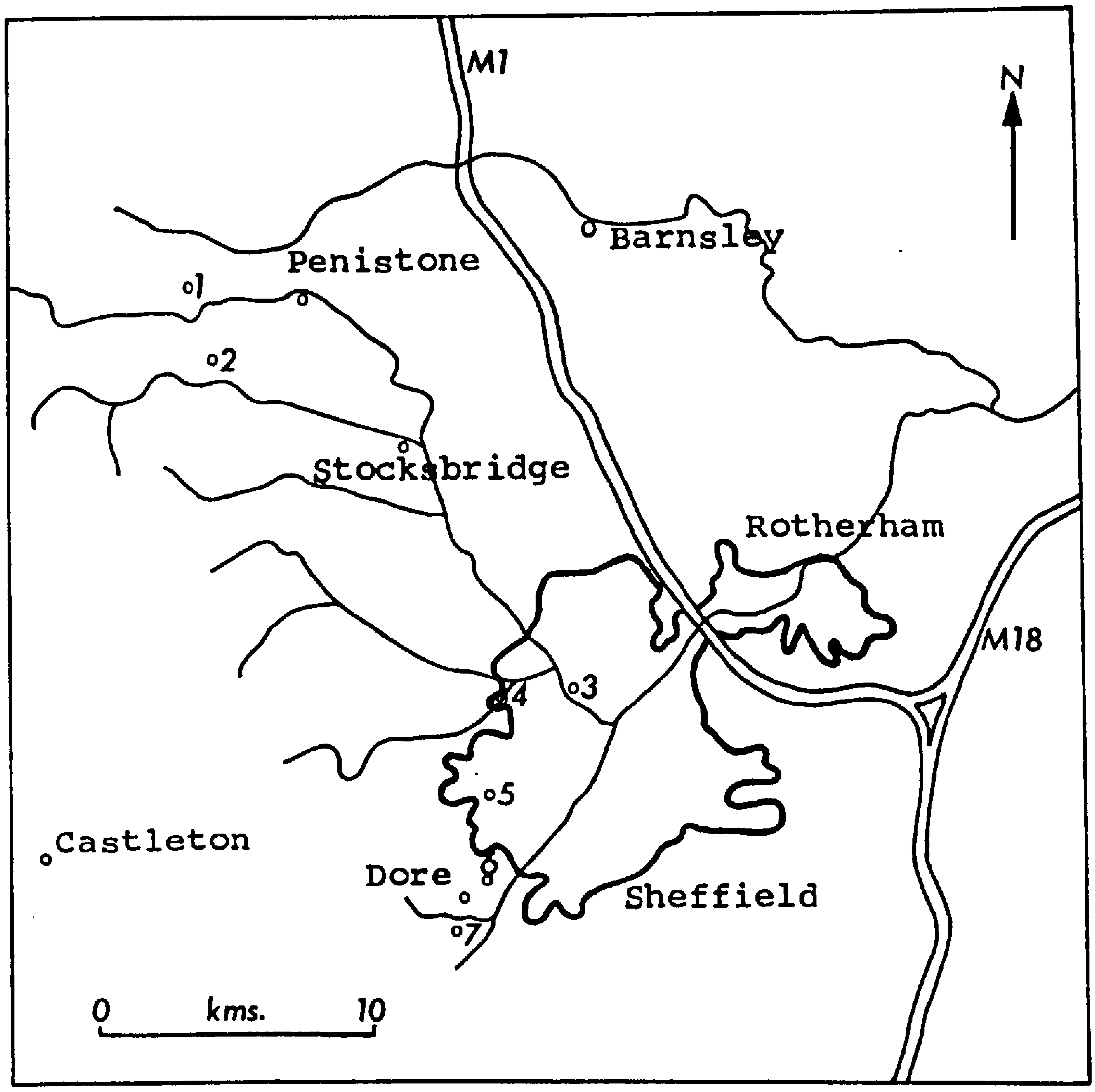
B. Sheffield Blue Ganister

(i) Field description

This is the type ganister and occurs below the Halifax Hard Mine/Alton Coal of Westphalian A age (Ramsbottom, *et al*, 1978). It is a fairly persistent horizon and extends as far N. as Huddersfield with only a slight change in lithology. Within this area it is not always exploitable and former workings were confined mainly to the region in between Sheffield and Penistone. Here the ganister is of good quality and averages 76 cms. in thickness, locally reaching its maximum of 1.68 m. South of Dore (Fig.3) the ganister locally passes into a fireclay, but further to the S. it regains many of its former characteristics and has been worked in the southern part of the Chesterfield district (Eden *et al*, 1957; Smith, Rhys and Eden, 1967). In this intermediate area of poor ganister development the Alton Coal also becomes attenuated and may be locally absent.

Present day exposures of the Sheffield Blue Ganister are poor and only 3 sections displaying this horizon were found (Fig.3); the best being old workings near Langsett. At Langsett the base and top of the ganister can be seen along with the overlying Alton Coal and Marine Band (Figs. 4 & 5). The ganister varies in thickness from 35 to 84 cms., due to an undulatory base and top. The base is particularly irregular and contains a series of bulbous downward projection of the ganister into the underlying kaolinitic clay (Fig.6).

GANISTER EXPOSURES IN THE SHEFFIELD REGION



Exposures visited during the present study.

1=Sheffield Blue Ganister,Middlecliff Quarry (SE 20150415).

2=Sheffield Blue Ganister,Langsett (SE 21300105).

3=Clay Ganister?,Neepsend Railway Cutting (SK 34508930).

4=Clay Ganister?,River Rivelin (SK 32358885).

5=Pot Clay Ganister,Porter Brook (SK 31758535).

6=Sheffield Blue Ganister,Tributary of Limb Brook (SK 31358185).

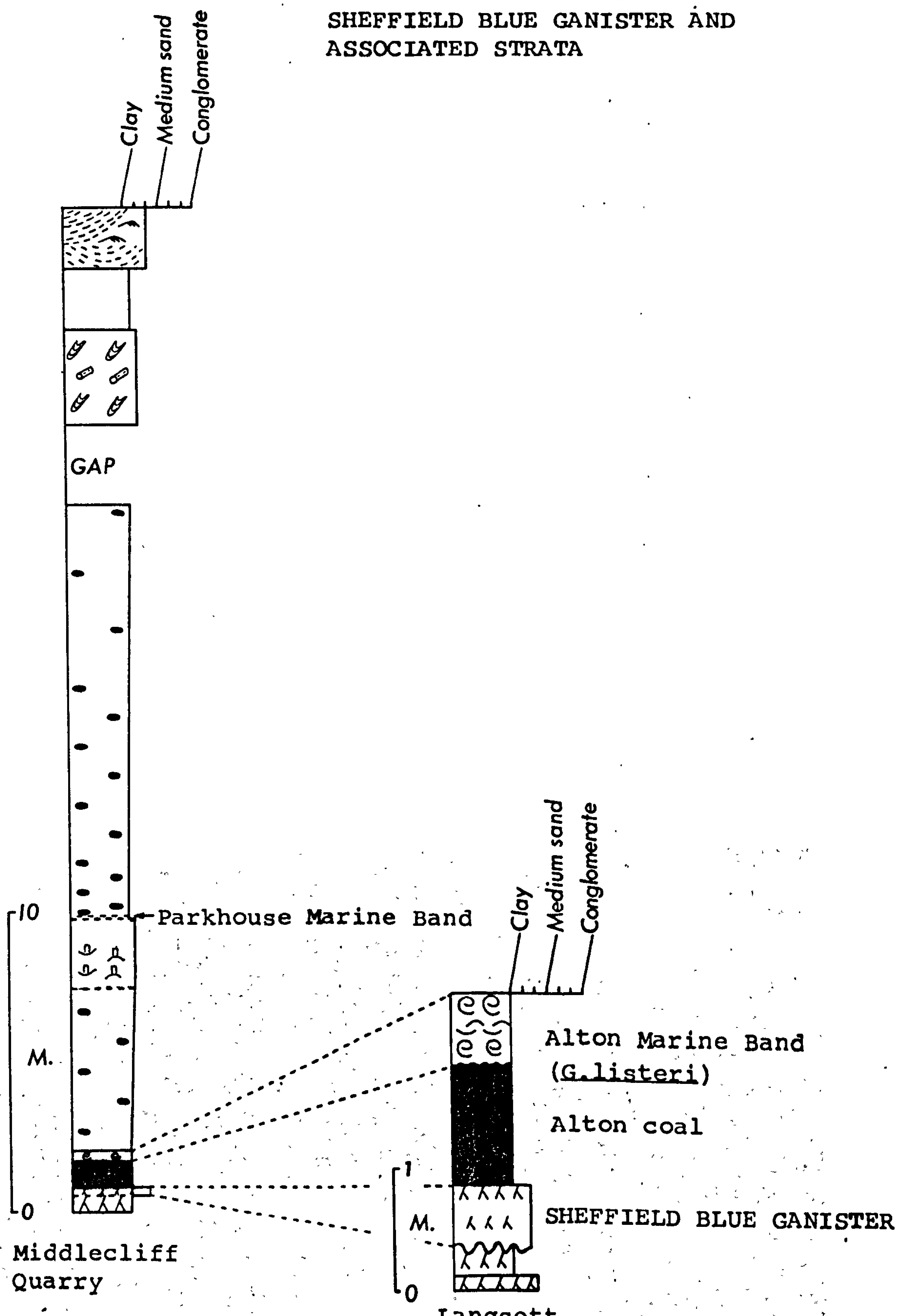
7=Clay Ganister,Dore Ganister Quarry (SK 29608080).

[symbol]=Outer limit of Sheffield and Rotherham urban areas.

The dominant zone of former ganister workings lies between Penistone and the Dore area where both the Sheffield Blue and Clay ganisters were once extracted.

Fig.3

COMPARATIVE SECTIONS THROUGH THE SHEFFIELD BLUE GANISTER AND ASSOCIATED STRATA



Note scale change between sections.

Fig.4

Exposure of the Sheffield Blue Ganister at Langsett showing the undulating top surface and the highly irregular base.Hammer(H) 33cms. long. Fig.5

Close up view of the base of the Sheffield Blue Ganister at Langsett displaying its highly irregular "knobbly" nature due to bulbous downward projections of the ganister into the underlying kaolinitic clays. Fig.6

The ganister is a hard very fine grained, moderately well sorted, quartz arenite (mean grain size = 3.26 ϕ, Fig.7). It is generally light grey in colour due to the presence of a small amount of finely disseminated clay and commonly has a dark blue stained upper surface from which its name is probably derived. Internally, it lacks sedimentary structures except for abundant fossil rootlets. These are present throughout the ganister and pass down into the underlying strata. Grain size does not appear to vary vertically, but there is a slight increase in the proportion of clay present near the base. At the top, the ganister contains a bed a few cms. thick which although broadly similar petrographically, tends to contain a small amount of pyrite and breaks away from the rest of the rock.

At Middlecliff Quarry approximately 3 kms. to the N.N.W. the same horizon is exposed together with a thick overlying sequence (Figs.3 and 4). Here a series of kaolinitic clays are worked from beneath the ganister which is of no economic importance due to its high clay and sulphur content. The geochemistry of this section, and others worked by the Hepworth Iron Company, have been extensively studied by Pearson and coworkers (Pearson, 1973, 1979; Ashby and Pearson, 1979; Curtis, Lipshie, Oertel and Pearson, 1980).

At Middlecliff Quarry, the Sheffield Blue Ganister consists of approximately 30 cms. of coarse siltstone (mean grain size = 4.35 ϕ, Fig.7), which is grey in colour due to the presence of abundant disseminated kaolinite, with minor amounts of mixed layer clays, carbonaceous material and pyrite. Occasional loose blocks of rooted, parallel laminated and current rippled muddy siltstone are present. None were

THIN SECTION ANALYSES OF THE SHEFFIELD GANISTERS AND ASSOCIATED STRATA

Horizon	Locality	Grain Size in ø	Sorting in ø	Quartz %	Mixed Layer Clay/Sericite %	Kaolinite %	Feldspar %	Muscovite %	Carbonaceous Material %	Heavy Minerals %	Pyrite %
Sheffield Blue Ganister	6	3.5	0.54	99.5							0.5
Sheffield Blue Ganister	2	3.32	0.66	98.5						1	0.5
Sheffield Blue Ganister	2	3.2	0.6	99					1		
Sandstone Below Sheffield Blue Ganister	2	2.85	0.62	91.5	5.5	2.5		0.5			
Sheffield Blue Ganister	1	4.35	0.54	83.5		14.5			1.5	0.5	
Clay Ganister	3	3.12	0.53	98							2
Sandstone Below Clay Ganister	3	3.4	0.6	83	8.5	7		1.5			
Pot Clay Ganister	5	2.85	0.56	98	1						1
Impure Pot Clay Ganister	5	3.05	0.62	93	5.5				1	0.5	
Sandstone Below Pot Clay Ganister	5	2.99	0.56	79	10.5	9.5	0.5		0.5		

Grain size and sorting, N=100
Mineralogy, N=200
Clay mineral identification confirmed by X-ray diffraction analysis.

Fig.7

seen *in situ*, but it is likely that these come from directly beneath the ganister (Ashby and Pearson, 1979).

The third exposure of the Sheffield Blue Ganister is in a tributary of Limb Brook N. of Dore. Here the ganister and the overlying coal and marine band outcrop in the stream banks. The ganister again has an irregular base resting on a kaolinitic clay, and varies in thickness up to 60 cms. The top few cms. of the ganister tend to be less pure due to the presence of abundant pyrite, which occurs both disseminated and as large fine grained aggregates up to 3.3 mms. long. The main portion of the ganister consists of a hard, rooted, very fine grained, moderately well sorted quartz arenite with some finely disseminated kaolinite (proved by X-ray diffraction analysis). Towards the base the clay content increases and the rock becomes softer.

At all the localities physical sedimentary structures are absent from the ganister and the main textural differences in the rock tend to be a result of rootlet penetration.

(ii) Petrography

The 'ganister' from Middlecliff is petrographically distinct from the other 2 occurrences due to its finer grain size and the abundance of kaolinite. The presence of 10% clay matrix (Fig.7) and its coarse silt grain size disqualifies it from being classified as a ganister as it does not fit into the quartz arenite category of Folk (1974).

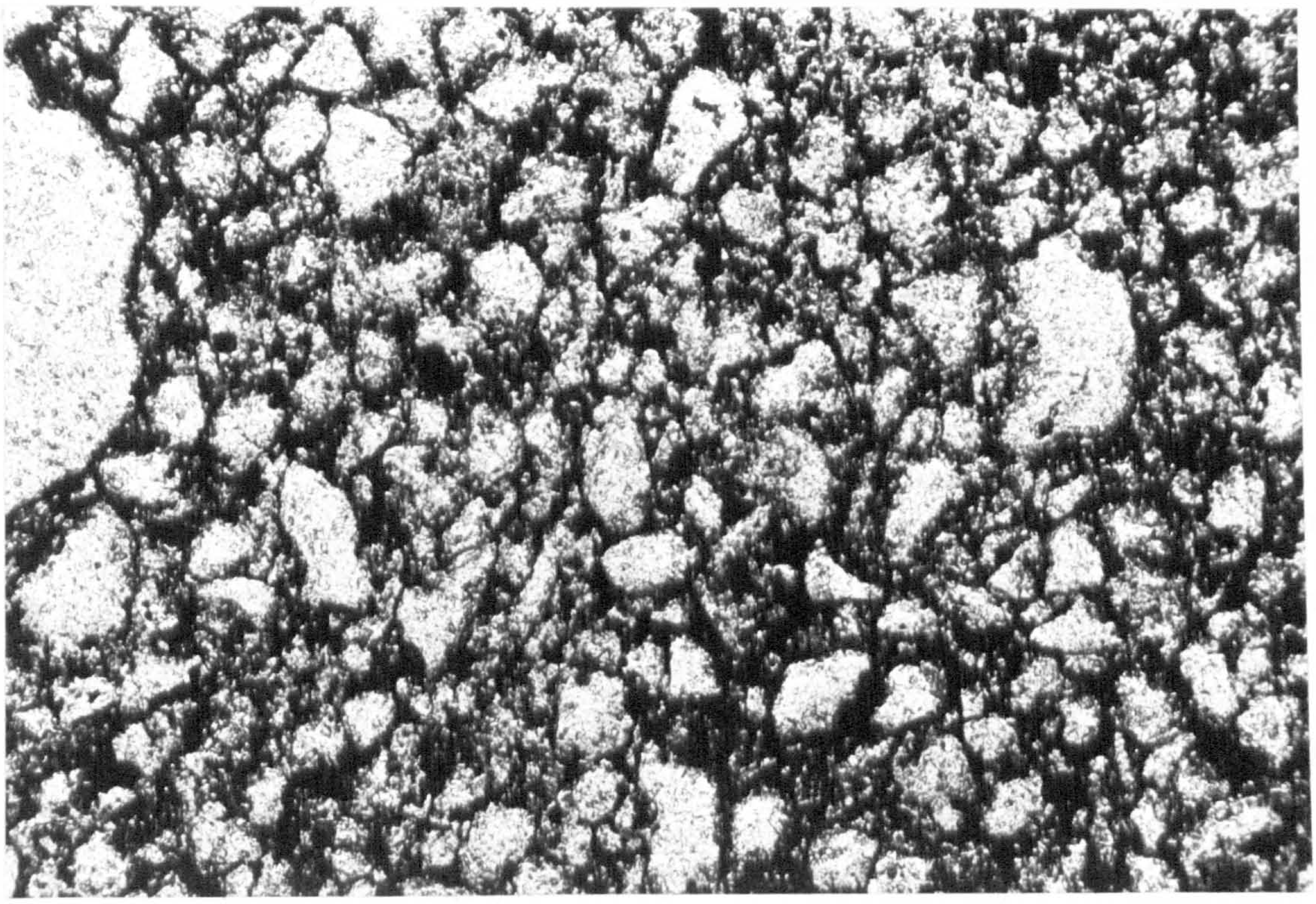
The ganister from both the other localities differs from that at Middlecliff and in thin section consists of approximately 99% quartz together with some very fine grained clays which tend to coat the framework grains. Heavy minerals are present and consist mainly of zircon, green tourmaline and opaques. Occasionally large quartz grains are present (up to 0.9 mm./0.18 ϕ) and stand out in marked contrast to the rest of the rock (Fig.8). Dust rims are occasionally present and generally show subrounded outlines of original detrital grains.

(iii) Diagenesis

Upon burial the ganister underwent compaction and cementation. Cementation occurred dominantly by the deposition of secondary silica both as overgrowths and microcrystalline quartz cement (generally $<$0.032 mm.). The latter may imply rapid cementation. However, the spatial occurrence of microquartz and overgrowths suggests that the main controlling factor was the distribution of fine grained clays (dominantly kaolinite). Variations in the occurrence of clays are a result of rootlet penetration and any concomitant pedogenesis.

In areas of fairly high clay content silica has been deposited as mainly microquartz cement due to the protection of framework quartz grains by clays and carbonaceous material. However, in relatively clay free areas silica has been able to nucleate on quartz grains and optically continuous overgrowths have developed (Heald and Larese, 1974).

Subsequent to cementation there has been the development of pyrite which tends to replace quartz grains. Often this occurs associated with organic matter which



Sheffield Blue Ganister stained with Malachite Green under plane polarized light.The stain has affected the interstitial fine grained clays(dominantly kaolinite)and these have masked the microquartz cement present.Dark areas thus represent microquartz and clay rich zones,framework quartz grains are unaffected.Length of photomicrograph approximately 1.35mm.

Fig.8

Edge of large aggregate of fine grained pyrite showing pyrite replacing framework quartz grains,Sheffield Blue Ganister,tributary of Limb Brook.Length of photomicrograph approximately 1.35mm.(crossed polarized light).

Fig.9

evidently produced the required reducing environment, e.g. rootlet outlines, but disseminated pyrite is also commonly present.

Rootlet outlines sometimes appear stylolitic suggesting late diagenetic dissolution of quartz. However, the growth of pyrite in such zones often obscures this feature.

Occasionally large fine grained pyrite masses are present at the top of the ganister. These embay and replace quartz grains (Fig.9) and probably result from the reducing environment produced during diagenesis of the overlying Alton Coal and Marine Band.

C. Pot Clay ganister

(i) Field description

The Pot Clay lies at the very top of the Namurian and is of Yeadonian, G_1 age (Ramsbottom *et al*, 1978; Fig.2). It is overlain by a thin coal, which is in turn followed by the Pot Clay (*Gastrioceras subcrenatum*) Marine Band (Eden *et al*, 1957) which marks the base of the Coal Measures. In the Sheffield region ganister at this horizon is unusual, but further to the S. in the Chesterfield district occurrences are more common and the rock was formerly worked at several localities (Smith *et al*, 1967).

The Pot Clay fireclay has been extensively quarried and mined in the Sheffield region for the manufacture of refractories due to its high kaolin content. Present day exposures of this horizon tend to be mainly natural ones.

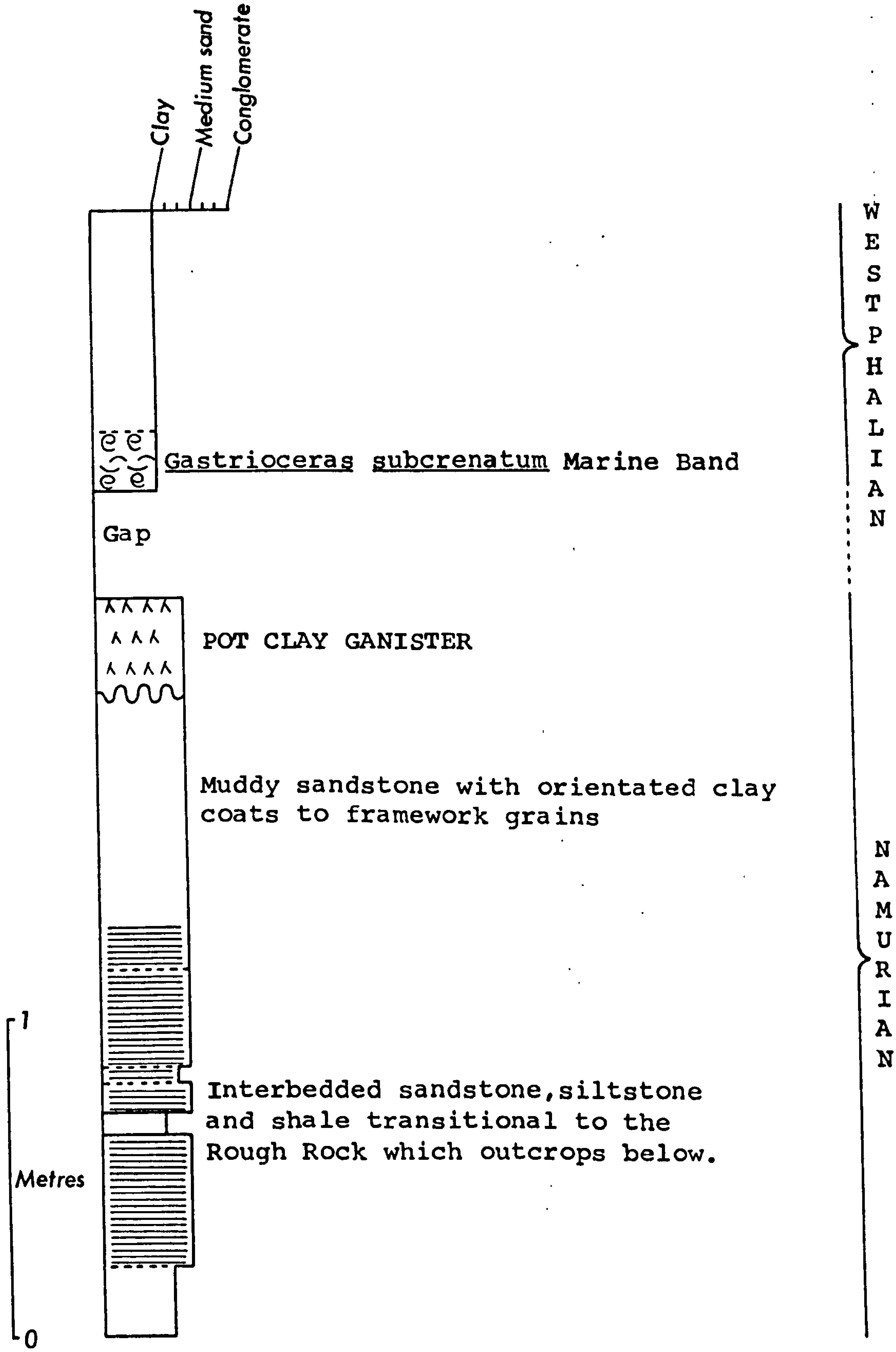
In Porter Brook (Fig.3) the only occurrence of ganister at this horizon in the Sheffield District is exposed, along with the overlying coal and marine band (Fig.10). The ganister varies in thickness due to an undulatory and 'knobbly' base similar to the Sheffield Blue Ganister, and averages approximately 35 cms. It consists of a rooted, fine grained quartz arenite and overlies a texturally less mature fine grained muddy sandstone approximately 90 cms. thick. The ganister shows no sedimentary structures and is penetrated by rootlets throughout, some of which pass down into the underlying sandstone. This lower sandstone does contain some parallel lamination towards the base, but this tends to die away upwards as the proportion of rootlets increases.

At the top, the ganister often shows an increase in the percentage of clay present, and as a result becomes darker in colour. This occurs in the top 7-8 cms. and occasionally forms a separate bed which breaks away from the rest of the rock.

The ganister seems to form a fairly localised lens, as elsewhere in the Sheffield District this horizon is represented by the Pot Clay fireclay. The latter is a kaolinitic clay penetrated by rootlets which is fairly wide-spread in occurrence and thus marks an extensive emergent period.

(ii) Petrography

In thin section the ganister consists of a fine grained, moderately well sorted quartz arenite, containing approximately 98% quartz with minor amounts of mixed-layer clays and pyrite (Fig.7). At the top, the clay content



SECTION THROUGH POT CLAY GANISTER
AND ASSOCIATED STRATA PORTER BROOK

Fig.10

increases to approximately 5.5% and consists mainly of sericite/mixed-layer clays. Zircon, green tourmaline, opaques and muscovite are all present in minor amounts.

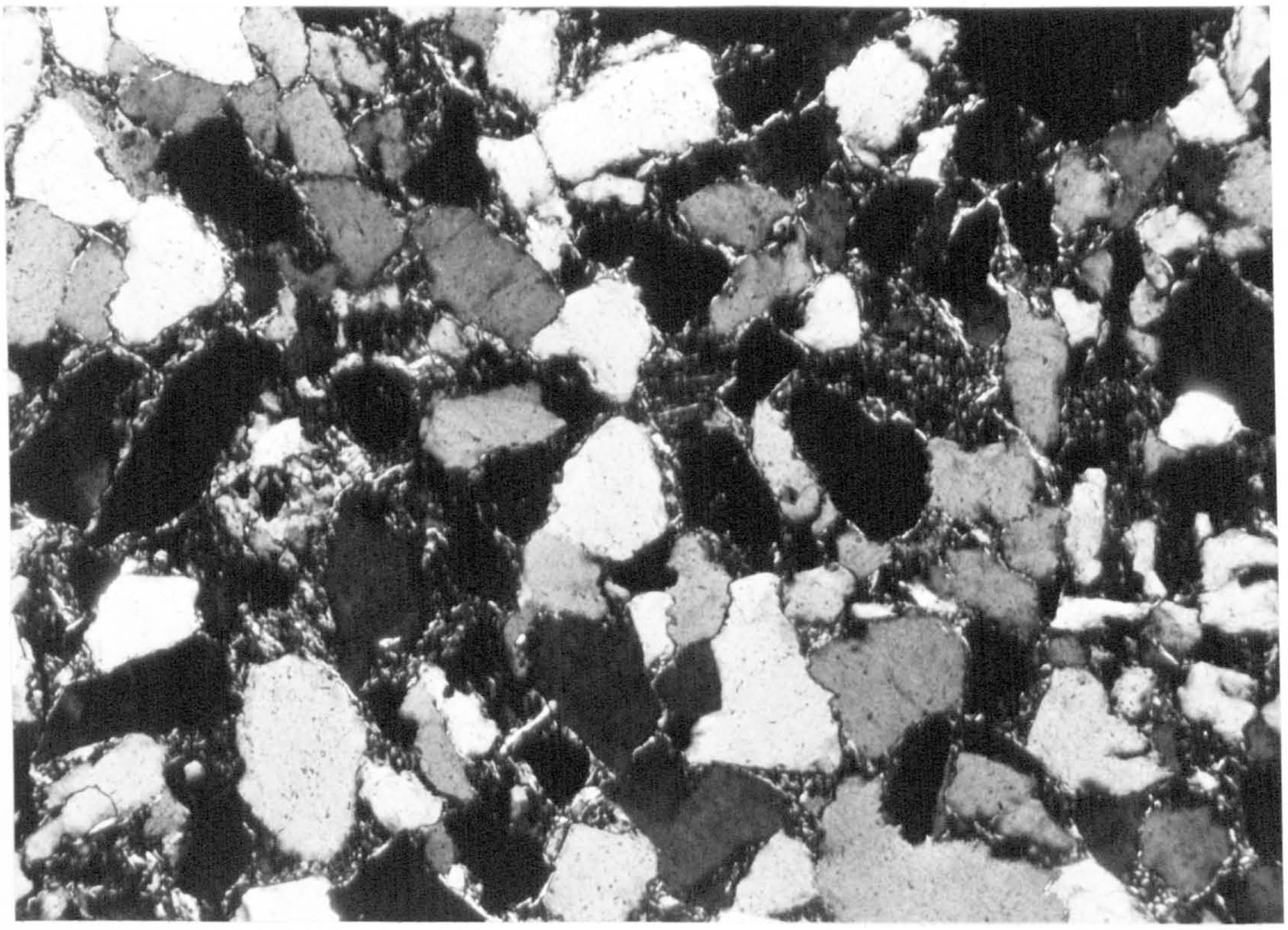
The directly underlying sandstone contains both kaolinite as pore fills and mixed-layer clays often forming orientated coatings to framework grains (Figs.11 and 12). This latter structure is known from sedimentary rocks (Bullock and Mackney, 1970), but is very common in soils and palaeosols where such coatings are termed cutans (Brewer, 1964; Teruggi and Andreis, 1971).

The increase in the percentage of quartz present from this underlying sandstone up into the ganister is of the order of 19% (Fig.7). Part of this is due to the decrease in the clay content which forms approximately 20% of the underlying sandstone.

(iii) Diagenesis

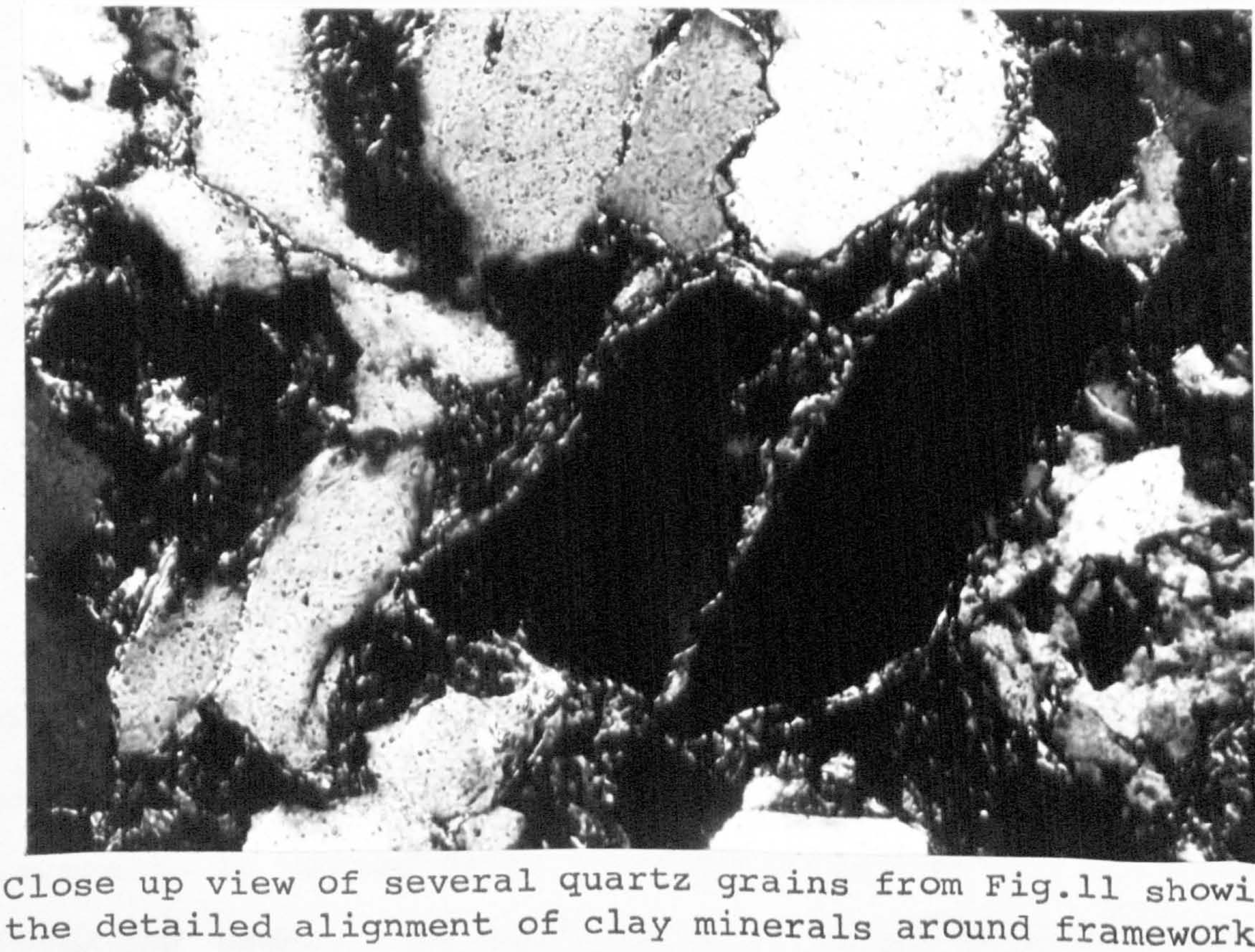
Diagenesis was broadly similar to that of the Sheffield Blue Ganister, but cementation was effected mainly by quartz overgrowths, with only minor development of microquartz cement along clay rich rootlet outlines. Silica cementation of the underlying sandstone was somewhat inhibited by the large proportion of clay present.

Carbonaceous rootlet impressions in both the ganister and underlying sandstone are often stylolitic in outline, indicating pressure solution of the adjoining quartz grains. The nature of these microstylolites suggests they are post lithification in origin (Jonas and McBride, 1977). Dissolution of silica along such horizons may have supplied some quartz cement to adjoining lower pressure areas within



Sandstone below Pot Clay ganister,Porter Brook showing sericitic mixed layer clay coatings to framework grains. Length of photomicrograph 1.35mm.(crossed polarized light).

Fig.11



Close up view of several quartz grains from Fig.11 showing the detailed alignment of clay minerals around framework grains.Length of photomicrograph 0.52mm.(crossed polarized light).

Fig.12

the rock. Pyrite sometimes occurs along these stylolitic rootlet outlines, where it replaces adjacent quartz grains and overgrowths. Occasionally stylolites are partially obscured by the growth of pyrite, which must therefore be very late diagenetic in origin.

D. Clay ganister

(i) Field description

The Clay ganister occurs below the Clay or Middle Band Coal of Westphalian A age (Ramsbottom *et al*, 1978) (Fig.2). It was formerly extensively quarried and mined in the Sheffield region, where according to Eden *et al*(1957) it was the main ganister worked. At least 3 refractory beds occur within approximately 8 m. of the Clay Coal horizon. Consequently where the Clay Coal is locally absent, identification of the Clay ganister becomes difficult if not impossible.

Three exposures of this horizon were visited, but only at Dore ganister quarry was the overlying Clay Coal present (Fig.13). As a result the exact stratigraphic position of the ganister from the other 2 localities remains in some doubt. However, the ganister from all 3 exposures is similar and they are treated as being the same horizon.

The exposure at Dore shows 72 cms. of ganister underlying the Clay Coal. The ganister consists of a fine grained quartz arenite penetrated by abundant fossil rootlets. Laterally it varies quite markedly in thickness, due to an irregular base. The ganister is thickest where it overlies

COMPARATIVE SECTIONS THROUGH THE CLAY GANISTER AND ASSOCIATED STRATA

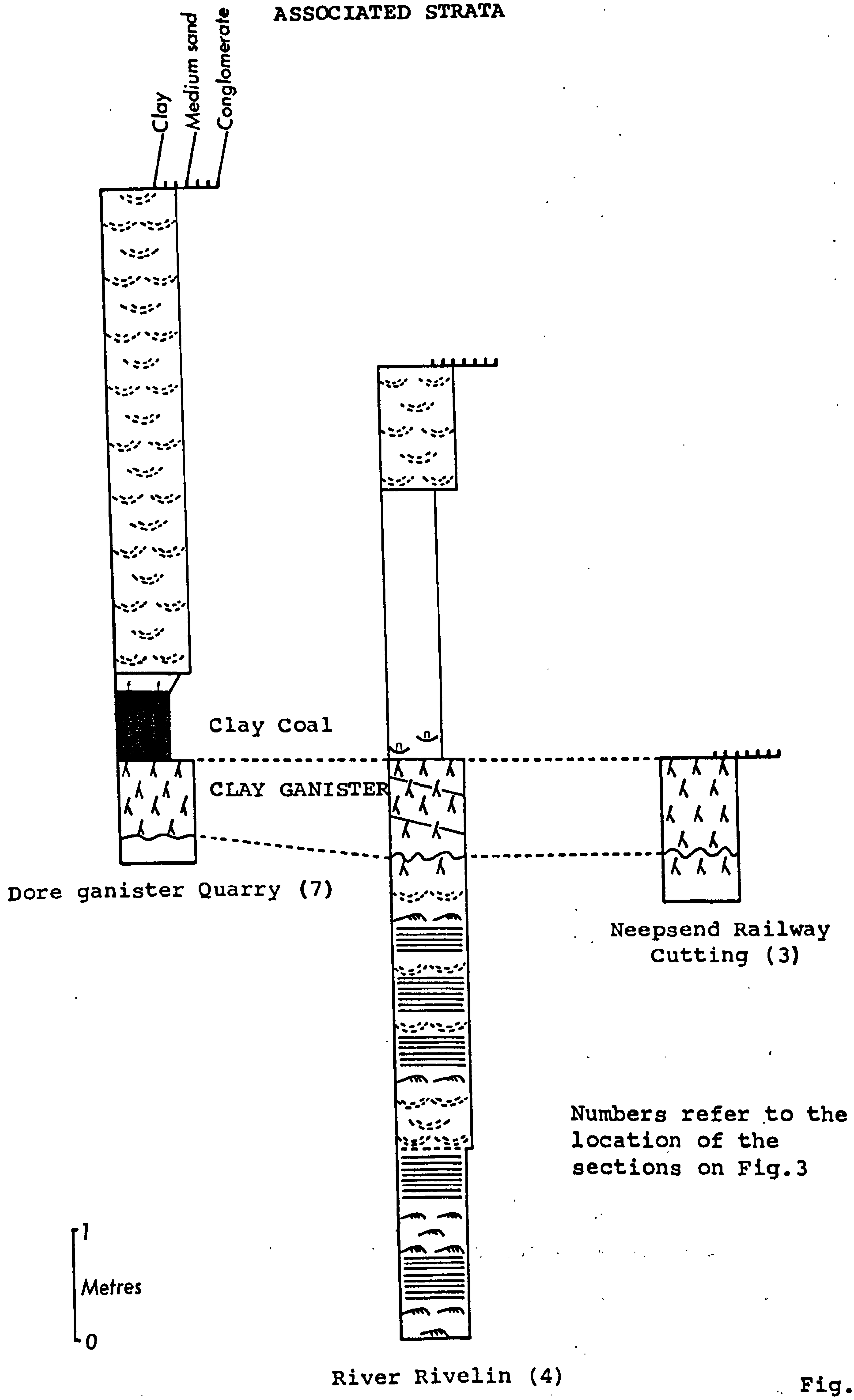


Fig.13

sandstone, but thins to approximately 30 cms. when the underlying horizon is a white kaolinitic clay.

The exposure in Neepsend Railway Cutting is very small due partly to its position between 2 small faults. Approximately 90 cms. of ganister is exposed lying on 45 cms. of fine grained sandstone (Fig.13). The ganister contains abundant fossil rootlets and consists of a very fine grained, moderately well sorted, subrounded quartz arenite (Fig.7), which is variable in thickness down to 40 cms. or less, due to a highly irregular base. The underlying sandstone contains fossil rootlets at the top and tends to be softer than the ganister due to the presence of a moderate proportion of clay (Fig.7).

In the River Rivelin a 9 m. high river cliff exposes a ganister at a similar horizon (Eden *et al*, 1957). The ganister forms the top of a 5.4 m. thick sandstone body which tends to coarsen upwards, and is overlain by a black shale containing occasional *Carbonicola sp.* (Fig.13). The ganister is up to 95 cms. thick, but again varies in thickness due to an irregular base, and consists of a fine grained quartz arenite penetrated by abundant fossil rootlets. Occasionally a very crude low angle bedding is visible in the ganister, but the effect of fossil rootlet penetration, tends to obscure this. As a result it is difficult to ascertain the significance of this bedding feature, which broadly resembles lateral accretion surfaces.

The sandstone directly beneath the ganister is moderately friable and contains fossil rootlets which decrease in abundance with depth. Below this upper rootleted zone, sedimentary structures are abundant and include parallel lamination, current ripple cross lamination and rare small scale cross-bedding. Thin mud laminae and mud drapes to ripples are occasionally present, particularly towards the base.

(ii) Petrography

The ganister from the River Rivelin contains a moderate proportion of clays and muscovite, making it fairly impure compared to the other 2 localities where it consists of a very fine-medium grained, clean quartz arenite, containing approximately 98% quartz. Sorting is moderately good, but is poor in samples from Dore. These exhibit large quartz grains (approximately 1.8ϕ) associated with very fine grained sand-silt size quartz (approximately 4 ϕ).

Associated fine grained sandstones are less mature due predominantly to a moderately high clay and mica content. In Neepsend Railway Cutting the sandstone below the Clay ganister contains approximately 15.5% clay, including both sericitic mixed layer clays and kaolinite. Occasionally the sericitic clays form orientated clay coats to framework grains.

(iii) Diagenesis

Diagenesis of the Clay ganister from Neepsend and the River Rivelin was very similar to that previously described for the Pot Clay ganister. At Dore, the Clay ganister contains patchy, occasionally separate developments of both quartz overgrowths and quartz cement. Often overgrowths are ragged and have evidently undergone some dissolution before deposition of the enclosing quartz cement (commonly <0.032 mm. in grain size). Generally the rock is grain supported with the quartz cement having developed in the intergranular pores. Occasionally, however, the quartz cement is too abundant to have formed in the above manner and the larger detrital components assume a 'floating' texture. This appears to be due mainly to recrystallisation of silt size quartz grains originally present within the rock.

At all 3 localities there has occasionally been late diagenetic development of pyrite, similar to the 2 previous examples.

E. Interpretation

(i) Diagnostic features of palaeosols

The recognition of a palaeosol depends on the presence of one or more criteria, the most important of which are:

1. Fossil roots and rootlets *in situ*

Colonization by land plants is positive evidence that the horizon under consideration acted as a soil. Burrows can in some cases appear similar to rootlets, and it is thus imperative for the two to be distinguished. In Carboniferous examples, the presence of large stigmarian roots with associated rootlets often acts as a safeguard against misidentification.

2. Cutans

According to Brewer (1964) cutans are plasma concentration or plasma separations associated with natural surfaces within the soil material, including the faces of peds, skeleton grains and the walls of voids (Plasma is that part of the soil material which is capable of being or has been moved, reorganized, and/or concentrated by the processes of soil formation. It includes all the material, mineral or organic, of colloidal size and relatively soluble material which is not bound up in the skeleton grains (Brewer and Sleeman, 1960)). Optically oriented assemblages of clay, previously termed "clay skins" are included within this group.

3. <u>Sepic plasmic fabrics</u>

Plasmic structure is the organization of the constituents of the plasma that have not been concentrated or crystallized to form pedological features and the associated very small voids which result from packing of plasma grains. Sepic plasmic fabric constitutes a plasmic structure in which there are recognizable anisotropic domains with various patterns of preferred orientation, i.e. plasma separations with a striated extinction pattern are present (Brewer, 1964).

The reliability of the last 2 criteria in the recognition of palaeosols has been the subject of debate (Bullock and Mackney, 1970; Teruggi and Andreis, 1971; Kroonenberg, 1978). It appears that although they may occur in sediments and sedimentary rocks, such structures are best developed in soils and palaeosols. This applies particularly to cutans, which according to Brewer (1964) are pedological features by definition.

(ii) <u>Origin of the Sheffield ganisters</u>

According to Pearson (1973) the *Sheffield Blue*

Ganister underwent leaching in a subaerial environment. This occurred above the water table and mechanical eluviation of kaolinite and other clay minerals took place. These were deposited immediately below the water table and gave rise to a zone of kaolinite enrichment. Gradual removal of clays and the breakdown products of unstable minerals resulted in the ganister. This period of soil formation seems to have been of fairly short duration as fresh muscovite flakes are present within the ganister.

The principal evidence Pearson cites for a pedogenic origin is the enrichment of quartz relative to zirconium in the ganister. Samples below the ganister show a perfect correlation between Zr and quartz and indicate progressive upward coarsening. The very high quartz content of the ganister is not matched by Zr, which cannot therefore be a result of sorting and must represent the leached horizon of a soil profile (Pearson, 1973).

Although the author does not totally agree with the above reasoning, several lines of evidence tend to support the idea of a palaeosol origin. The very fine grain size of the ganister argues against formation in a high energy environment, where such small grain sizes might normally be expected to be removed. The subrounded nature of most grains, presence of interstitial kaolinite and the very fine grain size of the enclosing sequence argues for deposition in a fairly low energy environment.

The thin nature of the deposit together with its large areal extent and local passage into muddy siltstone or fireclay also argues against a high energy sedimentary origin. The fact that associated sandstones are not all quartz arenites indicates that formation by erosion of a pure quartz source area is not plausible. Consequently, by a process of elimination this suggests that the quartz rich nature of the ganister probably arose by weathering and pedogenesis rather than by sedimentation (Horne, 1979a).

The presence of roots is irrefutable evidence that some pedogenesis has taken place, and the occurrence of a thick coal above may suggest this took place in a water-logged profile. However, the absence of any mottled or gleyed zones within the ganister indicates that generally the water table was low and waterlogged conditions during ganister formation were rare.

It is therefore suggested that pedogenesis took place above the water table. Like many associated coarser grained horizons, the parent material was probably a muddy very fine grained sand. Local variations in parent material probably led to absence or poor development of the ganister.

The main features of pedogenesis were the break-down of unstable minerals, and removal of the breakdown products and clays by downward eluviation, together with penetration of rootlets and obliteration of any sedimentary structures. Deposition of the clays lower down gave rise to kaolinite enrichment in the B-horizon, and a slightly muddy base to the ganister. The thickness of the kaolinitic clays beneath the ganister (20 cms. or more) suggest that in part they must be sedimentary in origin, as clay eluv-iation alone could not account for such thick deposits.

Development of the eluvial (A_2-ganister) and illuvial (B-clay rich) horizons began at each others expense, and resulted in the very irregular 'knobbly' junction between the two. Superimposed on this are irregularities due to roots and rootlets passing down from the A_2-horizon.[1] These have been infilled by quartz rich sand from above, resulting in small scale projections down from the base of the ganister. Such "bleached" A-horizons with undulating/tonguing basal contacts are common in present day podzols and podzolic soils. Development of the A_2-horizon over the B-horizon occasionally gave rise to sandy patches at the top of the clay which have subsequently become silicified.

In most areas it appears that development of a leached soil profile reached its conclusion. The underlying clay rich horizon must have impeded drainage, and as the proportion of clay increased due to eluviation, may have resulted in waterlogging and gleying of at least the lower part of the eluvial horizon. Soil horizons appear to have developed in the same position as previous lithological units and caused their differentiation to become more marked (Fig.14).

The Sheffield Blue Ganister thus represents the eluvial horizon of a palaeosol profile, in which the main formative process appears to have been the mechanical washing of clay down through the profile. As proposed by Pearson (1973) the period of pedogenesis was probably not very long (approximately several hundred years), and the increase in quartz content necessary over typical associated sandstones (approximately 8%) tends to support this.

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1. According to the Food and Agriculture Organisation system (1974) an A_2 (albic) horizon is termed an E-horizon. Other labels for this horizon include A_e and E_a (Cruikshank, 1972).

The presence of rootlets in the *Pot Clay ganister* and the occurrence of an overlying coal similarly indicate a period of pedogenesis in a waterlogged swamp environment. However, the occurrence of orientated clay skins to detrital grains in the sandstone below the ganister suggests that during pedogenesis the solum was freely drained, as such features commonly form above the water table by deposition of clays washed down from overlying horizons (Buurman, 1980). Together with the lack of structures indicative of gleying, this suggests that a freely drained soil profile is a more plausible situation. The lack of sedimentary structures in the ganister is probably a result of rootlet penetration, as they both show an inverse relationship with depth when traced into the underlying sandstones.

The occurrence of roots, cutans, and the quartz rich nature of the ganister as opposed to associated sandstones suggests formation in a leached soil profile similar to the Sheffield Blue Ganister. The abundance of clay, and the presence of cutans in the underlying sandstone indicate that leaching consisted predominantly of the downward mechanical eluviation of clay minerals (lessivage). Formation of cutans above the water table indicates that during ganister formation this probably lay over a metre below the surface.

Development of soil horizons in this case appears to have taken place without the aid of former lithology contrasts, but again resulted in an irregular base to the A_2-horizon. The thin muddy horizon at the top of the ganister may represent later reworking. However, such horizons are common in podzolic soils and thus it is very likely to have formed during the period of soil development. The increase in the percentage of quartz from the underlying sandstone up into the ganister suggests that approximately 10% clay was removed from the A_2-horizon during pedogenesis.

The presence of roots in the *Clay ganister*, association with less mature sandstones, lack of sedimentary structures, undulose basal contact and occurrence of occasional orientated clay skins indicate that the ganister formed by leaching of a less mature sand as in the previous examples. The increase in quartz content from the underlying sandstone is of the order of 15%. This could be accomplished by leaching of an original parent material containing approximately 7½% clays and unstable mineral grains (assuming equal volumes for the A_2 and B horizons). It is notable that where the underlying horizon is clay rich, the ganister is poorly developed, indicating that leaching was impeded in areas of poorly drained parent material.

All 3 occurrences of ganister appear to be similar in origin. The resultant profiles are very similar to present day podzolic soils, which tend to be soil type of the cool to cold temperate regions. During the Carboniferous Britain lay in the tropics (Faller and Briden, 1978). Podzols and podzolic soils are uncommon in this climatic zone, but examples are known and include the Padang soils of Indonesia (Hardon, 1937). These form on sandy parent materials under high rainfall which leads to strong leaching of any bases present (Young, 1976).

Classification of present day soils depends on the occurrence of diagnostic features or horizons. Palaeosols gradually lose many of these diagnostic characteristics, due to destruction or modification by post pedogenic processes (e.g. erosion, diagenesis, etc.), and as a result classification becomes difficult. Also over an area as large as the Sheffield region there is likely to be variation in the actual horizons and features developed, due to changes in parent material, drainage, etc. As a result each palaeosol is unlikely to classify as the same soil type over the entire area. However, bearing these points in mind the following classifications are suggested according to the Food and Agriculture Organization system (1974):

1. Sheffield Blue Ganister palaeosol - dystric podzoluvisol when there is no evidence of gleying within 50 cms. of the surface (A_2-horizon >50 cms.). Gleyic podzoluvisol or possibly a planosol when there is proof of gleying within 50 cms. of the surface (A_2-horizon < 50 cms.).

2. Pot Clay ganister palaeosol - dystric podzoluvisol where tonguing of the A_2-horizon is evident. Albic luvisol if the tonguing is absent.

3. Clay ganister palaeosol - when the underlying strata is sandstone, this classifies as an albic arenosol if horizons are poorly developed (A_2/albic horizon > 50 cms. thick) or dystric podzoluvisol if a clay rich (argillic) B-horizon exists. When the underlying strata is clay and the A_2-horizon < 50 cms. thick it becomes a gleyic podzoluvisol, or possibly a planosol.

The development and preservation of orientated clay coats to framework grains seems to be dependent on a freely drained sandy parent material. The Sheffield Blue Ganister appears to have developed on a stratified sequence which became clay rich with depth. As a result clay coats to framework grains were not developed.

Both the Pot Clay and Clay ganisters are commonly developed on sandstones. These porous parent materials enabled rapid leaching to take place, resulting in the development of a 'bleached' eluvial horizon within a fairly short time.

Development of the Sheffield Blue Ganister probably took longer, due to the clay rich nature of the underlying strata, which impeded drainage and thus inhibited leaching. The ganister appears to have developed along a slightly coarser grained horizon overlying these clays. (A similar relationship appears to exist where the Clay ganister overlies kaolinitic clays).

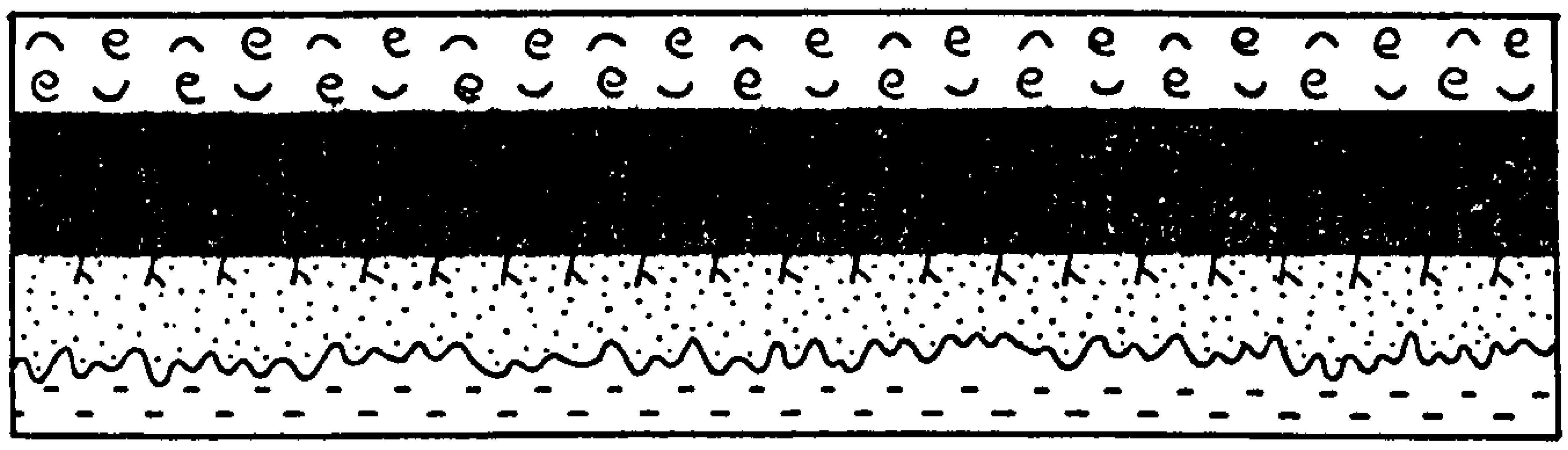
Texturally the Sheffield ganisters (except the Clay ganister from Dore) are unlike most types of silcrete (Smale, 1973), but do resemble to some extent the quartzitic type. Recognition of quartzitic silcretes is dependent on their identification as surficially cemented horizons. There is no evidence of the ganisters ever forming such horizons (e.g. no ganister clasts in associated fluvial deposits,etc.), and thus they are unlike previously described fossilized quartzitic silcretes (Selleck, 1978; Summerfield, 1979; Summerfield and Whalley, 1980).

The Clay ganister from Dore differs texturally from the other ganister occurrences in showing a patchily developed 'floating' fabric of quartz grains in fine grained quartz cement which is similar to the Terrazo type silcrete. However, the presence of sericite, muscovite and quartz overgrowths and the absence of TiO_2 rich cloudy areas is unlike most modern examples of Terrazo silcrete. As a result the texture is more likely to have originated by diagenetic recrystallisation of silt size quartz grains initially present within the rock. Thus the Clay ganister from Dore is similar to the other ganister occurrences, all of which represent true ganisters as previously defined.

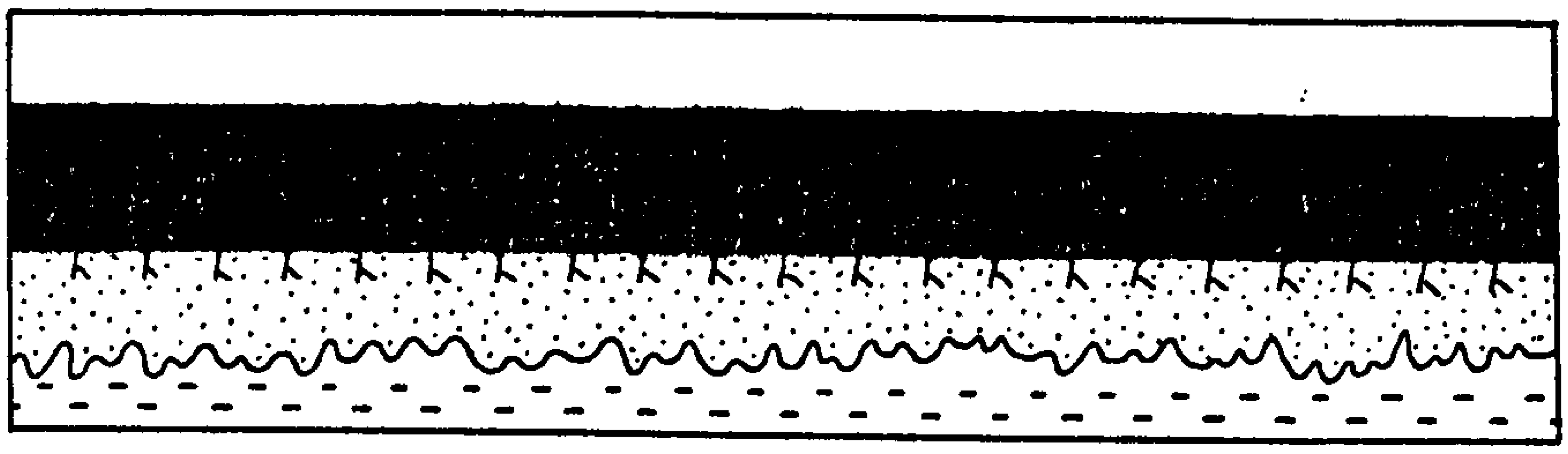
Formation of the Sheffield ganisters required freely drained conditions, which in certain cases, e.g. Sheffield Blue Ganister were widespread in extent. Freely drained palaeosols tend to be fairly uncommon in the Coal Measures, whereas hydromorphic palaeosols abound. Formation of such freely drained, widespread horizons may therefore require small scale falls of base level.

The production of leached palaeosol profiles thus took place under very different conditions to the associated overlying coal seams, which required waterlogged conditions (Fig.14). A subsequent relative rise in the water table is thus necessary. In the case of the Alton Coal, its widespread occurrence above the Sheffield Blue Ganister requires a regional change in base level. It is suggested that the relative rise in sea level which ended with the inundation of large areas and deposition of the Alton Marine Band may have been responsible (Fig.14). The slow rise in sea level causing waterlogging of onshore areas in which coal deposition then took place. Similar coal/marine band relationships on a much smaller scale have been described by Elliott (1974,

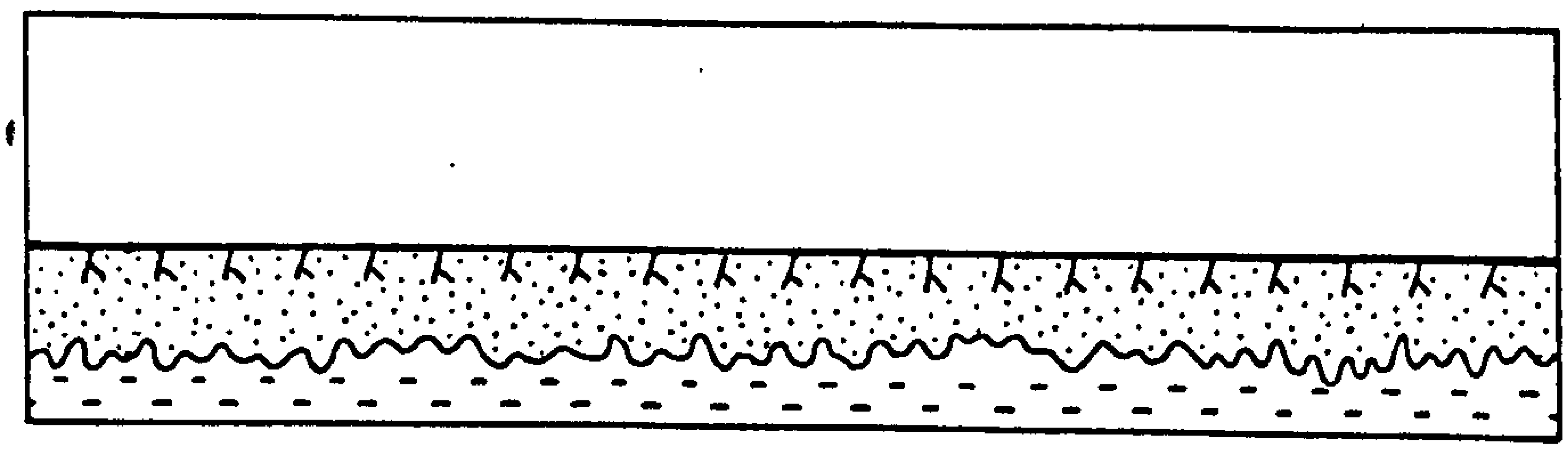
DIAGRAMMATIC REPRESENTATION OF THE INTERPRETED MODE OF ORIGIN OF THE SHEFFIELD BLUE GANISTER AND ASSOCIATED STRATA



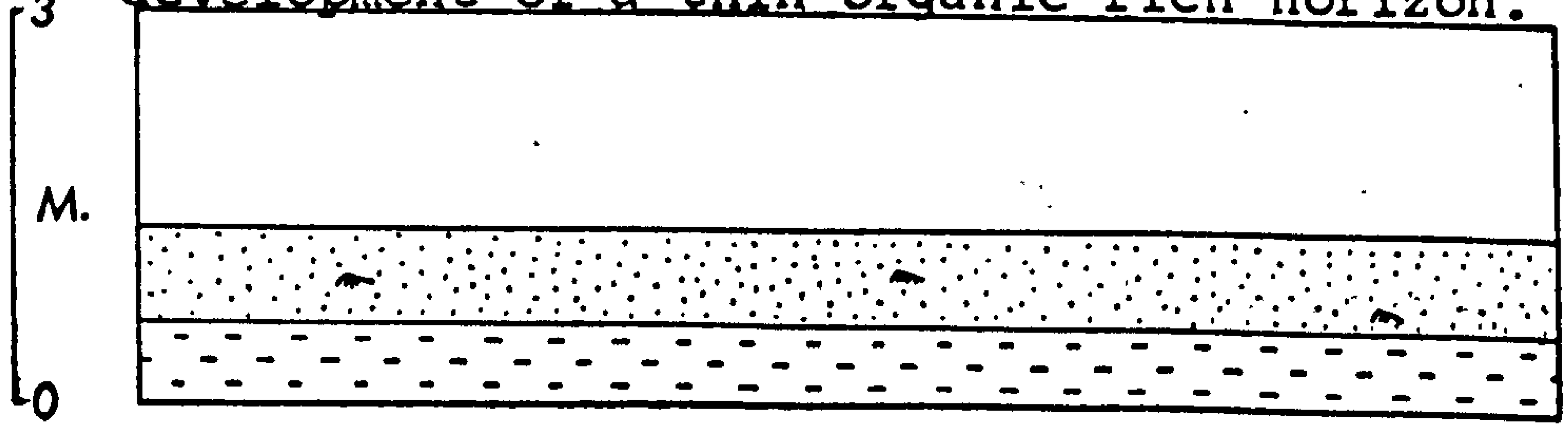
4)The relative rise in base level continues,and results in a widespread marine transgression, leading to deposition of the Alton Marine Band.



3)A relative rise in base level causes the development of a leached soil profile to cease. Colonization of the soil surface by a swamp type flora,and coal formation takes place.



2)A fall in the water table leads to strong leaching of the sand layer,and development of a bleached eluvial soil horizon with a tonguing basal contact.Colonizing plants destroy sedimentary structures by rootlet penetration,and lead to the development of a thin organic rich horizon.



1)Deposition of a thin(approximately 50cms.thick) very fine grained sand occurs over previously deposited kaolinitic clays.

Fig.14

1975) from the Carboniferous (Namurian) of the Alston Block.

A similar relationship may exist between the Pot Clay Coal and Marine Band. The Clay Coal, however, is unassociated with a marine band, and is much more variable in occurrence. As a result it probably requires local relative rises in the water table for its formation.

Due to their fine grain size, mature, moderately well sorted nature and original high porosity it is likely that silica cementation of the ganisters began fairly early during diagenesis (Heald and Renton, 1966; Jonas and McBride, 1977). The cementing silica may have come from various sources, e.g. diagenetic clay mineral alterations, dissolution of quartz and silicate grains, dissolution of opaline skeletal grains, etc. (Jonas and McBride, 1977). However, the general association of the ganisters with clay rich strata, suggests that clay mineral alterations and dissolution of silt size quartz fragments may have been important sources of silica for cement.

Another possible source is from the plants which colonized the ganisters. Silica is a common constituent of plants as opaline silica bodies (phytoliths) and opaline encrustations, and on their death this is returned to the soil (Ollier, 1969). During diagenesis these may become dissolved and reprecipitated in the more stable form of quartz. Retallack (1976) suggests that such phytoliths could provide all the necessary silica for ganister cementation.

This seems somewhat extreme, and in the case of the Sheffield ganisters other sources of silica seem to have been at least as important. Stylolites are occasionally present in the ganister and associated sandstones, indicating pressure solution. This may have supplied some quartz cement to adjoining lower pressure areas during late diagenesis. The replacement of quartz grains by pyrite similarly released silica to adjacent areas where deposition may have taken place.

F. Conclusions

Pedogenically formed quartz arenites are thus present within the basal Westphalian A succession of the Sheffield region. In most cases it appears that the parent material on which the soil profiles developed was a freely drained fine grained fluviatile/deltaic sand. This underwent rapid leaching due to its porous nature, and clays were washed down through the profile and deposited lower down occasionally as cutans. The period of pedogenesis was probably not long and soil horizons quickly developed. The type of vegetation and its density may have affected the rate of leaching (Bloomfield, 1953, 1956; Butuzova, 1962) causing resultant variations in the thickness and maturity of eluvial horizon. However, variations in parent material, and the depth and stability of the water table are probably more important in this respect, and result in major variations in ganister thickness and occurrence.

In most cases it appears that the actual amount of clay and unstable minerals that were removed from the eluvial horizon by leaching was probably less than 10%. Somewhat similar pedogenically formed quartz arenites (ganisters) have been described from the Triassic of Australia (Retallack, 1976, 1977). Like the Sheffield ganisters these formed by leaching of fluviatile deposits, but the water table generally was high and only a very thin (commonly <10 cms.) eluvial horizon developed. Consequently these palaeosols often show extensive evidence of gleying beneath the ganister horizon, and according to Stace *et al* (1968) classify as gleyed podzolic soils (under the FAO, 1974 system such palaeosols would probably classify as gleyic podzoluvisols). Evidence of gleying is not as common beneath the Sheffield ganisters and together with their thicker nature indicates formation in better drained sites.

The rate of development of the eluvial horizon and its resultant thickness depends on many factors including parent material, time, depth to water table, etc. As a result pedogenesis generally forms relatively thin quartz arenites normally less than 2m. thick. This is particularly true in lowland tropical areas where the optimum conditions for podzolization are not found.

CHAPTER THREE

CARBONIFEROUS STRATIGRAPHY AND SEDIMENTATION IN THE NORTHERN PENNINES

A. Introduction

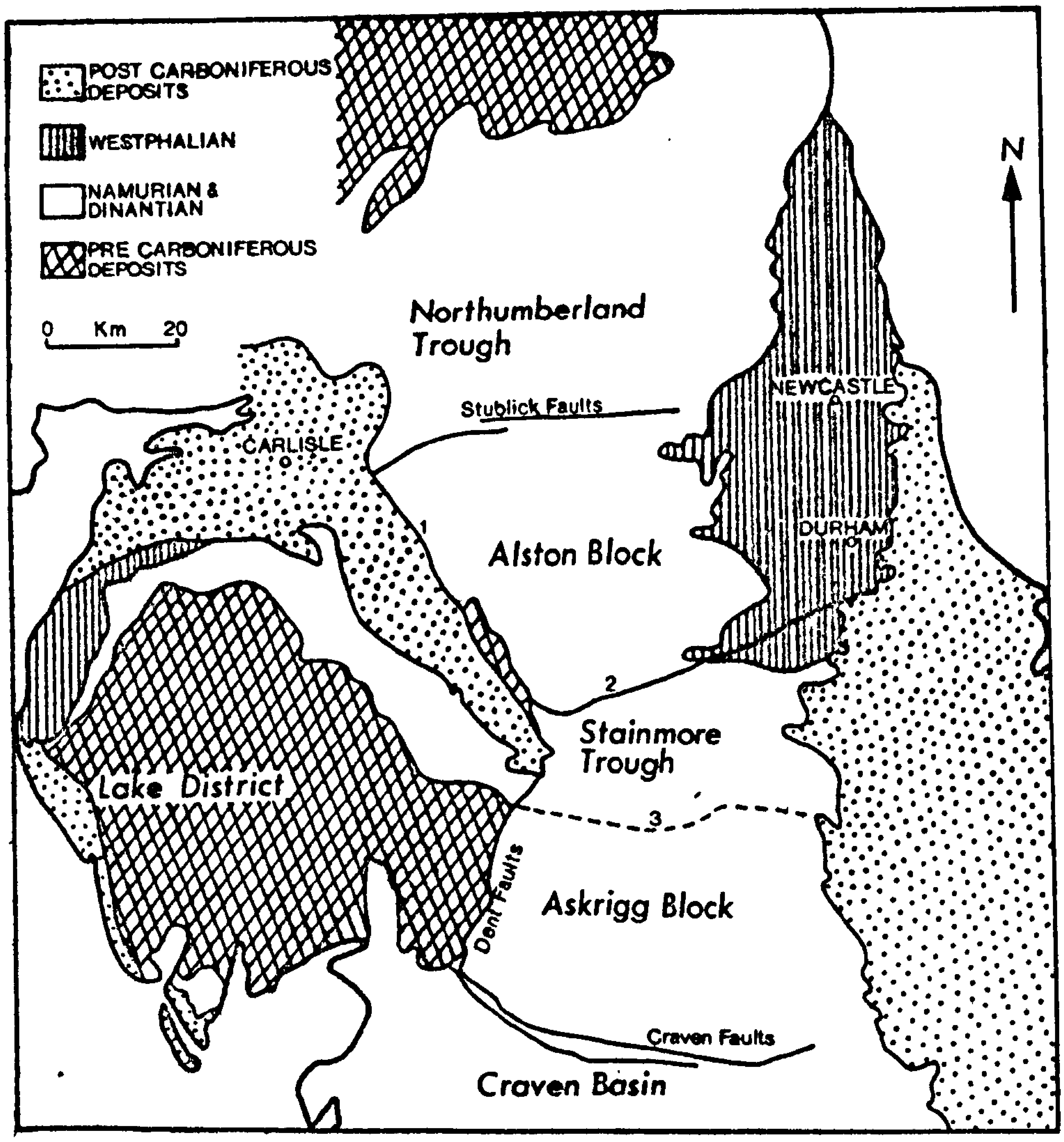
The Northern Pennines rise on the N. side of the Craven lowlands of Yorkshire, and extend northwards to the Tyne valley in Northumberland (Figs. 15 and 16). They consist of a belt of high moorland, approximately 50 kms. wide that is divided into 2 parts by the topographically lower, E.-W. orientated Stainmore pass.

The present study is confined mainly to the northern half of this region (the Alston Block, p. 58) centred on Weardale and Teesdale (Fig.16). In this area the highest peaks occur along the Pennine escarpment (e.g. Cross Fell 893 m.) which forms a superb natural boundary between the Pennines and the Vale of Eden. From this western extremity maximum elevations tend to decrease eastwards, and gradually the area merges into the low lying Durham Coalfield. The main rivers formed as consequents on this regional slope, and drain eastwards into the North Sea.

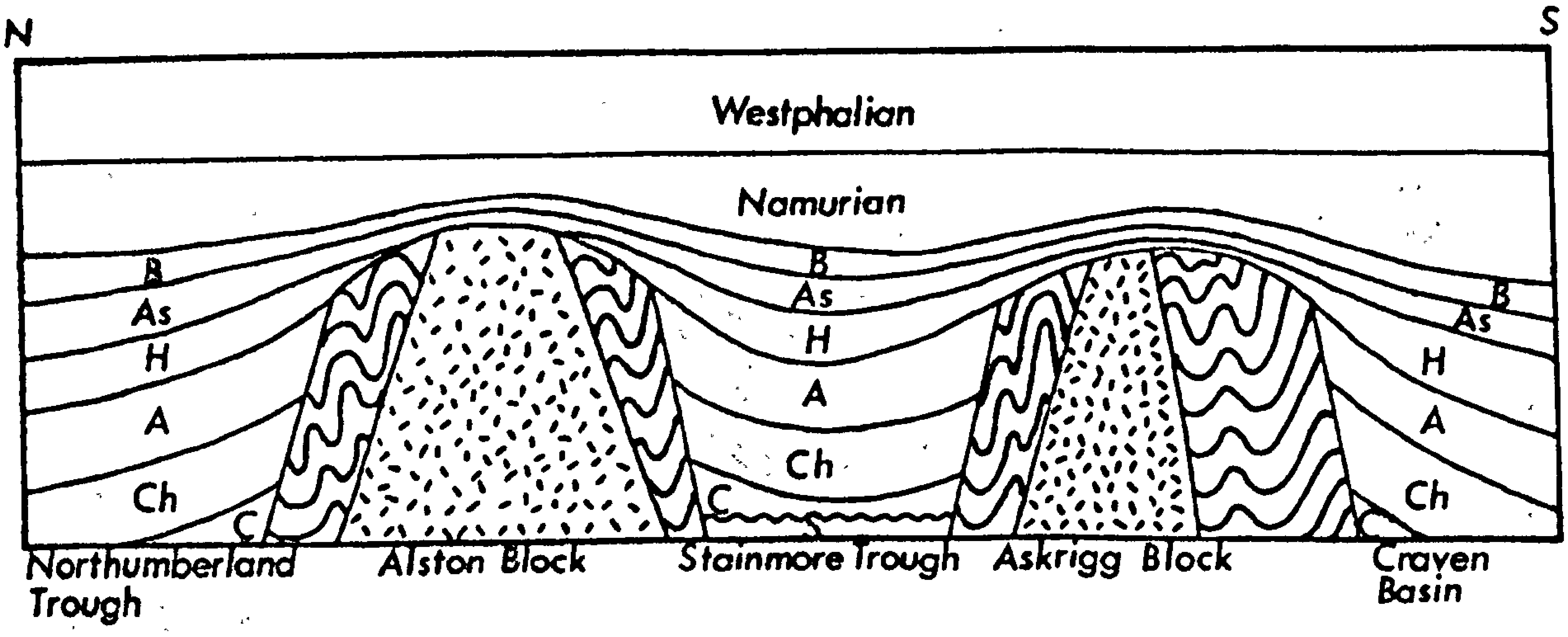
B. Geology of the region

(i) Stratigraphy

The Alston Block consists of an easterly dipping succession of Carboniferous rocks unconformably overlying a dominantly lower Palaeozoic basement. This basement outcrops in 2 main areas within the region, the Cross Fell inlier along the Pennine escarpment and the Teesdale inlier beneath



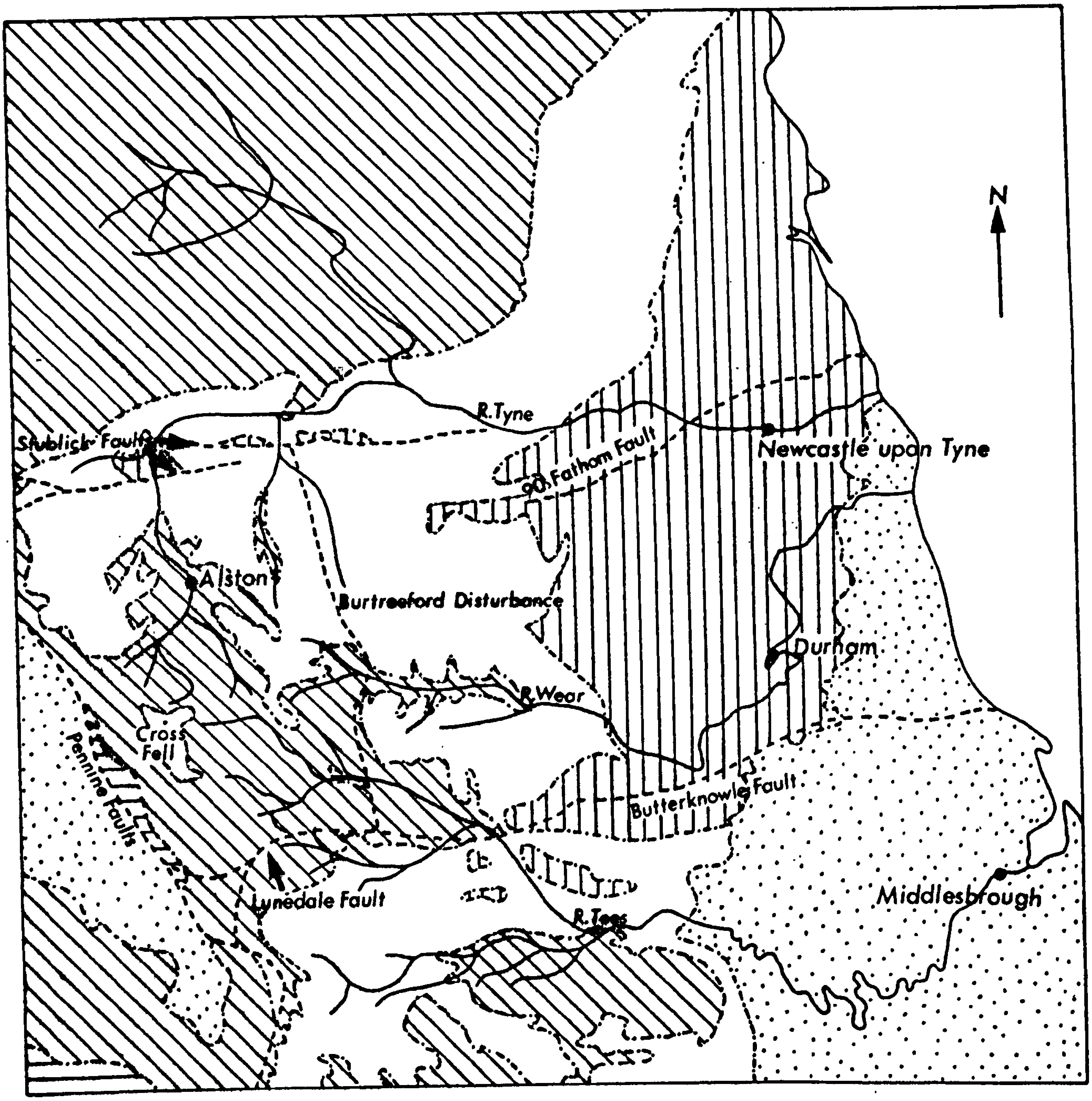
Geological sketch map of Northern England showing the Carboniferous outcrop and the fault lines surrounding the Alston and Askrigg Blocks. 1=Pennine Faults, 2=Lunedale-Butterknowle Fault, 3=Stockdale Monocline.



Diagrammatic N-S section across the Northern Pennines to illustrate the variation in thickness of the Carboniferous succession due to the block and trough structure. At the present day the block boundary faults cut both the Westphalian and Namurian strata as well. S=Silurian, C=Courceyan, Ch=Chadian, A=Arundian, H=Holkerian, As=Asbian, B=Brigantian. Length of section approximately 140 kilometres. ⁚=Granite ▨=Lower Palaeozoics and Precambrian?

Fig.15

GEOLOGY OF NORTH EAST ENGLAND



=Post Carboniferous

=Westphalian

=Namurian

=Dinantian

=Pre Carboniferous

The limits of the present study area are as follows:-R.Tyne (W-E portion), Pennine Faults, southern edge of map, N-S line approximately 10kms. west of Durham.

Fig.16

Cronkley Scar. Elsewhere the basement has been encountered in boreholes (e.g. Woolacott, 1923).

All the workable mineral deposits of the region occur in Carboniferous strata, and many of the stratigraphic names for horizons originate from the terminology of the early lead miners. Westgarth Forster (1809) used this terminology with other data from leadmining to build up a standard stratigraphic succession for the region. This has survived with only minor amendment to the present day. Subsequent work on the area included that of Winch (1817), Sopwith (1833) and Wallace (1861).

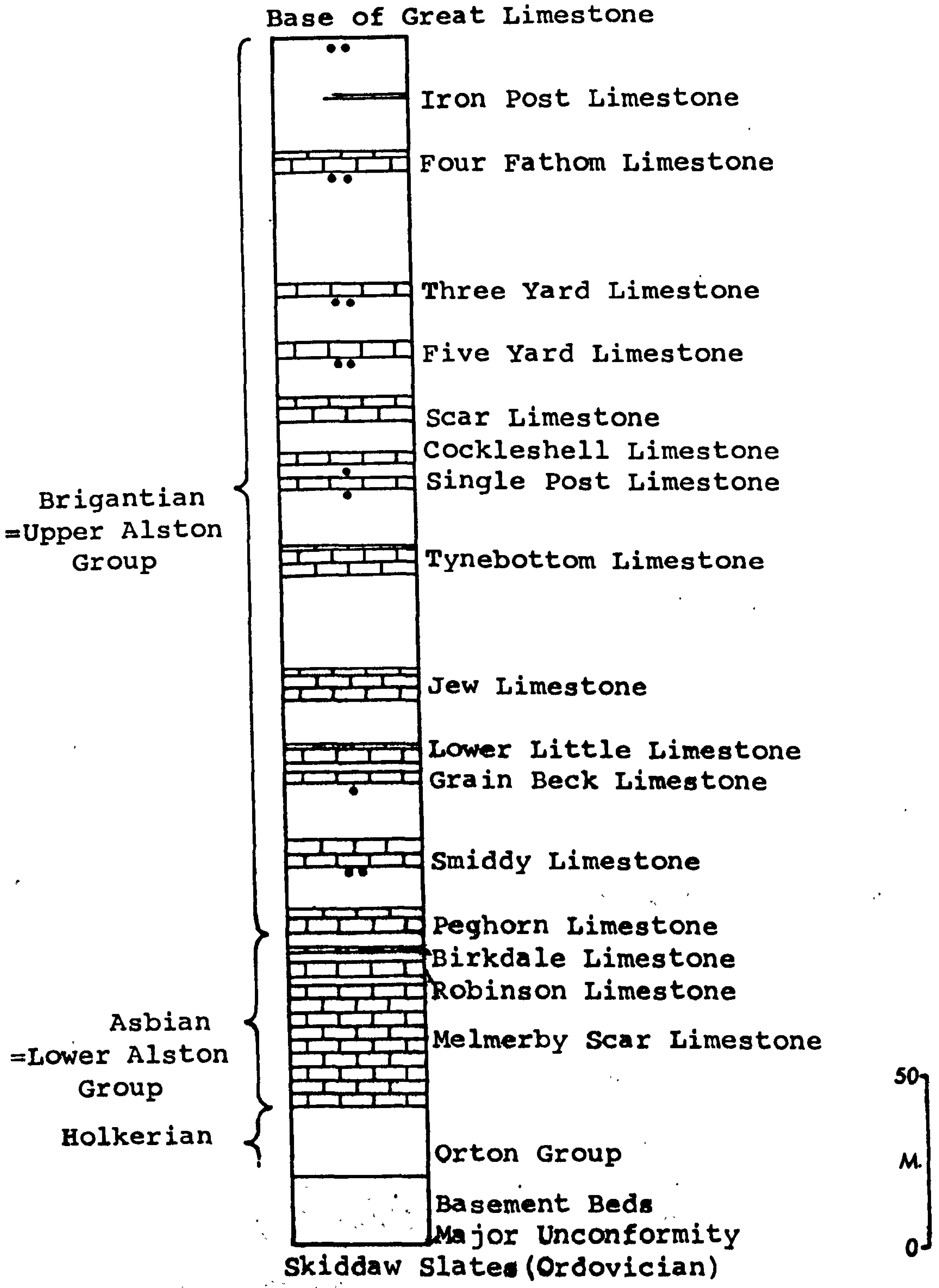
In the 1870's and 1880's the whole area was mapped on a 6" scale, and a series of 1" maps were published, but unfortunately no memoirs were produced. In these early days correlation and subdivision of the Carboniferous succession was based on lithology and it was not until the work of Smith (1910), and Garwood (1913) that a palaeontological approach was introduced. Subsequent work by Turner (1927), and Miller and Turner (1931) extended this approach. However, much of this work was based on Vaughan's (1905) Dinantion coral/brachiopod zones, and it was not until Bisat (1924) introduced the use of goniatites into the area, that reasonable correlations of higher parts of the succession could be made.

Goniatites are, however, fairly rare in the strata of the Alston Block, and as a result subdivision of the sequence has been a lengthy procedure. This has meant that although the main series boundaries are rigidly defined (Johnson, Hodge and Fairbairn, 1962; Mills and Hull, 1968), some of the stages are less well known. In recent years there has been a trend away from this type of subdivision, and Ramsbottom (1973, 1977a, 1979) has divided most of the Carboniferous into a series of major transgressive-regressive cycles, the recognition of which is based upon lithology, supported by available palaeontological information. These major cycles approximately coincide with previous stages, as the major transgression which began each cycle was accompanied by the associated fauna that is used to recognize each different stage. This new system has been accepted in part, and the current stratigraphic subdivision of the Carboniferous rocks of the Alston Block is shown in Figs. 17 and 18.

Besides this stratigraphic work attention also focussed on the mineral deposits and their origins. As a result of the nature and distribution of the deposits a series of gravity surveys were undertaken which suggested a granite batholith lay beneath the Carboniferous cover (Bott and Masson-Smith, 1953, 1957; Bott, 1960). The existence of the granite was later proved by a borehole, but instead of being intrusive into the Carboniferous it lay unconformably below (Dunham, Dunham, Hodge and Johnson, 1965). Later radiometric dating proved it to be of early Devonian age (Fitch and Miller, 1965).

Since the original mapping of the Geological Survey, there has been some remapping of areas, particularly by research students (Green, 1954; Short, 1954; Jones, 1956; Harbord, 1962; Pattinson, 1964). The Geological Survey started a similar programme in the 1920's and new revised sheets (Brampton, 18; Hexham, 19; Penrith, 24; Alston, 25;

DINANTIAN STRATIGRAPHY OF THE ALSTON BLOCK

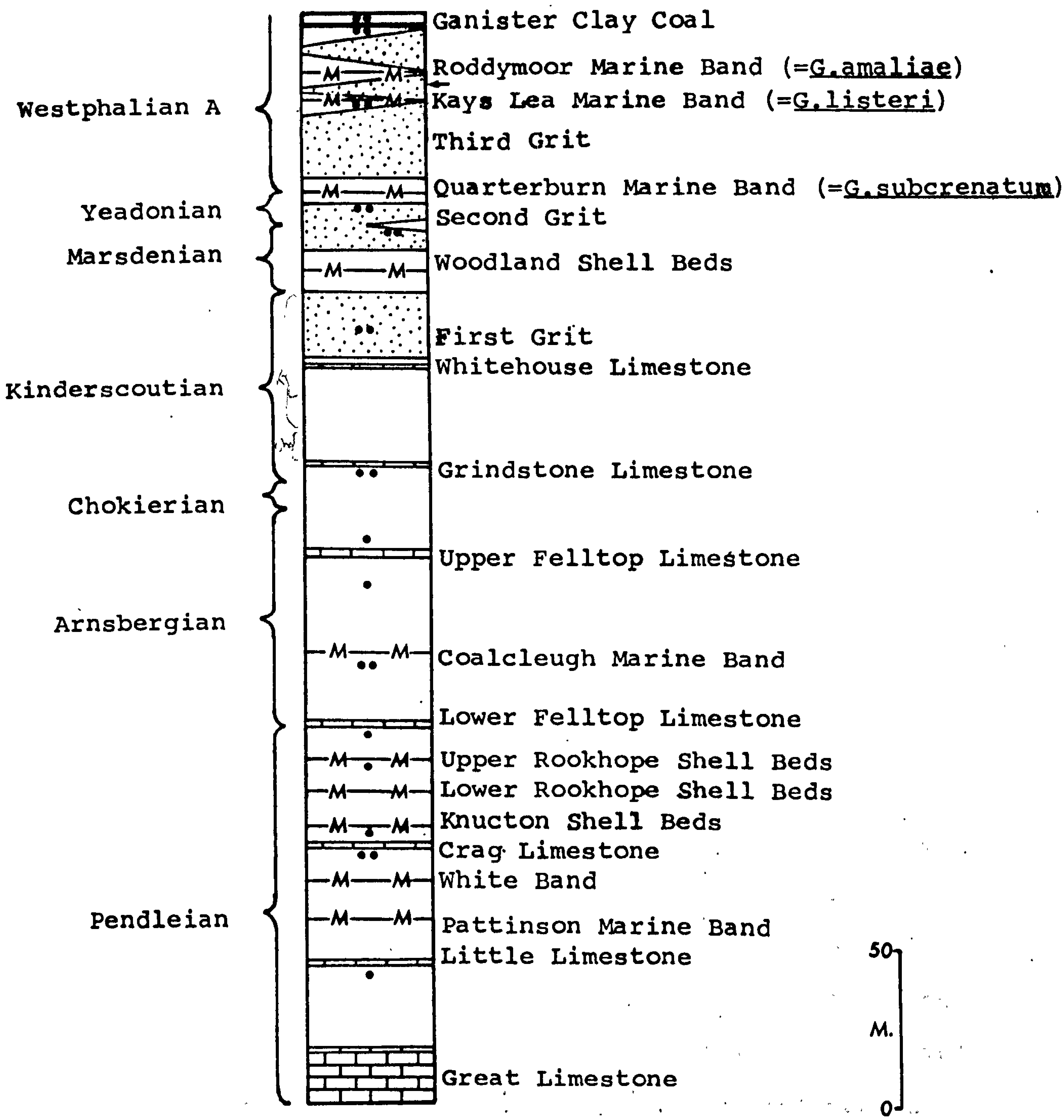


••=Worked occurrences of quartz arenite and ganister

•=Other horizons of quartz arenite and ganister known to author

Fig.17

NAMURIAN AND BASAL WESTPHALIAN STRATIGRAPHY OF THE ALSTON BLOCK



••=Worked occurrences of quartz arenite and ganister

•=Other horizons of quartz arenite and ganister known to author

Note that strata of Alportian age are completely absent on the Alston Block.

←= Third Grit of Mills and Hull, 1976.

Fig.18

Wolsingham, 26; Brough, 31; Barnard Castle, 32), and more rarely memoirs have been published (Brampton: Trotter and Hollingworth, 1932; Barnard Castle: Mills and Hull, 1976; Brough: Burgess and Holliday, 1979). As a result a firm stratigraphic framework for much of the region has been established. Even with this background of resurvey, there remain many areas where stratigraphic control is poor, and much more work needs to be done to determine successions and facies changes.

(ii) Structure

The structure of the Northern Pennines is fairly simple with dips in the Carboniferous strata only slight, and folds few in number, and generally only associated with faulting. This undeformed sequence overlies a much more highly contorted dominantly Lower Palaeozoic basement in a region bounded on all but its eastern side by faults (Fig.15). These facts led Marr (1921) to suggest that the Northern Pennines had acted as a rigid block since pre-Carboniferous times. This region became known as the Northumbrian Fault Block (Versey, 1927), and later became separated into the northern Alston Block (Trotter and Hollingworth, 1928), and the southern Askrigg Block (Hudson, 1938) (Fig.15). These 2 positive regions are separated by the Stainmore Trough (Dunham, 1948) or Cotherstone Syncline (Reading, 1957). Northwards the Alston Block passes into the Northumberland Trough across the Stublick-Ninety Fathom hinge line. Similarly southwards the Askrigg Block passes into the Craven Basin across the Craven Fault Belt.

The present research area is confined mainly to the Alston Block, but does extend into parts of the Stainmore and the Northumberland Troughs (Fig.16). Trotter and Hollingworth (1928) working mainly in the north western part of this area, proved that during Carboniferous times the block acted as a positive area relative to the more rapidly subsiding Northumberland Trough. The line of junction between the 2 zones is the Stublick Fault system on which there was active synsedimentary movement.

In the S. a similar relationship exists with the Cotherstone syncline where fault movement took place along the Lunedale-Butterknowle line. Differential subsidence occurred throughout the Lower Carboniferous but gradually decreased throughout the Namurian and by Westphalian times the relative movement of subjacent crustal blocks had almost ceased.

Post-Carboniferous movement along the boundary faults has taken place, and the present elevation of the Alston Block is thought to be due to Tertiary uplift (Trotter, 1929). The western limit of the Alston Block is taken along the Pennine Fault system. Much of the movement along this fault zone appears to be post-Carboniferous in age.

The main structural features on the Alston Block are the Teesdale dome, and the Burtreeford disturbance. The Teesdale dome consists of a gentle anticlinal structure, whose relatively flat top lies in the region of the head-waters of the River Tees and Maize Beck. In the neighbourhood of Langdon Beck this is cut by the Burtreeford disturbance, which consists of a N.-S. oriented E. facing faulted monocline. This divides the block in 2 parts, and is responsible for the presence of the Teesdale inlier on the upthrown side. In the region of Cowshill the downthrow is 77m. to the E., but further to the S. in Burnhope Burn this reaches 153m. (Dunham, 1948).

(iii) Carboniferous sedimentation

The fact that the Alston Block acted as a positive area relative to the more rapidly subsiding troughs to the N. and S., and the presence of granite beneath the Carboniferous cover, led Bott and Masson-Smith (1957), to suggest that the mass deficiency of the granite was responsible for the blocks restricted subsidence, and also its present day uplift. Similar conditions prevailed over the Askrigg Block to the S., and the recent discovery of the Caledonian Wensleydale granite (Dunham, 1974) indicates that perhaps similar isostatic adjustments took place in this region as well.

Besides the condensed nature of the sequence on the blocks, sedimentation also began much earlier in the troughs. The oldest known marine strata from the Stainmore Trough are of Courceyan age, whilst the Alston Block was not finally submerged until Asbian times (Fig.15). Earlier marine strata are known, but the Asbian transgression resulted in widespread limestone deposition over the entire block. This continued for the majority of Asbian time, resulting in the Melmerby Scar, Robinson and Birkdale Limestones. The succeeding Peghorn Limestone contains the *Girvanella* nodular band near the top which marks the base of the Brigantian. Above this the succession consists of rhythmically interbedded limestones, shales, sandstones, and thin coals which Phillips

(1836) termed the Yoredale Series from their type locality in North Yorkshire. This facies spans the Dinantian-Namurian boundary extending up to the last limestone in the succession. Geographically this facies can be traced northwards as far as Southern Scotland, and as far S. as the Craven Faults. Throughout this region there are variations, probably the most important of which is the northward splitting and thinning of many of the limestones (Hind, 1902; Johnson, 1960, 1962).

The rhythmic nature of this facies was noted by earlier workers (e.g. Miller, 1887) and subsequently many geologists have been intrigued by the conditions that led to their formation. In the United States similar Carboniferous sequences have been known for a long time (e.g. Dawson, 1853), and were termed cylothems by Wanless and Weller (1932). This term was eventually introduced into Britain by Dunham (1948) to describe the Yoredale rhythms.

Since the initiation of the term, research on cyclothems has consisted mainly of identification of their component parts, and formulation of models to explain their origin. The first result of this has been the emergence of the concept of an 'ideal' cyclothem. The component parts of these 'ideal' cyclothems vary between authors, but all agree that the basic necessary constituents in ascending vertical order are: limestone, shale, sandstone, seatearth, coal (Dunham, 1950; Weller, 1957; Johnson, 1959; Moore, 1960). Gradually there has been a trend away from this concept as cyclothems vary widely in their make up, and such 'ideal' sequences rarely occur.

The second result has been the development of a number of ideas concerning the cause of cyclothemic sedimentation, none of which alone has proved conclusive. This has led to continuing debate over the following causative mechanisms:-

(1) Eustatic sea level changes (Moore, 1950; Wells, 1960; Ramsbottom, 1973, 1977a).

(2) Climatic change (Brough, 1928; Beerbower, 1961).

(3) Vegetational control (Robertson, 1948).

(4) Variations in sedimentation rates due to delta switching (Moore, 1958, 1960).

(5) Tectonic control (Hudson, 1924; Brough, 1928; Weller, 1930, 1958; Dunham, 1950; Johnson, 1962, 1967; Bott and Johnson, 1967; Westoll, 1968).

(6) Variations in sediment compaction (Van Der Heide, 1950).

(7) Combined climatic and eustatic control caused by cyclic changes within the Gondwana glaciation (Wanless and Shepard, 1936; Wanless, 1950).

Of these ideas, the eustatic, tectonic and delta switching models seem most applicable to the Yoredale cyclothems. In recent years there has been a trend away from the tectonic 'hiccup' model (Selley, 1970), due in part to the widespread nature of the deposits and the resultant large scale earth movements that would be required. A very important feature of Yoredale sedimentation is that during deposition of over 490 m. of strata the sedimentary surface was always close to sea level. Maintenance of such conditions for approximately 8-10 million years, and preservation of a considerable sedimentary record requires slow fairly continuous subsidence in the depositional basin. Inevitably this must be tectonically controlled as sedimentary loading alone cannot produce the required effect (Bott and Johnson, 1967). Also relative movements between crustal blocks is known to have taken place. This is very unlikely to have occurred by a creep type mechanism along the hinge lines and undoubtedly short periods of fault movement must have taken place, thus giving tectonic 'hiccups'.

The fact that the sedimentary surface was maintained close to sea level means that changes from marine to non-marine conditions could be accomplished quite easily. Superimposed on this framework of overall slow tectonic subsidence other factors such as delta switching, eustatic changes, etc. could act and produce Yoredale cyclothems.

The idea of variations in rates of sedimentation producing the cyclothems has existed for a long time, indeed the presence of interbedded limestones, shales, sandstones and coals demand that such conditions must have existed. Moore (1955, 1958, 1960) working in the type area of the Yoredalesin Wensleydale concluded that the cyclothems resulted from intermittent deltaic invasions of a shallow limestone sea. Periodically the delta switched to a new area due to avulsion of the main channel, and the old delta underwent subsidence which carried it below sea level where limestone deposition began. Repetition of these events led to formation of the Yoredale Series. Moore likened the clastic portion of the Yoredales with the deposits of the Mississippi delta which is known to have undergone switching, and thus produced stacked sequences. Subsequent workers took up this idea (Jones, 1956; Harbord, 1962; Duff, Hallam and Walton, 1967), and as a result all Yoredale clastic sequences became regarded of Mississippi type delta origin. However, it should be noted that the modern Mississippi progrades into far deeper water than that in which the Yoredales formed, and is unassociated with any modern carbonates. Consequently differences exist between the Yoredale cyclothems, and modern Mississippi delta sequences (Moore, 1959).

Pattinson (1964) was one of the first to suggest that the Mississippi delta model for the Yoredales had become somewhat overused. Although he still recognized an overall deltaic origin, he also stressed the wide range of environments that existed under such a heading. Subsequent work has tended to develop the idea of a deltaic origin, and gradually the recognition of associated subenvironments has increased (Elliott, 1973, 1974, 1975).

The idea of delta switching as the causal mechanism of cyclothem formation has declined in popularity, as it cannot explain features such as coal lying directly on or in limestone (Smith, 1912; Elliott, 1973). Also limestones formed in one area should be contemporaneous with deltaics formed in another, as submergence of the abandoned delta lobe will be concomitant with growth of a new delta. This has led to the idea being discarded as a mechanism on its own.

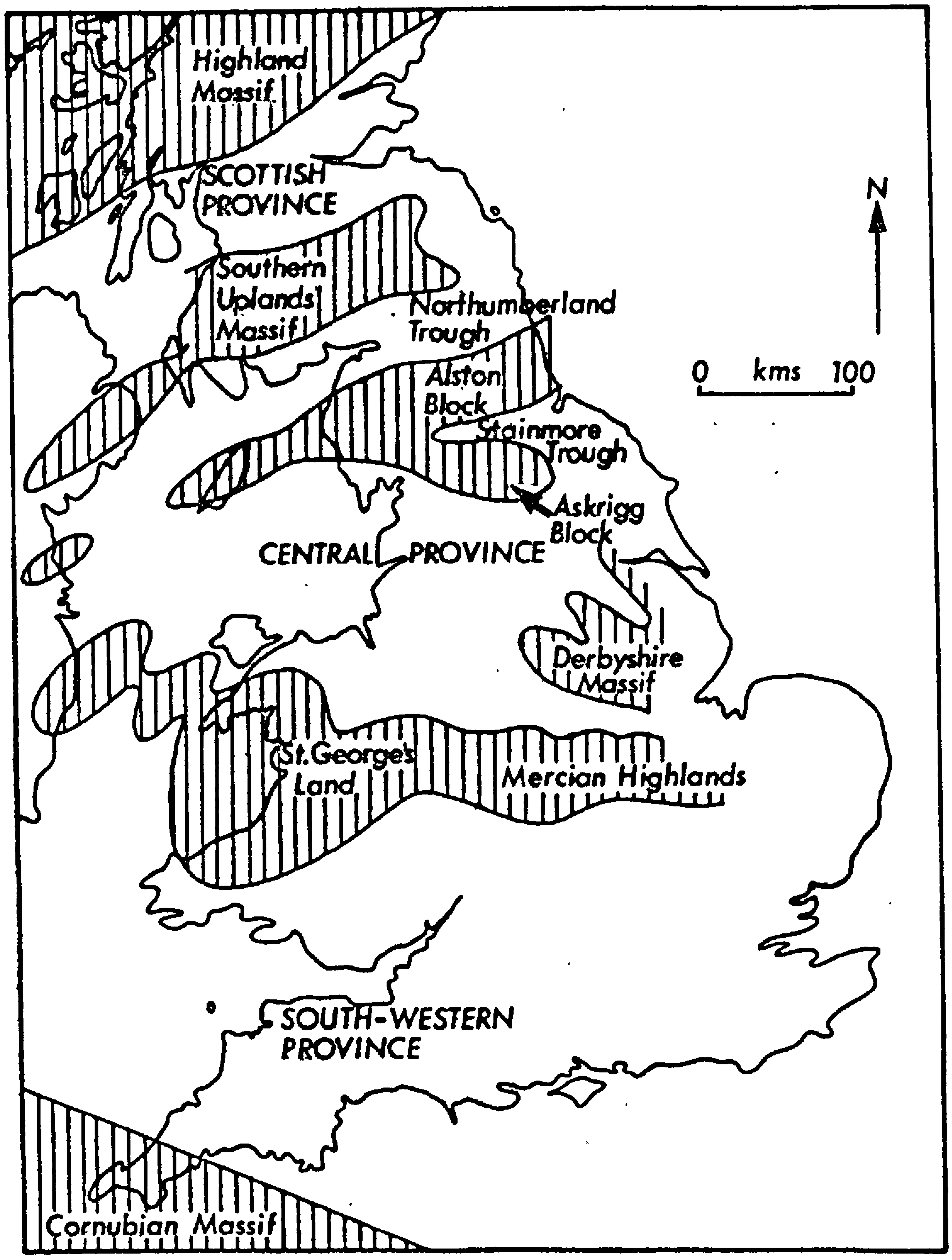
In recent years, the idea of eustatic sea level changes leading to cyclothem formation has resurged. This has occurred particularly through the work of Ramsbottom (1973, 1977a, 1979), who has invoked eustatic changes and used these as stratigraphical markers to subdivide the Dinantian and Namurian. However, the criteria for recognition of an eustatic sea level rise are not by any means conclusive, and the cause of the sea level changes remains unknown. Changes due to glacial cycles in Gondwanaland cannot be applied to the Lower Carboniferous as unequivocal glacial deposits of this age are unknown. Thus until any evidence to the contrary arises, alternative mechanisms have to be used. The most obvious of these are changes in sea floor spreading rates, which alters the bulk volume of oceanic ridges (Van Andel and Heath, 1970; Hallam, 1973). Such eustatic changes tend to be long period, large scale transgressions and regressions, unlike the shorter periodicity necessary to form most Yoredale cyclothems. Possible causes of rapid eustatic rises in sea level include dessication of ocean basins, regional tectonic movements, and large scale submarine volcanic outpourings (Schlager, 1981). However, sufficient data on these processes does not exist, consequently whether the periodicity and scale of these events is similar to that necessary to produce Yoredale cyclothems remains unknown.

Thus the eustatic theory really requires a causative mechanism, and must be able to exhibit unambiguous intercontinental correlations of transgressive and regressive phases before it can be wholly acceptable. It is very unlikely that during a period as long as the Carboniferous that some eustatic changes did not take place. Whether these were sufficiently frequent to cause cyclothem formation remains problematical.

It thus seems evident that during formation of the Yoredale cyclothems, tectonic movements, delta switching, and eustatic changes all took place to some degree. These affected a broad flat coastal plain and associated shallow-marine sea extending to the Craven district in the S., and resulted in deposition of the Yoredale series. Each major limestone represents a marine transgression which was followed by clastic deposition due to progradation of the shoreline. During formation of any individual cyclothem one or more of the 3 main causative mechanisms may have been operating, and resulted in the actual sequence preserved. Detailed analysis of a particular cyclothem should therefore elucidate the conditions that controlled its formation, and the depositional environments that were present. Cyclothems can vary widely in composition, and any general model to explain their origin is probably an oversimplification. Each cyclothem is an independent unit, and should be treated as such in its interpretation.

During formation of the Yoredale series open marine conditions lay to the W. (Whitehaven district, etc.), and S. (Craven lowlands, etc.) of the Alston Block, and land lay to the N. and N.E. (Gilligan, 1920; Johnson, 1972), (Figs. 19 and 20). In this zone between truly marine and truly terrestrial conditions the Yoredales reach their acme. Sediment was supplied to the depositional basin from this northern landmass, and often led to delta progradation into the shallow-marine seas which commonly encompassed the region (Johnson, 1960, 1962).

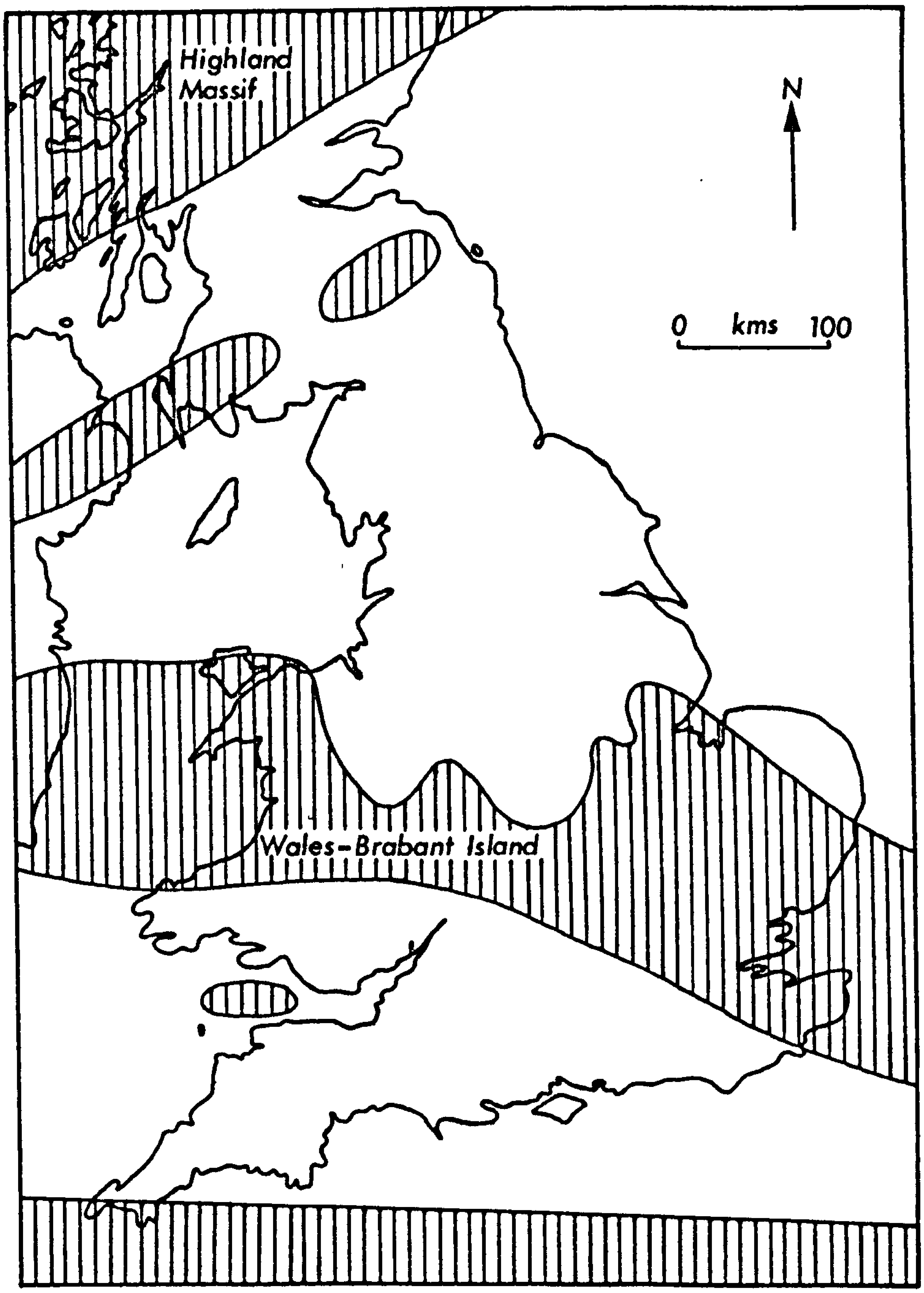
DINANTIAN PALAEOGEOGRAPHY



Palaeogeographic reconstruction of the main provinces of Dinantian sedimentation in Britain,modified from George (1969).The margins of the massifs are approximate at best and particularly in offshore areas become somewhat conjectural.Regions such as the Alston and Askrigg Blocks became submerged towards the end of the Dinantian and formed sites of slow regional subsidence.Deposition also took place on the Derbyshire Massif which throughout this period formed a shallow shelf region.The remaining massifs contain no marine Dinantian deposits and existed as land areas.

Fig.19

NAMURIAN PALAEOGEOGRAPHY



Palaeogeographic reconstruction of the main land areas in Britain during deposition of the Namurian, after Ramsbottom(1969). North of the Wales-Brabant Island terrigenous sediment was derived mainly from the northern Highland Massif. Locally, however, the Wales-Brabant Island supplied quartz rich sediments to the Central England Province.

Fig.20

Overlying the Yoredale Series of the Alston Block are the 3 Durham Grits. These were formerly regarded to be of 'Millstone Grit age' (Forster, 1821), but only the First and Second Grits are Namurian, the Third Grit being Westphalian A in age (Johnson, 1972; Mills and Hull, 1976). In many areas the concept of the 3 grits is something of an oversimplification, and the succession consists of up to 115 m. of interbedded very coarse to fine grained sandstones, shales and coals. When present, the grits consist of thick (approx. 20 m.) often very coarse grained and pebbly sandstones, and are equivalent to some of the higher grits of the Craven Basin which are interpreted as being fluvial and deltaic in origin (Walker, 1966; Collinson, 1968, 1969; McCabe, 1977, 1978; Jones, C.M., 1980). No detailed sedimentological work on the Durham Grits has been undertaken, but Jones (1956), and Pattinson (1964) suggest a broadly similar fluvial and deltaic origin.

Overlying the Durham Grits are the productive Coal Measures of the Northumberland and Durham Coalfield, which consist of interbedded shales, sandstones and coals. Marine bands are present, particularly towards the base of the succession, and many contain impoverished faunas compared with their more truly marine representatives in the Midlands (Calver, 1968). Non-marine bivalves, however, are fairly abundant, and are invaluable in zonation and correlation at certain levels.

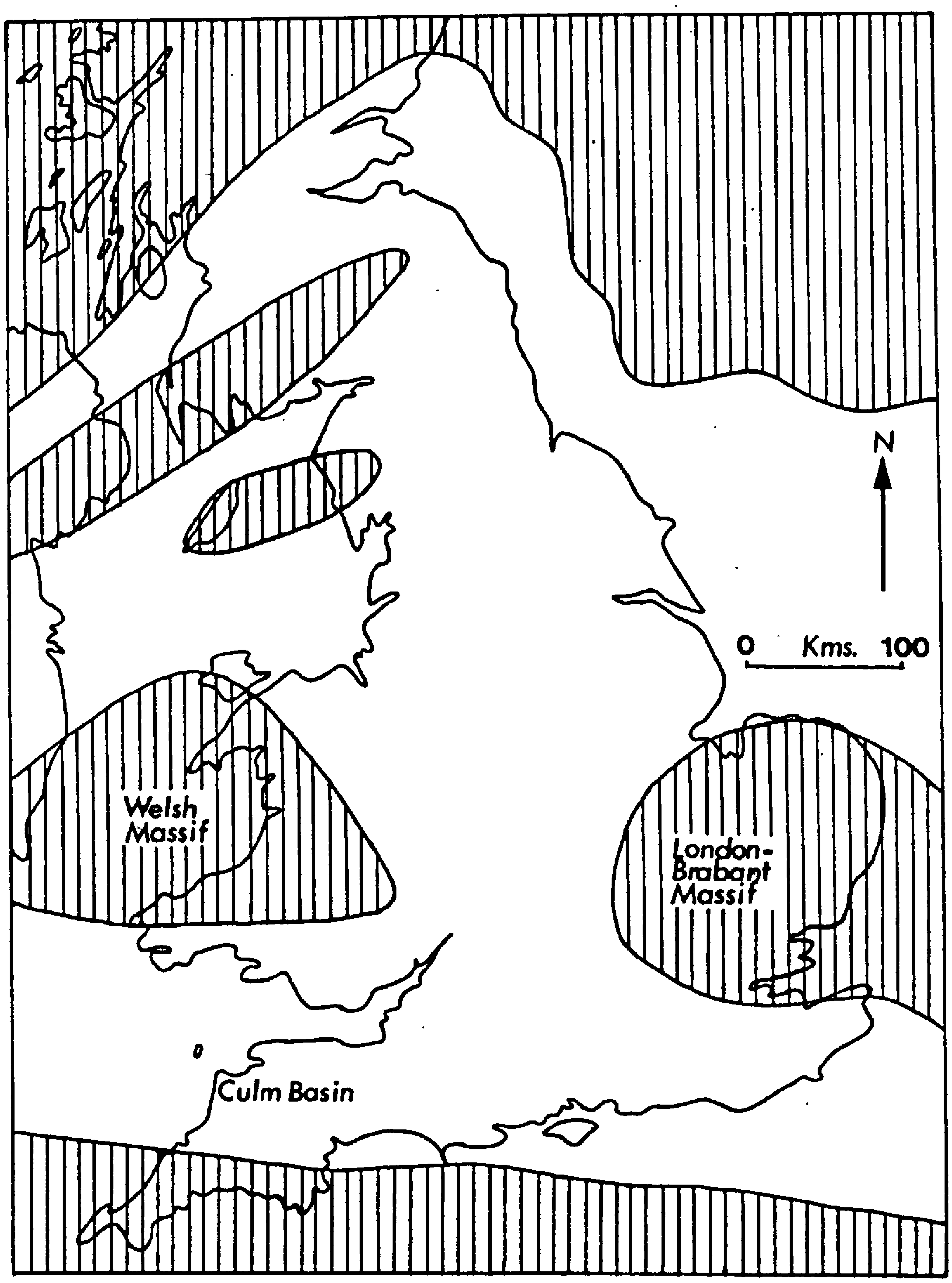
Economically workable coals occur throughout the succession, but are most common in Westphalian B where individual seams up to 2.4 m. thick are present. Above this they tend to become thinner, more widely separated, and locally suffered pre-Permian erosion.

The abundance of coals, rootlet beds, non-marine bivalves and channel sandstones led many workers to suggest that a delta top environment persisted during deposition of the Coal Measures (Land, 1974; Mills and Hull, 1976; Jones, J.M., 1980). More detailed work has suggested a broad virtually flat coastal plain (Clarke, 1963; Haszledine and Anderton, 1980; Heward and Fielding, 1980). This was crossed by a number of rivers which often built out small deltas into the abundant shallow lakes. Occasionally fairly large areas were starved of detritus, and coal swamp conditions prevailed.

Deposition on the coastal plain generally took place below or close to the water table as evidence of well drained conditions or dessication are rare. It thus formed a vast flat swampy area which probably lay close to sea level, and periodically underwent low energy transgressions due to relative sea level rises.

Palaeogeographically the Westphalian was broadly similar to the Namurian with the Caledonian source highlands to the N. and N.E., and more normal marine conditions to the S. (Fig.21). Gradually the coastal plain appears to have prograded southwards, and as a result the effect of the southern marine zone on the Northern Pennine region progressively declined throughout Westphalian time.

WESTPHALIAN PALAEOGEOGRAPHY



Palaegeographic reconstruction of Britain during the Westphalian,modified from Ziegler(1981).Land areas represent zones of non-deposition.Elsewhere sedimentation took place predominantly in fluvial and deltaic environments,except in the Culm Basin.Here deltaic sediments in the Westward Ho! area pass southwards into interbedded sandstones and mudstones of submarine fan origin.

Fig.21

C. Ganisters and quartz arenites

(i) Introduction

Within the Carboniferous succession of the Alston Block a wide variety of sandstone types are present. Texturally and mineralogically immature sandstones are the most abundant, but the sequence also contains a moderately large proportion of clean quartz arenites. These stand out in marked contrast to the less mature sandstones, and are particularly common in strata of Brigantian to Westphalian A age (Figs.17 and 18). Throughout this stratigraphic interval they are unevenly distributed, indicating that only during certain periods of time were conditions suitable for their formation.

Ganisters (as defined p. 5) are of much more restricted occurrence, for 2 main reasons. Firstly, ganisters are a particular type of quartz arenite which require specific conditions for their formation. Consequently they would be expected to be less common in occurrence than ordinary quartz arenites. During formation of the Carboniferous of the Alston Block the required conditions for ganister formation appear to have been rather rare.

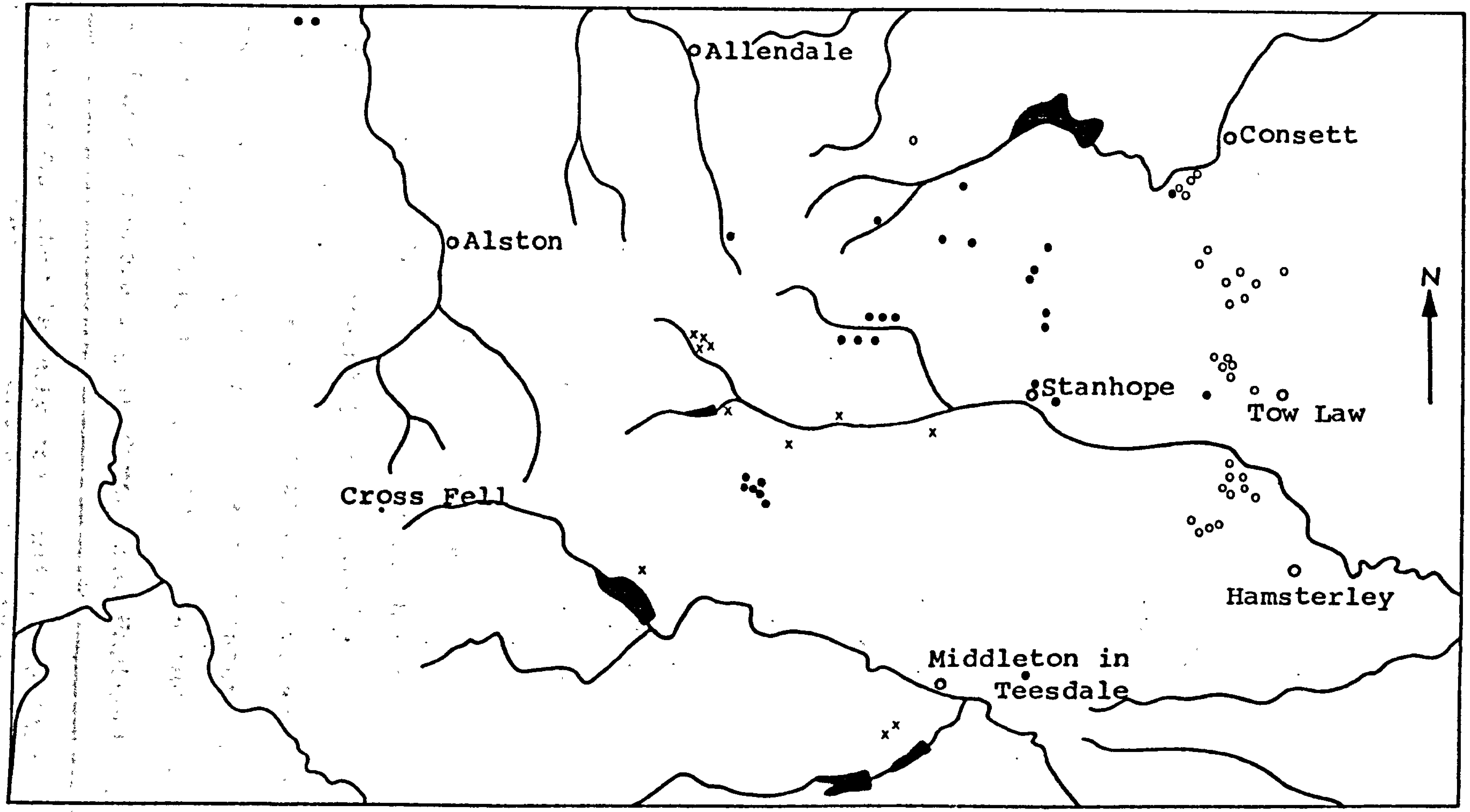
Secondly, ganisters occur as thin quartz arenitic horizons, exposures of which are generally very small and infrequent. Previous moderately large exposures in 'ganister' quarries are at the present day commonly obscured, due mainly to the method of extraction and also subsequent tipping. As a result although a large number of thin clean quartz arenites do occur within the Carboniferous succession, it is often impossible to deduce their environment of formation, owing to poor exposure. Evidence of a pedogenic origin is imperative before a quartz arenite can be termed a ganister, and thus proven ganisters are rare. It is, however, very likely that many unrecognized pedogenically formed quartz arenites are present within the Carboniferous succession of the Northern Pennines.

True ganisters are only definitely known from the Nattrass Gill Hazle (Brigantian), Firestone Sill (Pendleian) and basal Westphalian A. However, thin rooted quartz arenites occur at many other horizons, particularly within the basal Westphalian A, and include the celebrated Tow Law ganister.

This was probably the most sought after rock for refractory purposes in the Northern Pennines as in many respects it is almost identical to the Sheffield Blue Ganister. It outcrops mainly in the area immediately N. and N.W. of Tow Law, where it has been worked extensively both by quarrying and mining. An abundance of similar thin quartz arenites and ganisters occur close to this horizon, and these have been worked mainly in the area between Consett and Hamsterley (Fig.22). Most of these horizons appear to be lenticular, and cannot be traced far laterally. As a result each horizon was worked by only 1 or 2 small quarries in a limited area. In 1920 there were over 15 quarries working in the Consett to Hamsterley region, but by 1925 only a few remained (Collins, 1925) and of these several had begun mining due to increasing overburden thickness.

One of the last 'ganister' quarries to close was the West Butsfield Quarry (NZ 09504425) owned by the Consett Iron Company. This was one of the largest quarries in this

LOCATION MAP OF THE MAJOR "GANISTER" QUARRIES AND MINES ON THE ALSTON BLOCK



o = Westphalian A
• = Namurian
x = Dinantian

0 Kms 10

The regional tectonic dip is to the E. This results in the observed spatial distribution of the ages of the horizons worked.

Fig.22

region and worked a relatively thick quartz arenite (up to 3.2 m.) in a small inlier in Butsfield Burn. Today, as with several other quarries, this is being used as a council rubbish tip and most of the section is obscured.

Owing to the larger scale of workings and their more remote location, quarry sections in many of the Dinantian and Namurian quartz arenites and ganisters are much better preserved. Also in the upland areas, where these rocks outcrop, natural sections are much more abundant. The Dinantian and Namurian horizons most widely exploited for refractory purposes have been the Firestone Sill ganister,[1] Harthope Ganister, High Brig Hazle, Grindstone Sill, and several horizons in the Second Grit. A variety of other horizons have also been utilized, the stratigraphically lowest being a quartz arenite beneath the Smiddy Limestone at East Cowgreen (Dunham, 1948).

(ii) <u>History of ganister and quartz arenite extraction</u>

The need for a source of siliceous refractories within the region arose as a result of the development of an iron and steel industry particularly on the Northumberland and Durham coalfield. This began with the setting up of iron furnaces by the Derwent Iron Company at Consett in 1840. In 1845 a blast furnace was built at Stanhope and the Weardale Iron Company was formed which only a year later built 6 furnaces at Tow Law (Raistrick, 1968). By 1850 there were 38 blast furnaces operating in Durham and Northumberland of

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1. The term ganister is only spelt with a capital G, where it forms an essential part of the stratigraphical name for a particular sandstone horizon, e.g. Mirk Fell Ganister.

which one third were at Consett (Bowden and Gibb, 1970). The growth of the industry and the need for ganister and silica bricks led to a search for suitable refractory horizons. This resulted in the exploitation of the abundant thin quartz arenites and ganisters in the basal Westphalian A which were close to the main producing centres of Consett and Tow Law. Most operations were on a small scale and only lasted a few years.

Gradually the majority of production switched from these thinner horizons to the more remote, generally thicker deposits of Teesdale, Weardale, and the Tyne valley. By 1916 the largest producer in the area was the Sandy Carr ganister and firestone quarry (NZ 08703865) with an output of approximately 280 tons a week. By 1925, however, this quarry had ceased production (Collins, 1925). Subsequently by far the majority of production has come from the Harthope Ganister Quarries whose total output must have exceeded any other single horizon. These lie on the Teesdale-Weardale watershed (Fig.22) between Langdon Beck and St. Johns Chapel, and at one time supplied raw material for use in the Sheffield area.

With the decline in the iron and steel industry in the region, and due to cheaper sources elsewhere there has been a major decrease in ganister and quartz arenite extraction. Finally with the closure of the Consett iron and steel works extraction has ceased. The last operating quarries in the region were those of British Steel at Harthope which were last worked in 1978.

D. Aims of research

The present research has had 2 main aims:

(1) To define the term ganister. This has involved research outside the Northern Pennines and is discussed in Chapters 1 and 2.

(2) To deduce the depositional environment and diagenetic histories of the so called 'ganisters' of the Northern Pennines, and to decide which classify as true ganisters under the new definition.

By far the major proportion of the research undertaken has concerned the 'ganisters' of the Northern Pennines. In this area a wide variety of quartz arenites have been termed 'ganister' due to their ability to be used in the production of siliceous refractories. The present study has been mainly confined to these horizons, but rocks of similar lithology which have not been worked, generally due to inaccessibility, have also been studied.

The main bulk of the field and laboratory work has lain in the detailed petrographical, sedimentological and occasionally pedological study of each particular quartz arenite horizon. In many cases it has also been necessary to examine other clastic and non-clastic parts of the succession to gain a broader understanding of the various depositional environments that existed in the region during the Carboniferous period. Integration of the results from these 2 sources has enabled a better overall understanding of Carboniferous depositional environments to be gained.

At the outset another major aim was to deduce the diagenetic histories of the rocks in question. Being quartz arenites they consist of a dominantly stable mineralogy which commonly results in a fairly simple diagenetic history. Variations do occur, but generally most horizons show a similar sequence of events. Consequently this has perhaps not received as much attention as originally intended.

Detailed study of each particular horizon has in many instances resulted in the ability to predict sand body geometry and trend. Often a relationship exists between vertical sedimentary sequences, depositional environment and sand body geometry. Thus, models arising from the present study may be useful in the prediction of subsurface sandbody parameters where the only available data are vertical logs.

In some instances elucidation of depositional environment and sand body trend has been important in defining the limits of some associated facies. This is particularly important in the case of coals, which although generally thin in this region are of high rank and have been worked in several areas up till recently. Models defining the limits of these economic coal deposits may prove valuable in any further exploration that is undertaken.

The main aims of this thesis have therefore been to define the term ganister and deduce the depositional environments and diagenetic/pedogenic histories of the 'ganisters' of the Northern Pennines. This has been confined mainly to the Alston Block because this was by far the dominant area of 'ganister' extraction owing mainly to its proximity to areas of iron and steel production.

The clastic Carboniferous (Brigantian-basal Westphalian A) sediments of the Alston Block have for a long time been considered to be of deltaic origin. In fact there has been very little detailed work on Carboniferous depositional environments in this area. Although the present study is confined to rocks of a particular lithology, they are moderately abundant within the local succession. Analysis of such horizons tends to demonstrate the wide range of depositional environments that existed on the Alston Block during deposition of the Carboniferous, many of which are not truly deltaic. This has important implications for the overall deltaic model as well as the mode of cyclothem formation and is discussed in Chapter 8.

From the present study it is apparent that the majority of well exposed, clean quartz arenites on the Alston Block, formed in one of the following ways:-

(1) By leaching in a palaeosol profile (ganisters)
(2) Reworking in a barrier island setting
(3) Reworking in a high energy shallow-marine environment.

In Chapters 4, 5 and 6 each of these modes of origin are discussed in turn, by detailed analysis of individual horizons studied. Often owing to poor exposure it is not possible to give an unequivocal mode of origin to certain horizons. Several quartz arenites which were once extensively worked for refractory purposes fall into this category, and these along with a variety of other 'ganisters' are discussed separately in Chapter 7.

CHAPTER FOUR

TRUE GANISTERS - QUARTZ ARENITES OF PALAEOSOL ORIGIN

A. Introduction

A wide variety of palaeosols occur within the Carboniferous deposits of the Northern Pennines. These include types where pedogenesis has resulted in the formation of a quartz arenitic (ganister) soil horizon. Recognition of such an origin is difficult unless exposure is good. This is often not the case, and as a result clearly demonstrable occurrences of ganister tend to be rare.

This chapter largely concerns the most notable occurrence of ganister in the Northern Pennines, which occurs at the top of the Firestone Sill. Several other minor horizons are also considered.

B. Firestone Sill

(i) Description

The name Firestone Sill, arose from the rock being used as a hearthstone for fireplaces (Forster, 1821) sill being a local term for a hard bed (Arkell and Tomkeieff, 1953). The Firestone Sill occurs at the top of the White Band cyclothem of Namurian (E_1, Pendleian) age (Hull, 1968; Ramsbottom, *et al*, 1978). It is present throughout most of the Alston Block and when traced southwards into the Stainmore Trough passes into the Uldale Sill which forms the upper half of the Ten Fathom Grit (Reading, 1957; Burgess and Holliday, 1979). Within the confines of the Alston Block, the name Firestone Sill is often given to any sandstone occurring directly below the Crag Limestone (Fig.23). As a result the name is applied to sandstones varying widely in character and lithology. Generally these variations can be explained in terms of the existence of 2 distinct facies (Dunham , 1948).

(a) Facies A

This facies outcrops extensively in a N.W.-S.E. trending zone from N. of Alston to Middleton-in-Teesdale. In this region Facies A is not ubiquitous, sometimes Facies B occurs, and locally sandstones of the Firestone Sill may be absent altogether. Facies A consists of an erosively based, fine to very coarse grained sandstone up to 20 m. thick. Commonly it overlies shales and at the base contains large intra-formational shale clasts (up to 80 cms. or more in length) and small vein quartz pebbles (generally <8 mm. long). Above this erosive base sandstones tend to fine upwards, and are dominated by planar and trough cross-bedding in sets up to 1 m. thick. Occasionally reactivation surfaces are present. Palaeocurrent dispersion tends to be low at any one locality, and regionally palaeocurrents are directed towards the S. and S.E. (Fig.24).

The top of Facies A is commonly penetrated by abundant rootlets and overlain by a coal which occasionally reaches a sufficient thickness (50 cms. or more) to have been mined. This coal was considered by Smith (1912) to be equivalent to the Oakwood Coal of the Tyne area, which reaches up to 1 m. in thickness (Jones and Cooper, 1972). The sandstones of Facies A are both texturally and compositionally fairly immature and contain moderate amounts of feldspar and clay

SECTION THROUGH PART OF THE UPPER LIMESTONE GROUP TO SHOW THE STRATIGRAPHIC POSITION OF THE FIRESTONE SILL

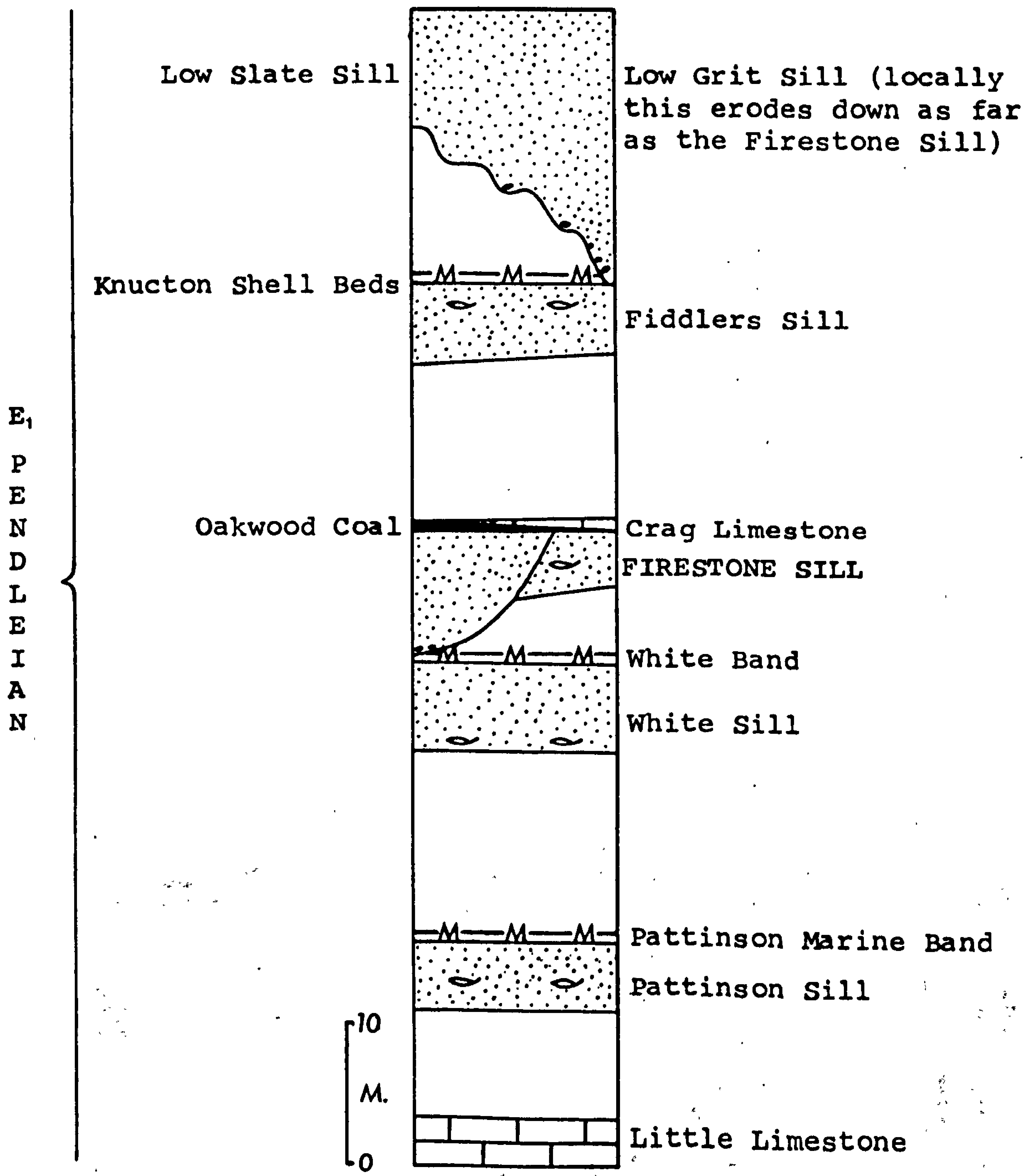
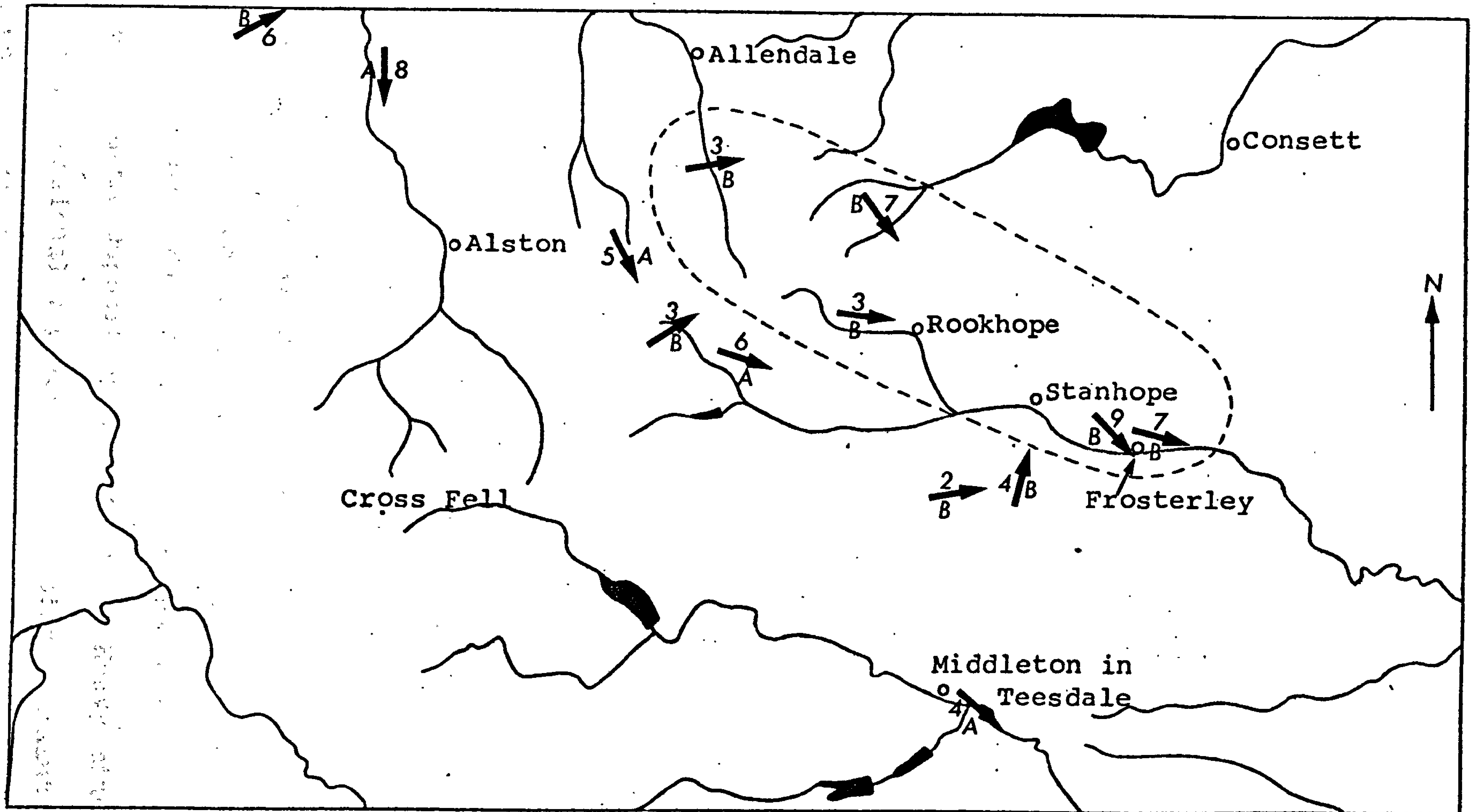


Fig.23

FIRESTONE SILL PALAEOCURRENTS



⟵ =Vector mean at each locality
A/B =Facies at each locality
3 =Number of cross-bedding readings
- - - =Dominant zone of ganister formation

Fig.24

minerals (Fig.25).

Typical exposures of Facies A can be seen in the River West Allen (NY 79854520) and the South Tyne Valley (NY 68605442), and are common throughout the Brampton Area (Trotter and Hollingworth, 1932).

(b) Facies B

Facies B outcrops extensively between East Allendale and Frosterley. Other occurrences exist to the S. and W. of this area, but differ slightly in mineralogy, sedimentary structures and palaeocurrents. This variation is gradual and thus no further subdivision of Facies B is made.

Facies B consists of a fine to medium grained sandstone containing subrounded, moderately well sorted grains (Fig.33). This sandstone is generally <10 m. thick (average approx. 6 m.) and forms the top of a coarsening upward sequence which begins with the fossiliferous White Band (Fig.26). Sandstone beds range from a few cms. up to 1 m. or more in thickness, and are commonly interbedded with thin shale laminae.

Sedimentary structures are variable in occurrence and tend to be dominated by parallel lamination, trough cross-bedding (including broad shallow forms up to a few metres wide and a few 10's cms. deep) and wave and current ripples. Other structures occasionally present include low angle lamination, planar cross-bedding, interference ripples, and rare low angle depositional surfaces. Heavy mineral laminae are occasionally present and consist dominantly of zircon and tourmaline.

POINT COUNT ANALYSES OF TRUE GANISTERS
AND ASSOCIATED STRATA

Horizon/ Facies	Quartz %	Mixed Layer Clay/Sericite %	Kaolinite %	Felospar %	Muscovite %	Carbonaceous Material %	Heavy Minerals %	Goethite %	Biotite %	Calcite %	N
Firestone Sill Facies A	78.5	4.5	8	8	0.5	0.5					200 [1]
Firestone Sill Facies B	89.17	7	0.58	1.5	0.42	0.33	0.08	0.92			1500 [6]
Firestone Sill Ganister	95.53	1.76		0.63	0.193	1.78		0.063		0.038	1900 [8]
Top Of Nattrass Gill Hazle East Blackdene	81.5									18.5	200 [1]
Sandstone Beneath Ganister, Nattrass Gill Hazle, East Blackdene	83	14	0.5					2	0.5		200 [1]
Top Of Lower Ganister, Bessys Bank, Castleside	92		0.5				0.5	7			200 [1]
Lower Ganister, Bessys Bank, Castleside	99							1			400 [2]

N=Total number of point count measurements(number in top right hand corner refers to the number of thin sections analysed)

Fig.25

COMPARATIVE SECTIONS THROUGH THE WHITE BAND CYCLOTHEM

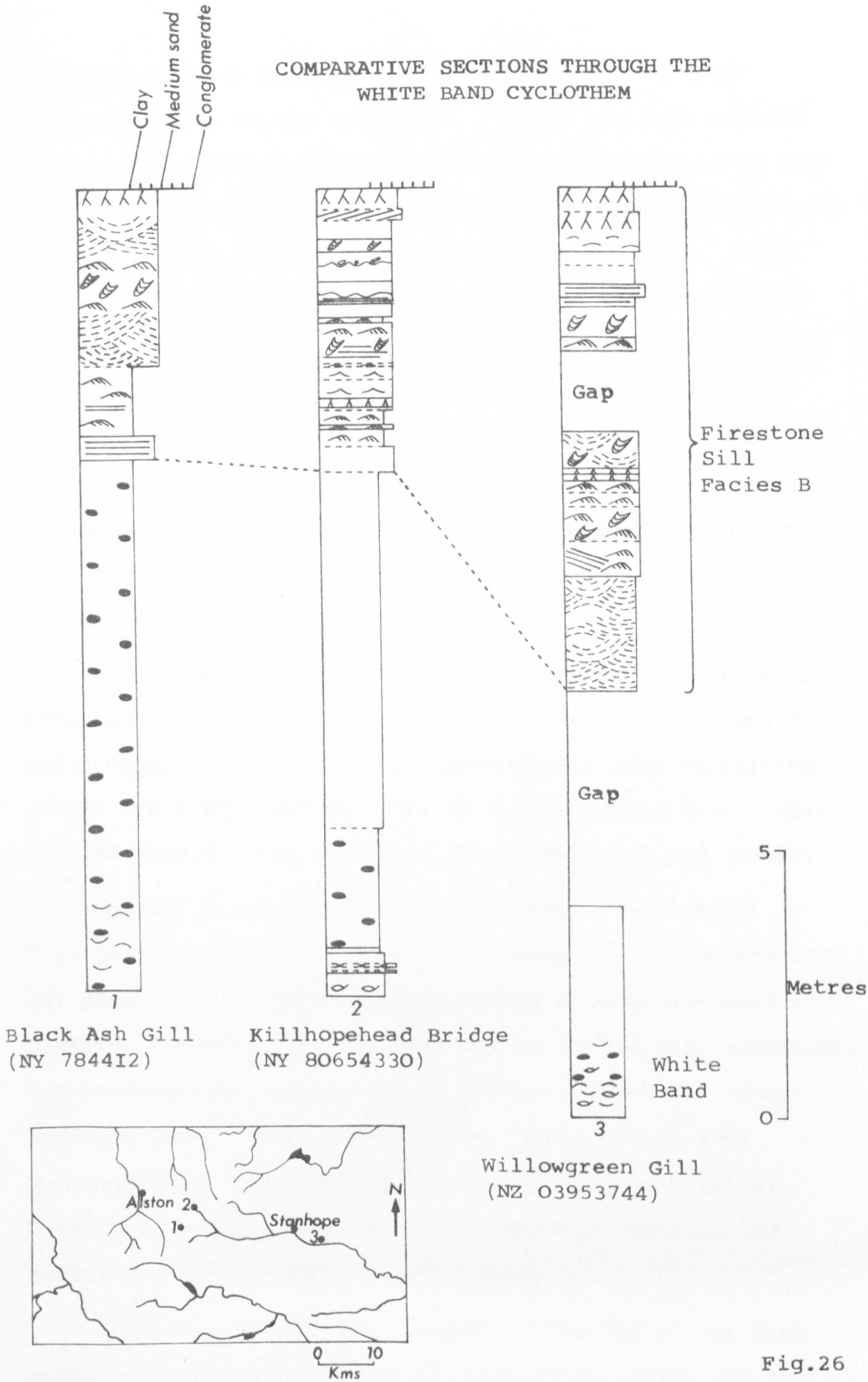


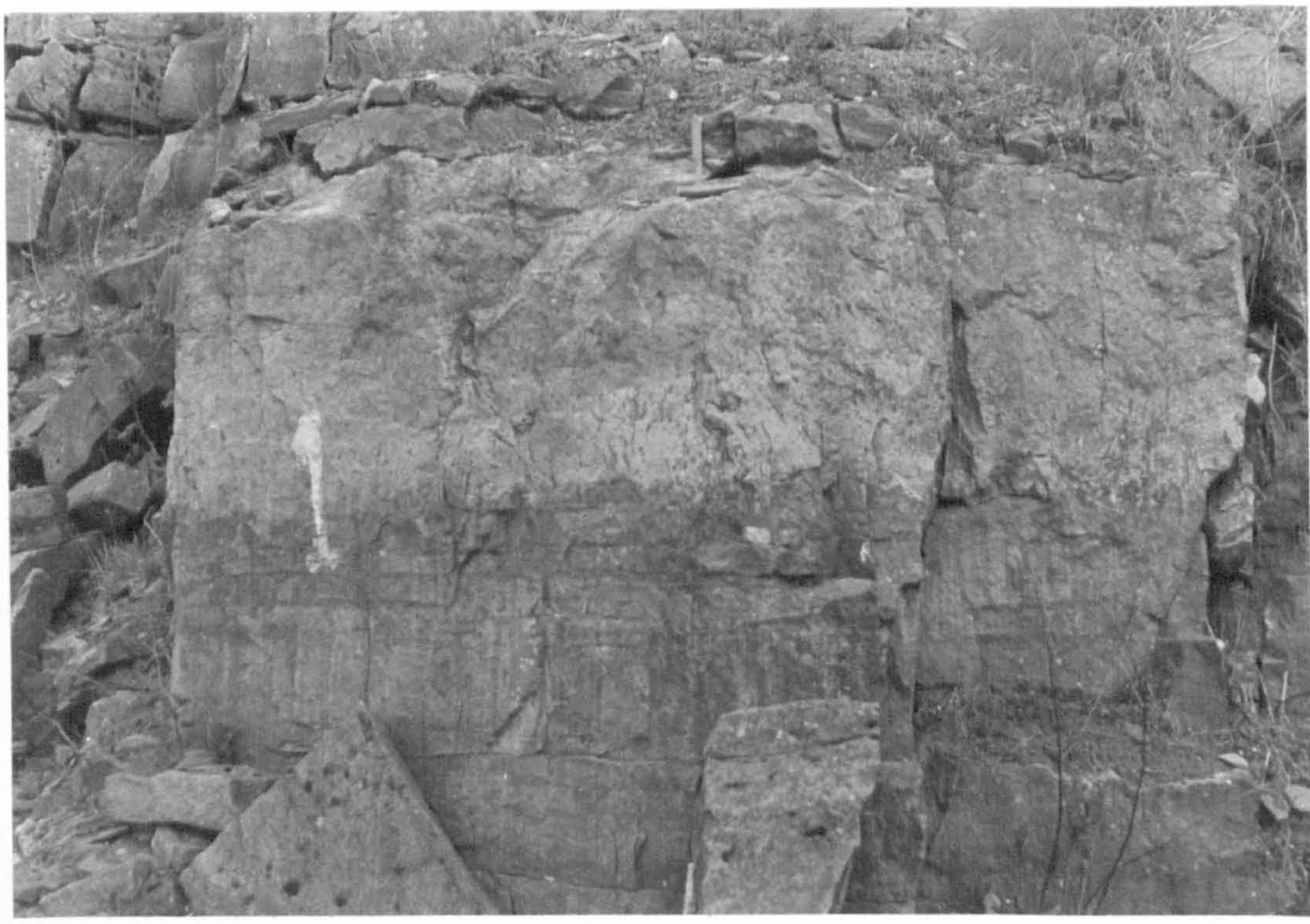
Fig.26

Occasionally obscure ripple-like structures occur towards the top of the sand body. These are well exposed at both Round Hill Quarry (NZ 01203835) and Willowgreen Gill (NZ 03953744) and consist of low amplitude (generally several mm. high), long wavelength (up to several 10's cms. long). features which commonly have convex upward top and bottom surfaces (Figs. 27, 28, 29 and 30). Internally they consist of clay and carbonaceous rich zones which are often finer grained than the enclosing sediment. Lamination is occasionally present within these structures, but is commonly discordant with their external form and passes out into the host sediment (Fig.30). Rootlets and burrows often distort and truncate these structures.

Palaeocurrents from Facies B sandstones show variable directions, with perhaps a dominant trend to the E. and S.E. and a minor trend to the N.E. particularly from localities within the normal outcrop area of Facies A (Fig.24). Wave ripples show crestal trends of approximately E.S.E.-W.S.W.

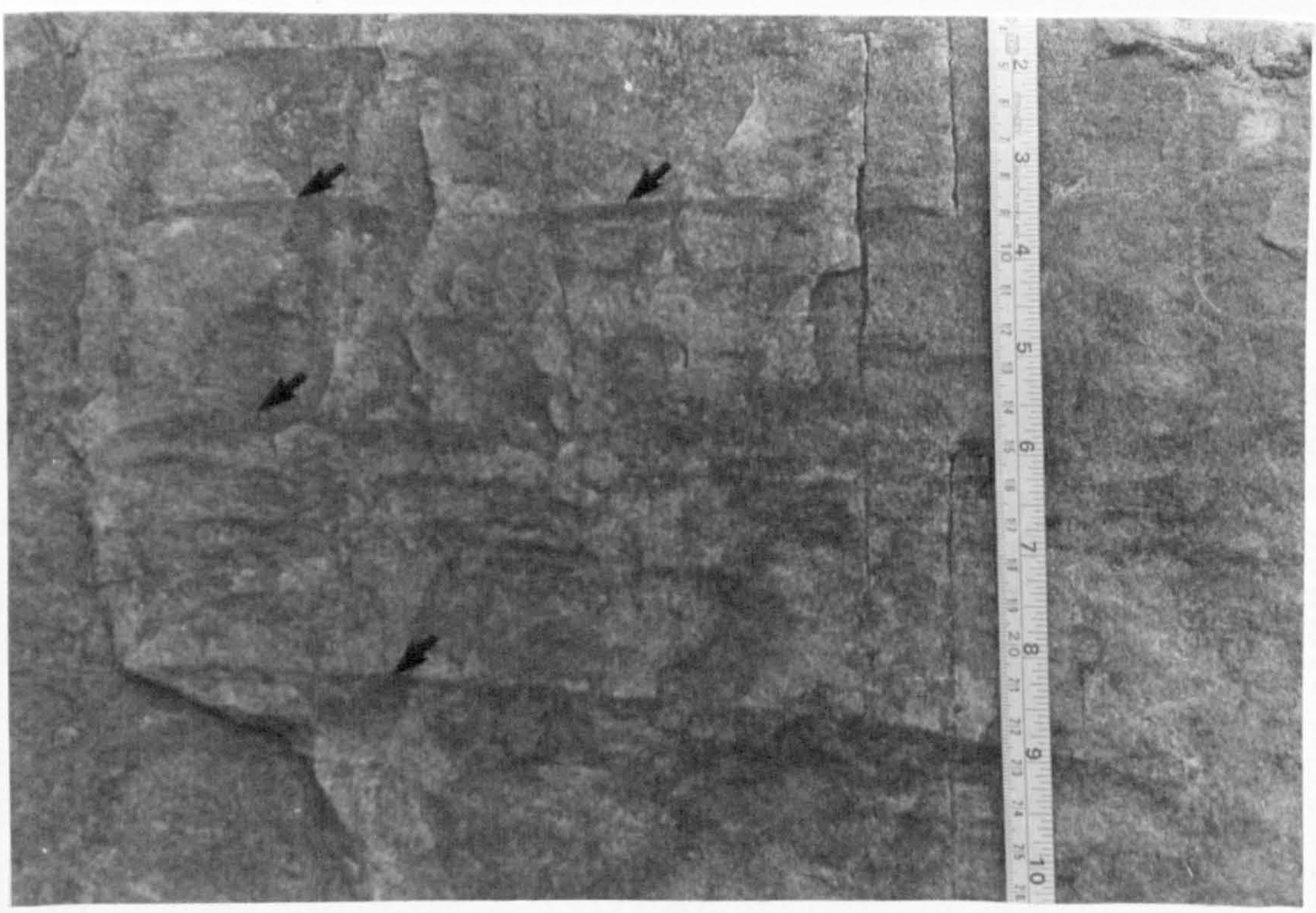
Drifted plant debris is fairly common, and marine fossils are present at several localities, e.g. Nookton Burn (NY 92404732). These occur as washed in accumulations of bivalve, brachiopod and crinoid debris in the main sandstone, and occasionally *Lingula sp.* is present within the interbedded shales. Trace fossils are common and include *Monocraterion*, *Cosmorhaphe*, *Rhizocorallium* and possibly *Skolithos*, as well as other non diagnostic vertical and horizontal burrows and surface traces.

Rootlets are commonly present at the top of the sandstone body, often resulting in destruction of any sedimentary



Top of Firestone Sill,Round Hill Quarry showing white irregularly based leached zone overlying subarkosic Facies B sandstone with obscure ripple-like structures(hammer 33cms.long).

Fig.27



Obscure ripple-like structures from subarkosic Facies B sandstone,Firestone Sill,Round Hill Quarry.Note low amplitude and long wavelength.Left hand margin of rule is in centimetres.

Fig.28

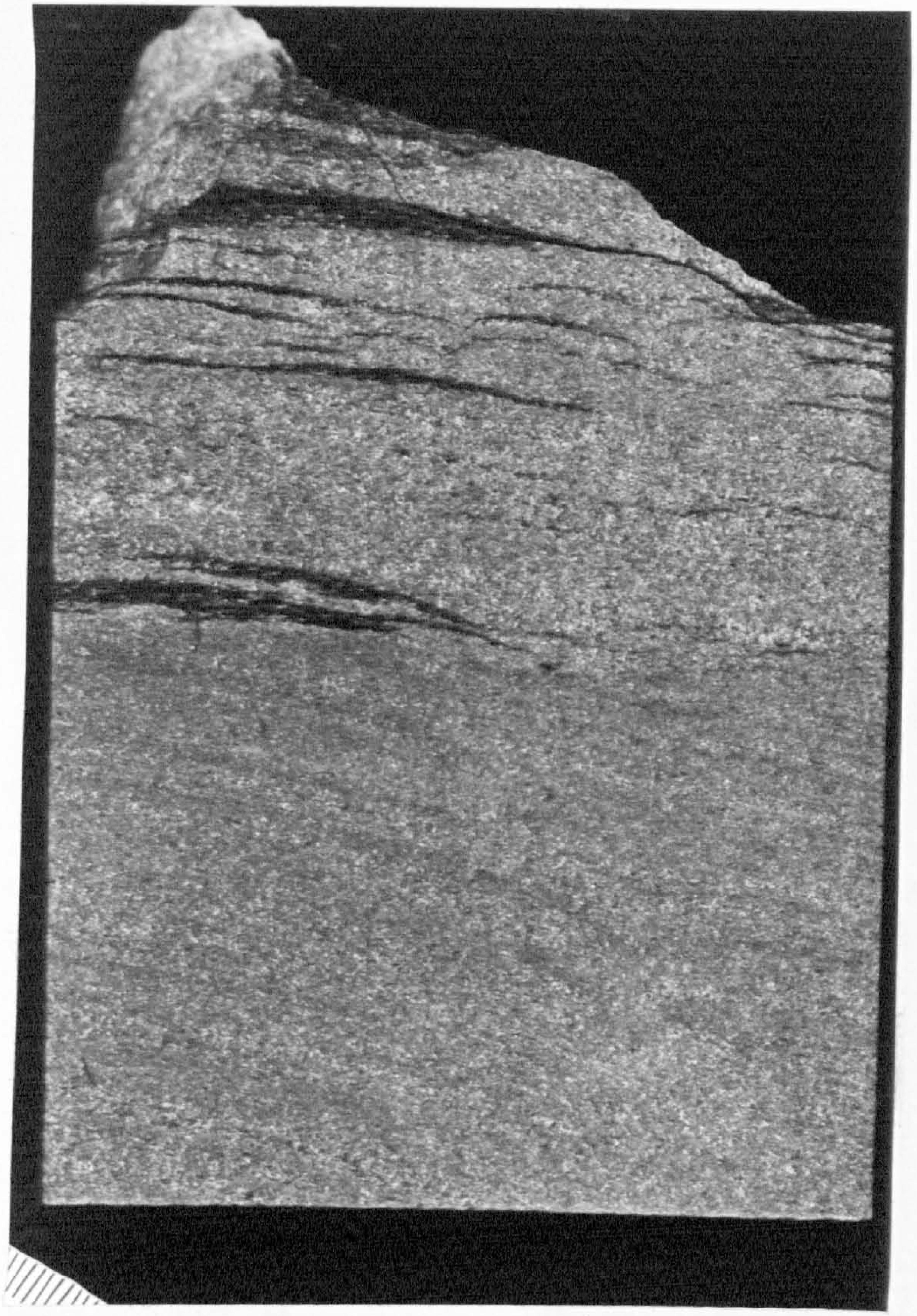


Fig.29

Dark clay and carbonaceous rich ripple-like structures commonly showing convex upward top and bottom surfaces,Firestone Sill,Round Hill Quarry.Scale divisions in mms.

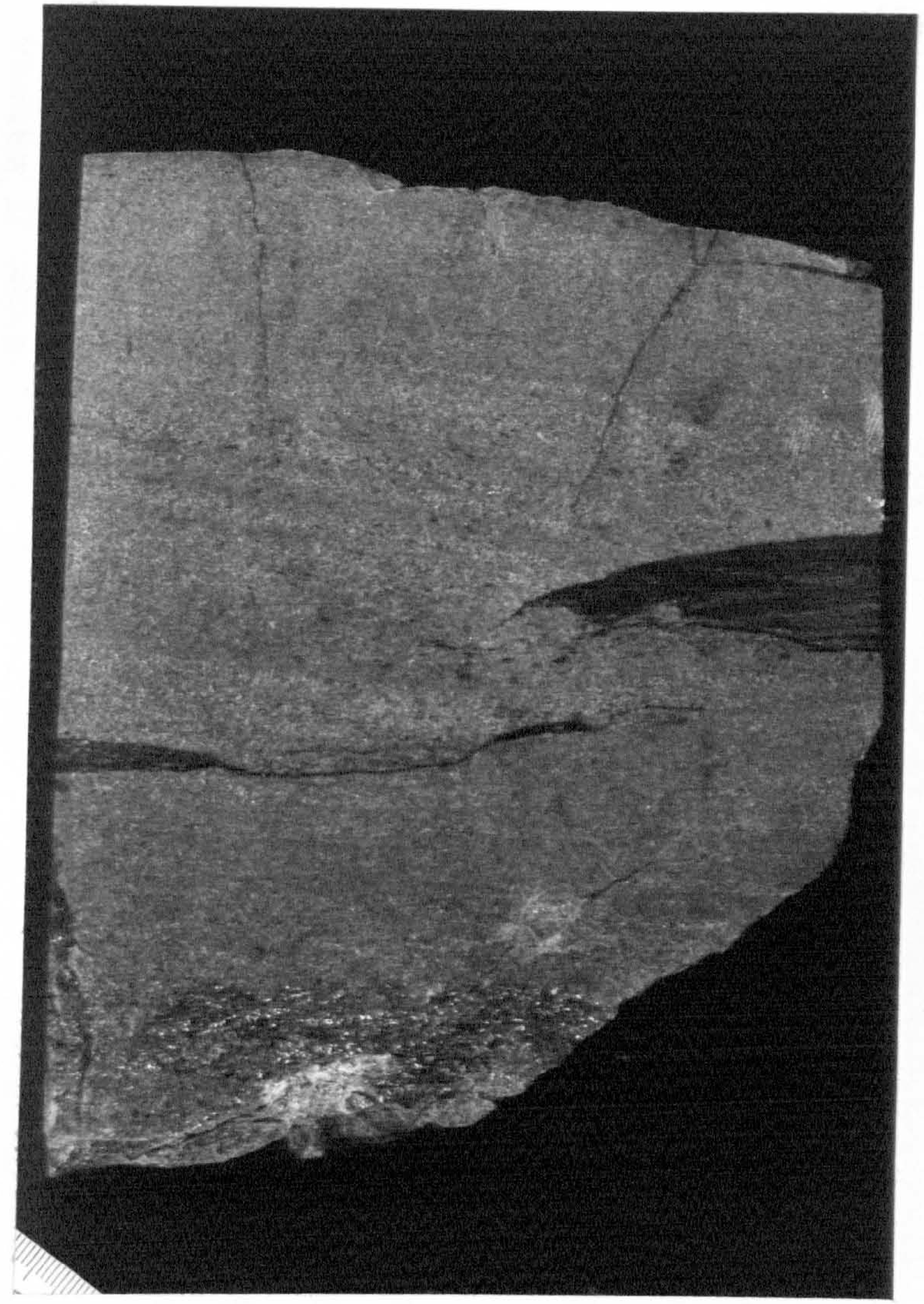


Fig.30

Dark ripple-like structures showing a discordant relationship between internal lamination and external form.Internal lamination is concordant with lamination preserved in the enclosing sediment, Firestone Sill,Round Hill Quarry.Scale divisions in mms.

structures. In this uppermost zone a true ganister (94-98% quartz) is often developed and stands out in marked contrast to the underlying less mature sandstones (up to 20% feldspar, muscovite and clay minerals) (Figs. 25 and 27). Occurrences of the previously described ripple-like structures are restricted to the sandstones directly beneath the ganister.

Above Facies B a thin coal (generally several cms. thick) is often developed, followed by fossiliferous shales beneath the Crag Limestone. Occasionally the interval between the Firestone Sill and Crag Limestone is thicker and consists dominantly of unfossiliferous shales. The geometry of Facies B tends to be sheet-like over a fairly large area. Variations in thickness up to several metres occur, and may be due to an uneven basal surface or the existence of a slight topography on top of the sand body (or a combination of both). Post depositional erosion does not appear to be a major factor. Occasionally the top has been reworked during the transgression which preceded deposition of the Crag Limestone, but this is generally restricted to *Zoophycos* burrows which affect the top few cms.

Typical exposures of this facies occur at Round Hill Quarry and Nookton Burn.

(c) <u>Relationship between facies</u>

The junction between the 2 facies is never seen in the field. Occasionally they are closely juxtaposed and it is unlikely that a complete transition occurs between them. Pattinson (1964) considered the contact was more likely to be erosional. This view is shared by the present author.

Near Middleton-in-Teesdale, in the workings of Coldberry mines, Facies A reaches its maximum thickness of 20 m., whilst only a mile away it is almost completely absent (Dunham, 1948). Such a large thickness variation is unlikely to result from a transitional passage from sandstone into shale and as Facies A is erosively based, suggests that Facies A infills a series of hollows eroded into shale or the sandstones of Facies B. Jones (1956) mapped several thick developments of Facies A in the Middleton-in-Teesdale area, showing that they consist of N.-S. or N.W.-S.E. oriented ribbon-like bodies up to 1.2 kms. wide.

(ii) Interpretation

(a) Facies A

Jones (1956) considered the ribbon-like deposits of Facies A in the Middleton-in-Teesdale area to be of distributary mouth bar origin. However, ribbon shaped sand bodies can form in many other environments (e.g. barrier island, fluvial channel, tidal sand ridge, etc.).

The erosive base and fining upward nature of Facies A argues against a distributary mouth bar origin as these have transitional contacts with adjoining facies, and coarsen upwards from underlying delta front, and prodelta muds (Fisk, 1961; Gould, 1970; Elliott, 1978a). The described characteristics, unidirectional palaeocurrents trending parallel with the axis of the sandstone bodies, and the lack of any marine fauna, suggests deposition in a series of fluvial channels flowing towards the S./S.E. (Allen, 1965; Collinson, 1978).

(b) Facies B

The coarsening upward nature of this facies together with the transition from marine to terrestrial conditions suggests formation as a prograding shoreline deposit of either beach or deltaic origin (Bernard, Le Blanc and Major, 1962; Coleman and Wright, 1975; Harms *et al*, 1975). The variable palaeocurrent pattern, presence of marine fossils and trace fossils, and the sheet-like geometry argues against deposition in a river-dominated environment and suggests formation in a prograding beach complex. However, the proportion of feldspar, muscovite and clays present, together with the subrounded nature of grains suggests that reworking was limited, perhaps due to an abundant sediment supply. Alternatively, these textural and mineralogical features may result from reworking of highly immature source material.

Sediment is commonly supplied to prograding shorelines by longshore drift from areas of fluvial imput. Consequently Facies B probably accumulated downdrift from a fluvial system or in an interdistributary setting.

Prograding shoreline deposits of this type are forming at the present day (Curray and Moore 1964; Psuty, 1965; Curray, Emmel and Crampton, 1969; Morgan, 1970). In these modern examples sand supplied by rivers is reworked into a beach ridge. Rapid sediment supply causes longshore bars to accrete which eventually become emergent and form a new beach ridge. Continuation of this process results in shoreline progradation and formation of an accretionary beach ridge complex. This consists of a regressive sheet sand whose upper surface is uniformly furrowed by the parallel beach ridges which are up to 2 m. high and spaced at intervals of approximately 50 m. Plants colonize the tops of the ridges and swamps form in the low lying areas giving coal forming conditions. During storms, or floods fine grained sediment is often supplied to these low lying areas. Finally thin fine grained fluvial overbank deposits may cover the top surface of the accreting complex.

The overall sequence formed by such a prograding beach complex would have many similarities with Facies B. The lack of true swash lamination remains a problem, and may be due to:

(1) Inability to differentiate swash lamination from horizontal lamination in small exposures,

(2) Plant colonization and destruction of swash lamination by rootlets. Commonly at the top of Facies B rootlet penetration has resulted in a total loss of sedimentary structures. This is the most likely zone in which swash lamination would have been present.

Marine fossils are fairly uncommon within the Firestone Sill and normally occur as washed in accumulations probably formed during storms. Thin interbedded rootlet horizons are possibly preserved during similar events, when sand is washed into colonized areas landward of the new beach ridge.

The texturally more mature, occasionally bioturbated sands towards the top of Facies B seem to represent foreshore and upper shoreface deposits. In these zones wave energy is high resulting in abundant reworking and removal of fines. Conditions are fairly inhospitable for most life forms except possibly deep burrowers, resulting in the preservation of vertical burrows and very little fauna.

Interbedded sandstones and shales at the base of Facies B represent quieter water deposition offshore, where sand is occasionally introduced during storm events.

At 2 localities (Cow Burn, NY 98903710; Halton Lea Gate, NY 6605830), sandstones of Facies B are generally too texturally immature to have accumulated in the beach zone. These localities are outside the main area of occurrence of Facies B, and although the overall sequence is similar, cross-bedding is more abundant and palaeocurrents are towards the N. These features together with their close association with outcrops of Facies A suggests a mixed origin, perhaps resulting from storm washover deposition, and occasional fluvial influxes.

The obscure ripple-like structures within Facies B sandstones are restricted to zones directly beneath occurrences of ganister. The discordant relationship between their external morphology and their internal lamination which is concordant with the lamination in the host sediment suggests a diagenetic origin. Burrows and rootlets truncate and distort these features indicating very early diagenetic formation, and together with their occurrence beneath the ganister this suggests they are pedogenic in origin. They are therefore discussed in more length in the section on the Firestone Sill ganister.

(c) Overall depositional environment

Formation of a prograding beach ridge complex requires an abundant sediment supply, probably by longshore drift from areas of fluvial imput. Rivers supplying sand must therefore transect or border the prograding beach complex. The deposits of Facies A may represent these, thus making the 2 facies contemporaneous in origin.

It is suggested that Facies B formed in an interdistributary setting where sediment accumulation was fairly high, but wave reworking was possible (Fig.31). In this zone the interaction of fluvial, nearshore and shallow-marine processes can produce complex sedimentary sequences and palaeocurrent patterns.

Palaeocurrents from Facies A together with its spatial occurrence suggest derivation of sand from the N./N.W. The presence of fairly fresh plagioclase and orthoclase feldspar together with the lack of large amounts of strained or metamorphic polycrystalline quartz suggests an igneous source. Fragments of chert and fine grained quartz arenite indicate the presence of sedimentary rocks in the source area. On this evidence it is suggested that the source was not too far distant and may have been the granitic intrusions and older Palaeozoic rocks of the Southern Uplands of Scotland.

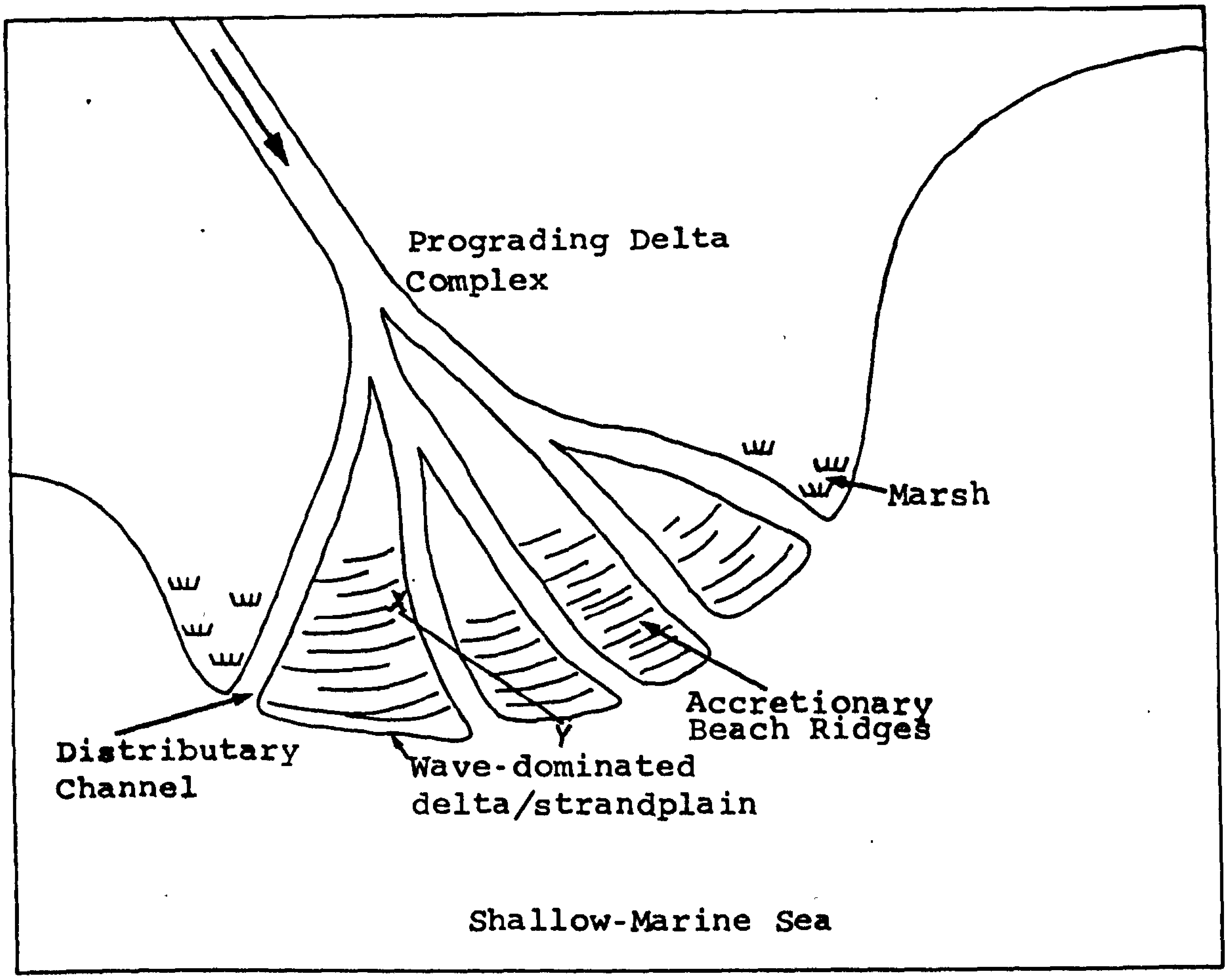
Fluvial systems from this region entered the area mainly in the N.W. Palaeocurrents from Facies B probably reflect in part an E.S.E. direction of littoral drift from this region of river input.

(iii) <u>The Firestone Sill ganister</u>

(a) <u>Description</u>

The top of the Firestone Sill contains a patchy development of ganister up to 1.5m. thick. This is generally

Interpreted depositional environment of the Firestone Sill



Interpretive section through deposits formed along line XY

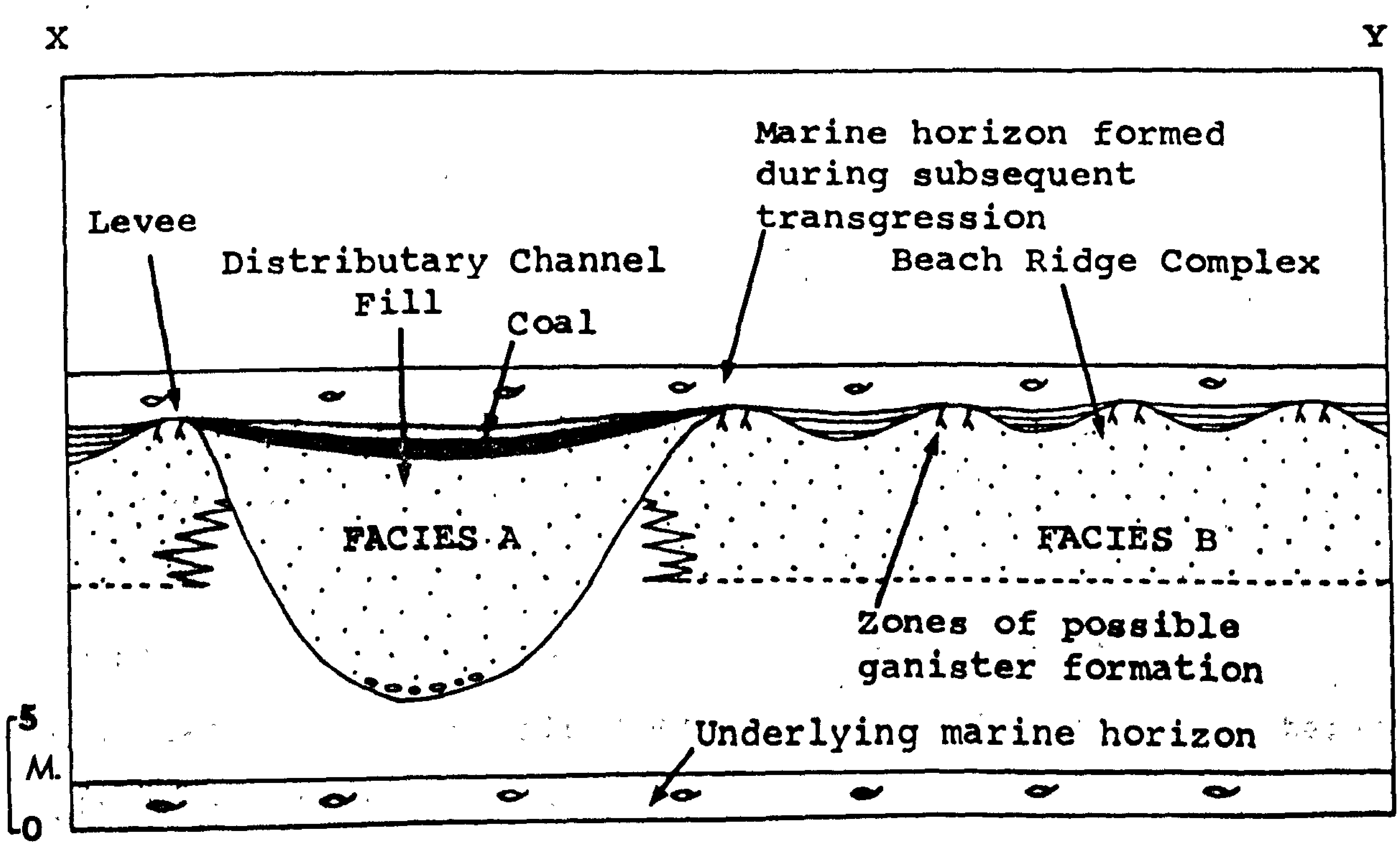


Fig.31

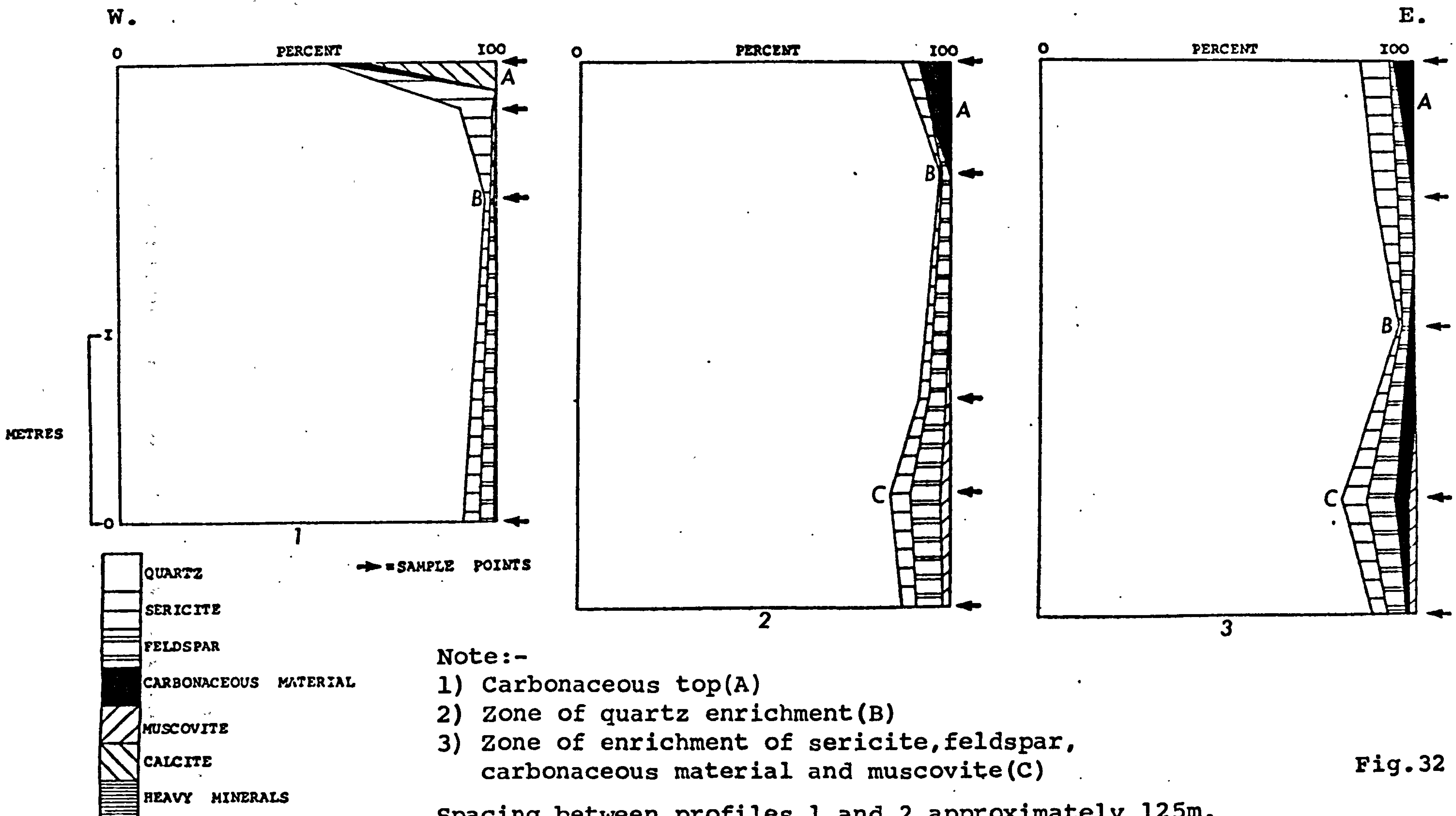
restricted to Facies B, and has been worked for the manufacture of silica bricks at Round Hill Quarry, Nookton Burn, Halton Lea Gate , the eastern side of East Allendale, and in the Rookhope area.

The best exposure of this horizon occurs at Round Hill Quarry, Rogerley Intake. Here interbedded fine to medium grained feldspathic and micaceous sandstones occasionally separated by thin shale laminae are overlain by a very irregularly based quartz arenite (ganister)(Fig.27). This contains a small percentage of sericite near the top and is overlain by a black carbonaceous rich sandstone.

Rootlets are very prominent in the topmost layers and decrease in abundance with depth. Many pass through the quartz arenite into the underlying sandstone and are often infilled with the mature, white sandstone from above. Besides small scale irregularities produced by rootlet penetration, the base of the quartz arenite often tends to be highly undulating, with downward projections up to 36 cms. deep. Although more irregularly distributed and larger in scale, these undulations are broadly similar to those seen at the base of the Sheffield Blue Ganister.

Sedimentary structures are generally absent from the quartz arenite and have probably been destroyed by rootlet penetration. Texturally this horizon consists of a moderately well sorted fine to medium grained sandstone, containing approximately 94-97% quartz (Figs. 25 and 32). Feldspar is occasionally present and is often highly altered with sericite forming along cleavage traces.

VERTICAL PROFILES THROUGH THE TOP OF THE FIRESTONE SILL, ROUND HILL QUARRY, ROGERLEY INTAKE



Note:-
1) Carbonaceous top(A)
2) Zone of quartz enrichment(B)
3) Zone of enrichment of sericite, feldspar, carbonaceous material and muscovite(C)

Spacing between profiles 1 and 2 approximately 125m.
Spacing between profiles 2 and 3 approximately 20m.

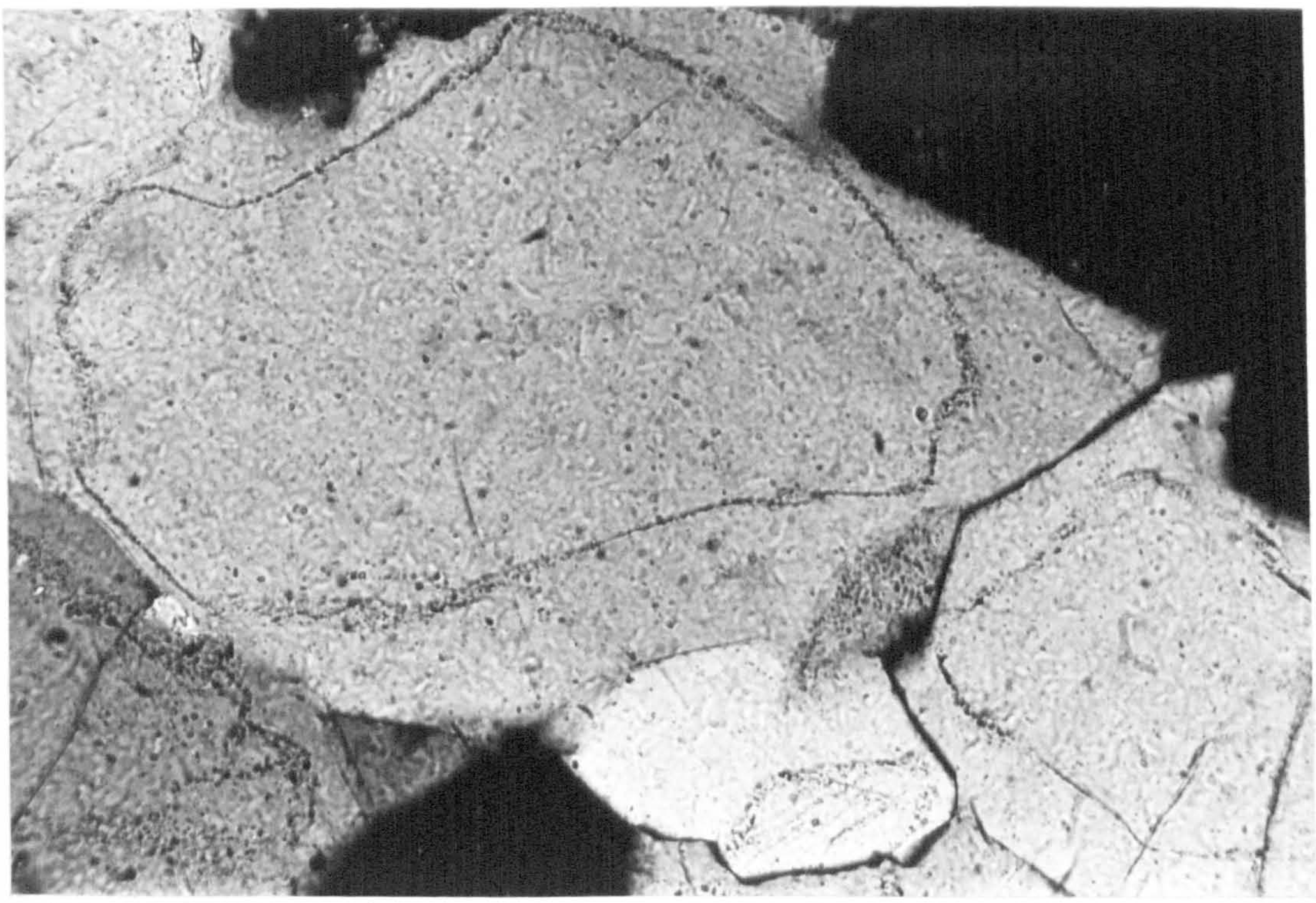
Fig.32

In the underlying sandstone the proportions of clay, feldspar, mica and sometimes carbonaceous material increase and occasionally clays form orientated coatings to framework grains (Fig.34). These are common in the previously described ripple-like structures (p. 87), which also contain well developed laminated clay void linings. Beneath this zone the content of clay and carbonaceous material decreases into the underlying sandstones (Fig.32).

Occurrences of the ganister are virtually restricted to the region between East Allendale and Frosterley, where it is generally of the order of 1 m. thick (Fig.24). Actual sequences vary slightly, but show a broad similarity to that at Round Hill. Most occurrences of the ganister are overlain directly by the Crag Limestone or its local equivalent. In Nookton Burn the top of the ganister shows a patchy development of quartz rich (<a few cms. across) and carbonaceous rich zones which appear to result from bioturbation by both animals and plants.

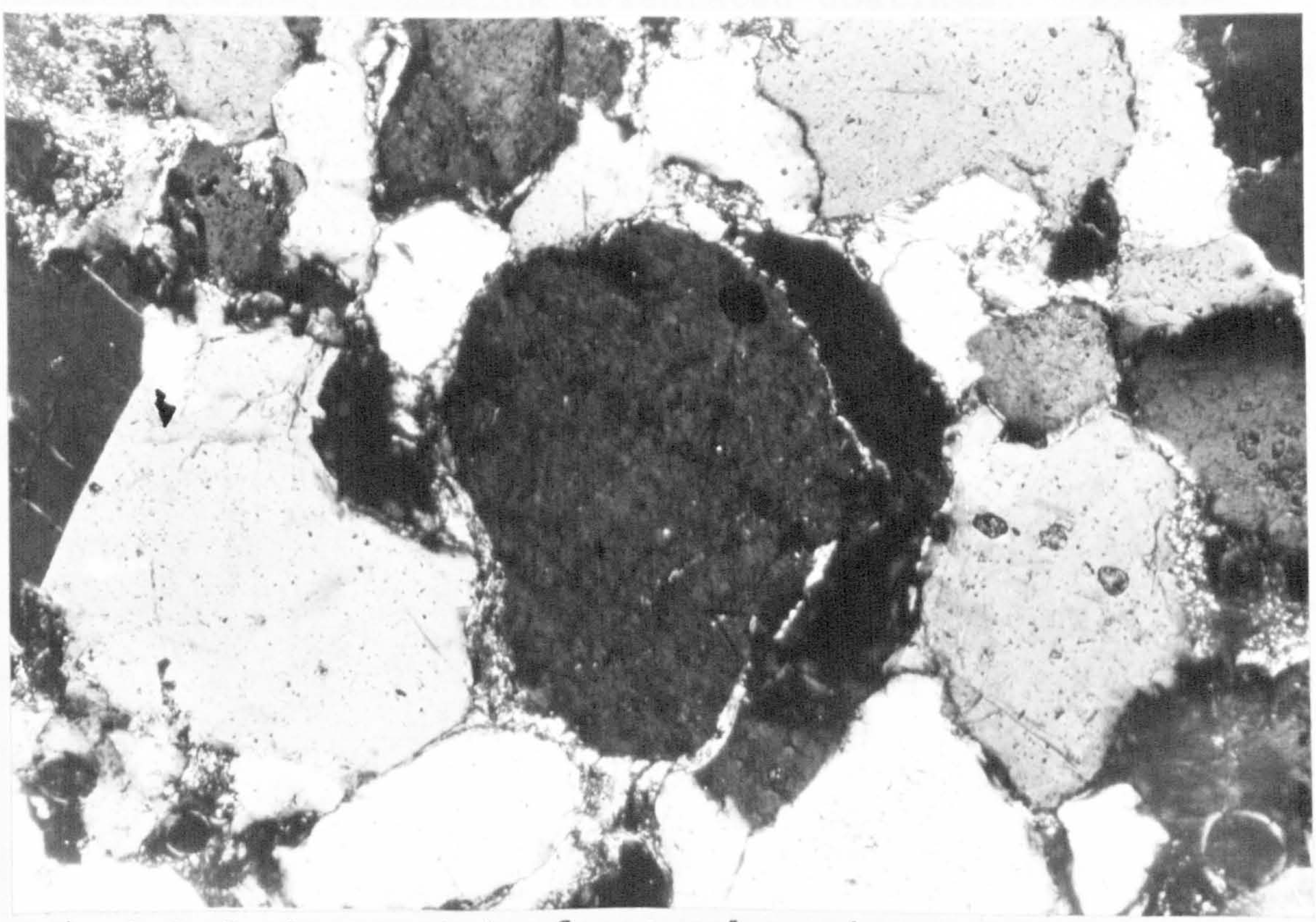
(b) Diagenesis

Diagenesis has primarily resulted in cementation by interlocking quartz overgrowths in optical continuity with framework grains. Dust rims are common, and patches of carbonaceous material along them often show signs of having partially replaced the original detrital grains. Often in the top few 10's cms., abundant carbonaceous material has inhibited quartz cementation and pronounced dissolution of detrital quartz grains has occurred. Overgrowths have developed in these regions, but often show signs of replacement.



Subrounded detrital quartz grain showing well developed dust rim and overgrowth, Facies B, Firestone Sill, Willowgreen Gill. Length of photomicrograph 0.52mm. (crossed polarized light).

Fig.33



Orientated clay coat to framework grain, Facies B sandstone beneath ganister, Firestone Sill, Round Hill Quarry. Length of photomicrograph 1.3mm. (crossed polarized light).

Fig.34

Beneath the Crag Limestone at Round Hill Quarry carbonate rich fluids have been introduced into the top few cms. of the Firestone Sill. This has resulted in replacement of quartz grains and deposition of a poikilotopic calcite cement (Fig.32). These fluids, derived from the overlying calcareous sediments were introduced after at least some quartz cementation had taken place as both overgrowths and original detrital grains have been replaced. The silica released by this process may have been a source for quartz overgrowths forming elsewhere.

Some orientated clay coatings to grains may have formed diagenetically (Wilson and Pittman, 1977). Where overgrowths form, any disorientated clay present will be displaced outwards and eventually aligned by being squeezed between grains, producing orientated coatings. Alternatively, clay rich solutions passing through the sandstone could also give rise to clay coatings by the sieving out of clays held in suspension (Bullock and Mackney, 1970).

Other diagenetic features include the alteration of feldspars to sericite, precipitation of siderite, commonly in close association with carbonaceous material, and the iron staining of clays. In places a late stage influx of iron has resulted in dissolution, of quartz grains and formation of pyrite, particularly along carbonaceous root outlines.

(c) <u>Interpretation</u>

Many of the features present at the top of the Firestone Sill in Round Hill Quarry and at other localities suggest that pedogenesis has led to the development of soil horizons, and formation of the quartz arenite (ganister). These include:-

(1) The presence of large *Stigmaria sp.* and associated fossil rootlets provide positive evidence of emergence and colonization by plants. Due to the porous sandy nature of the parent material, probably only a short period of time (several hundred years) would be necessary for a leached soil profile to develop.

(2) Above the texturally mature quartz arenite there is often a separate dark coloured sandstone bed up to a few 10's of cms. thick. This contains abundant carbonaceous rootlet outlines and admixed carbonaceous material and sericite (Fig.32).

The very fine grain size of the carbonaceous material and clays, together with its irregular distribution and disseminated nature and the lack of any sedimentary lamination argue against a purely sedimentary origin, and suggest formation by biogenic mixing. The presence of roots and occasional burrows tends to support this.

Similar horizons are very common in present day soil profiles where soil organisms and roots incorporate plant debris into the top of the soil producing an organic rich horizon (Hunt, 1972; Birkeland, 1974).

(3) The quartz arenite lacks any sedimentary structures and at Round Hill lies with a very irregular often undulating contact on subarkosic sandstone. The nature of the contact does not appear to be erosive and is generally too irregular to be due to loading.

Such white quartz rich horizons with irregular basal contacts are very common in podzols and podzolic soils where differential leaching of the A_2-horizon has taken place (Daniels, Gamble and Nelson, 1967; FAO, 1974).

(4) The sandstone underlying the quartz arenite occasionally contains orientated clay coats to framework grains and laminated clay void linings. These are particularly common in the ripple-like features which are known to have formed soon after deposition. Although such clay coatings and void linings can form diagenetically, they appear to be most common in soils and palaeosols (p. 38). Their occurrence relative to the overlying horizons tends to support a palaeosol origin, although some poorly developed examples may be diagenetic.

(5) Feldspars tend to be moderately common and fairly fresh in the sandstones beneath the quartz arenite, but decrease in abundance and become more altered upwards (Fig.32). This suggests that the feldspars in the upper horizon probably underwent weathering concomitant with plant colonization of the sand body. The presence of up to 2% feldspar in these upper horizons suggests that this period of weathering was probably of fairly short duration.

(6) The sandstone beneath the quartz arenite often shows an increase in the percentage of clay and occasionally carbonaceous material relative to the surrounding strata (Fig.32). Generally this increase is due to the presence of grain coatings and void linings which are particularly common in the ripple-like structures. Such horizons

enriched in clay and carbonaceous material are common in present day podzols and podzolic soils.

Besides the above features, the fact that the ganister never exceeds 1.5m. in thickness, its large spatial occurrence and occasional rapid variations in lithology all suggest a pedogenic rather than a sedimentary origin.

It therefore seems likely that the top of Facies B was emergent for a sufficient time for a palaeosol to develop. The character of the horizons formed, together with their contacts suggest that the palaeosol represents a podzolic soil profile. Such soils can form relatively quickly, particularly on porous sandy parent materials, and incompletely developed examples may form in a few hundred to several hundred years. The presence of feldspar in the ganister horizon tends to support the idea of fairly rapid development.

During palaeosol development, the breakdown of unstable minerals and downward translocation of their alteration products, along with clays and occasionally organic matter led to quartz enrichment in the ganister (A_2) horizon (Fig. 35). Deposition of these constituents lower down in the soil resulted in a horizon of accumulation. Clays deposited in this zone (B-horizon) led to the formation of orientated clay coatings to framework grains and laminated void linings. Pedogenically produced examples of these structures (argillans) do not form below a permanent water table (Buurman, 1980). Iron and organic matter were also deposited in small amounts in this illuvial horizon. Deposition in the B-horizon appears to have taken place preferentially in finer grained

INTERPRETIVE MEASURED VERTICAL SECTIONS THROUGH THE TOP OF THE FIRESTONE SILL, ROUND HILL QUARRY, ROGERLEY INTAKE

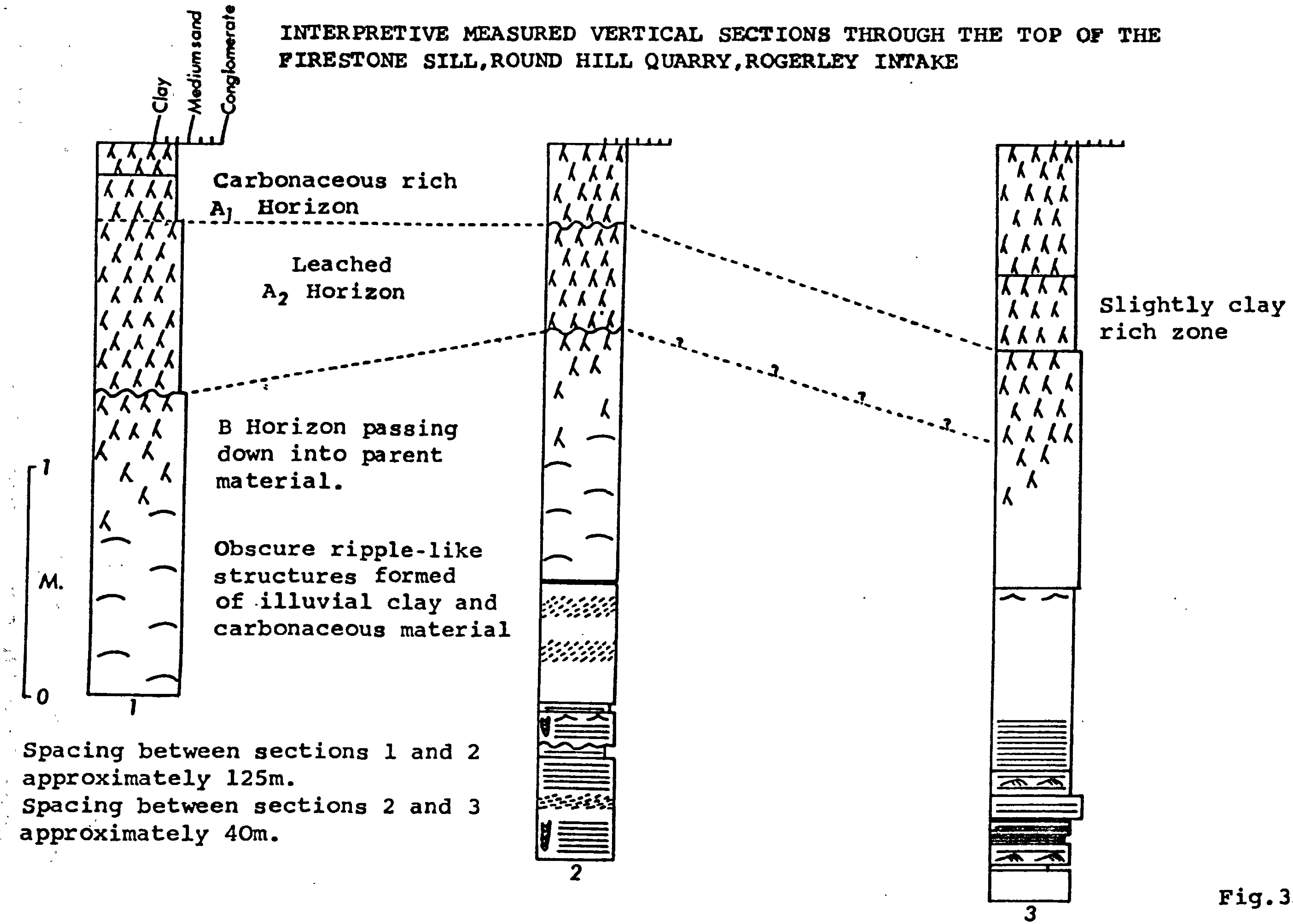


Fig.35

or slightly less permeable zones resulting in the development of the ripple-like features.

Removal of elements from the upper horizons by rootlets may have taken place to some degree very early during soil formation, but would have gradually decreased with time as leaching proceeded. Elements absorbed by plant rootlets would be returned to the soil surface on death of the plants (Ollier, 1969), and would then be available for redistribution throughout the soil profile. An approximate balance probably existed between constituents removed by plants and those returned to the soil surface. Gradually with the development of the A_2 (ganister) horizon by leaching, rootlets would be forced to penetrate deeper to gain the necessary nutrients for plant growth.

Differential leaching of the A_2-horizon may have occurred due to the presence of cracks, root holes, etc. (Buurman, 1980) or possibly due to protection from overlying large roots (Butuzova, 1962), or the effect of overlying plants (Buol,Hole and McCracken, 1973). If sufficient time was unavailable these may have had a marked effect on the homogeneity of the A_2-horizon. The porous sandy nature of the soil meant that leaching was able to progress rapidly under the prevailing humid tropical climate, providing the water table remained fairly low.

In many places a good leached soil profile and associated ganister did not develop and pedogenesis merely consisted of rootlet penetration and incorporation of organic matter into the top of the sand body. Perhaps, the water table was higher in these areas, and thus removal of material by leaching was not possible. This variation in height of the water table may have been due to the existence of a slight topography on top of the Firestone Sill.

The virtual restriction of the ganister to the East Allendale-Frosterley area, and its formation within sandstones of Facies B indicate the more mature nature of the parent material, and the better drained conditions within these deposits. During formation of the ganister, coal swamp conditions seem to have persisted in many areas where Facies A occurs. It is therefore very likely that the main belt of ganister development formed a slight topographic high above adjacent areas. The presence of a topographic high in this region may have been due to the prograding beach ridge origin of Facies B, as such prograding complexes would normally build up above adjacent fluvial channel deposits. Within the main belt of ganister occurrence, local absence or poor development of ganister may be due to more local variations in the depth to the water table resulting from the ridge and trough topography of the beach complex. Similar variations in soil development from troughs to ridges are known on modern prograding beach ridge deposits (Young, 1976).

The succeeding Crag Limestone transgression occurred across this coastal zone. Deposition of this marine horizon tended to occur almost directly on top of topographic highs, but was often separated from the Firestone Sill in lower areas by fine grained deposits and peats (Fig.31). This is exemplified by the fact that occurrences of ganister are overlain closely by the marine horizon, whereas elsewhere fine grained deposits commonly intervene.

The Firestone Sill ganister and its associated palaeosol exhibits variations in the thickness and nature of the horizons developed, and as a result varies in its classification. At localities where tonguing of the A_2-horizon is present, e.g. Round Hill Quarry, it classifies as a dystric podzoluvisol, where tonguing is absent it becomes an albic luvisol, e.g. Nookton Burn, and when horizons are virtually absent, e.g. E. side of East Allendale an albic arenosol (FAO, 1974).

C. Minor ganister horizons

(i) Introduction

Many thin often local developments of quartz arenite containing fossil rootlets occur within the Northern Pennines. Most are poorly exposed and deduction of their origin is often problematical. However, a few horizons show evidence of some pedogenesis apart from rootlet penetration and probably represent true ganisters. The horizons to be discussed range in age from Dinantian to Westphalian A. and probably represent only a small proportion of those present within the local Carboniferous succession.

(ii) Nattrass Gill Hazle, East Blackdene (NY 88123878)

(a) Description

The Nattrass Gill Hazle takes its name from a right bank tributary of the South Tyne approximately 1.6 kms. S. of Alston; hazle being a local term for any fine grained sandstone (Arkell and Tomkeieff, 1953). Stratigraphically it lies at the top of the Three Yard Limestone cyclothem of Brigantian D_2 age (George *et al*, 1976).

Throughout the Alston Block, the Nattrass Gill Hazle is a fairly impersistent horizon, varying in thickness and lithology, and sometimes being absent altogether. On the Alston Block, only at Lanehead (NY 83854217) has this horizon been worked for refractory purposes. Further S. at Wensley, North Yorkshire (SE 077910) a sandstone at the same horizon has been quarried for a similar purpose (Strahan, 1920).

At Lanehead a thin bed of slightly micaceous sandstone containing abundant fossil rootlets was worked from beneath the Four Fathom Limestone. This sandstone varied in thickness from 77 cms. to 1.54 m. and was worked along with an underlying 1.84 m. bed of quartzitic sandstone (Strahan, 1920). Present day exposures in these quarries are poor with only 66 cms. of fine grained, well sorted quartz arenite containing abundant fossil rootlets visible beneath the limestone.

A better exposure occurs in East Blackdene where 1 to 1.1 m. of fine grained sandstone containing abundant fossil rootlets directly underlies the Four Fathom Limestone. Often the top few cms. of the sandstone contains crinoid ossicles indicating reworking by the transgression which preceded deposition of the limestone. Beneath this reworked zone the sandstone consists of a hard fine grained quartz arenite which passes down into a softer, muscovite and clay rich (approximately 14.5% clay) fine grained sandstone (Fig.25). Sericite is the dominant clay mineral in this latter sandstone and often forms orientated coatings to framework grains. Sedimentary structures are absent, perhaps due to their destruction by rootlets.

(b) Diagenesis

Cementation of the top of the Nattrass Gill Hazle at East Blackdene has occurred mainly by the formation of quartz overgrowths. In places of high clay content, quartz has been inhibited from nucleating on detrital quartz grains. As a result cementation has been restricted and the rock tends to be moderately friable. Directly beneath the Four Fathom Limestone calcium carbonate rich solutions have invaded the rock, resulting in replacement of overgrowths and detrital quartz grains by calcite (Fig.25).

(c) Interpretation

The presence of fossil rootlets, and the transition downwards within a single bed from quartz arenite to texturally less mature sandstone containing orientated clay coats to framework grains, suggests that quartz enrichment at the top of the Nattrass Gill Hazle at East Blackdene took place by pedogenesis.

Breakdown of unstable minerals and removal of their alteration products and clays, resulted in formation of the ganister A_2-horizon. While deposition of clays lower down, often as coatings to framework grains led to development of an illuvial B-horizon. The transitional nature of the contact between the 2 horizons suggests that the period of pedogenesis was probably fairly short lived. The increase in quartz content necessary (7-8%) to produce the A_2-horizon tends to support this.

The top of the Nattrass Gill Hazle includes thin quartz arenites containing abundant fossil rootlets at several other localities e.g. Stanhope Burn (NY 98853995) and Horsley Burn

(NY 96353732). At these localities good evidence of quartz enrichment by pedogenesis is lacking, and a purely sedimentary origin with only slight pedogenic alteration is suggested for these occurrences.

(iii) Steeley Burn ganister, Satley (NZ 12174420)

(a) Description

A series of small bluffs alongside Steeley Burn expose a thin rootlet penetrated quartz arenite, and associated strata (Fig.36). Stratigraphically this section is of Westphalian A age and lies below the Ganister Clay Coal which outcrops on the slopes above.

The quartz arenite is approximately 28 cms. thick (71 cms. or more at maximum, Collins, 1925) and commonly lies with a sharp irregular contact on a fine grained micaceous sandstone (Fig.36). The quartz arenite is subject to marked changes in lithology both vertically and laterally, and occasionally shows a transition down into less mature clay rich sandstone. Often rootlets passing down into the clay rich sandstone are infilled with quartz arenite from above and stand out in contrast to the host sediment (Fig.37). This tends to be a very fine to fine grained sandstone containing silt size quartz grains and abundant very fine grained disseminated clays.

(b) Diagenesis

Diagenesis of the quartz arenite has consisted mainly of cementation by the formation of interlocking quartz overgrowths. The underlying clay rich sandstone lacks abundant overgrowths due to the inhibiting affect of clays. This has resulted in the development of some fine grained

MEASURED VERTICAL SECTION THROUGH THE STEELEY BURN GANISTER AND ADJACENT WESTPHALIAN A SEDIMENTS, STEELEY BURN, SATLEY

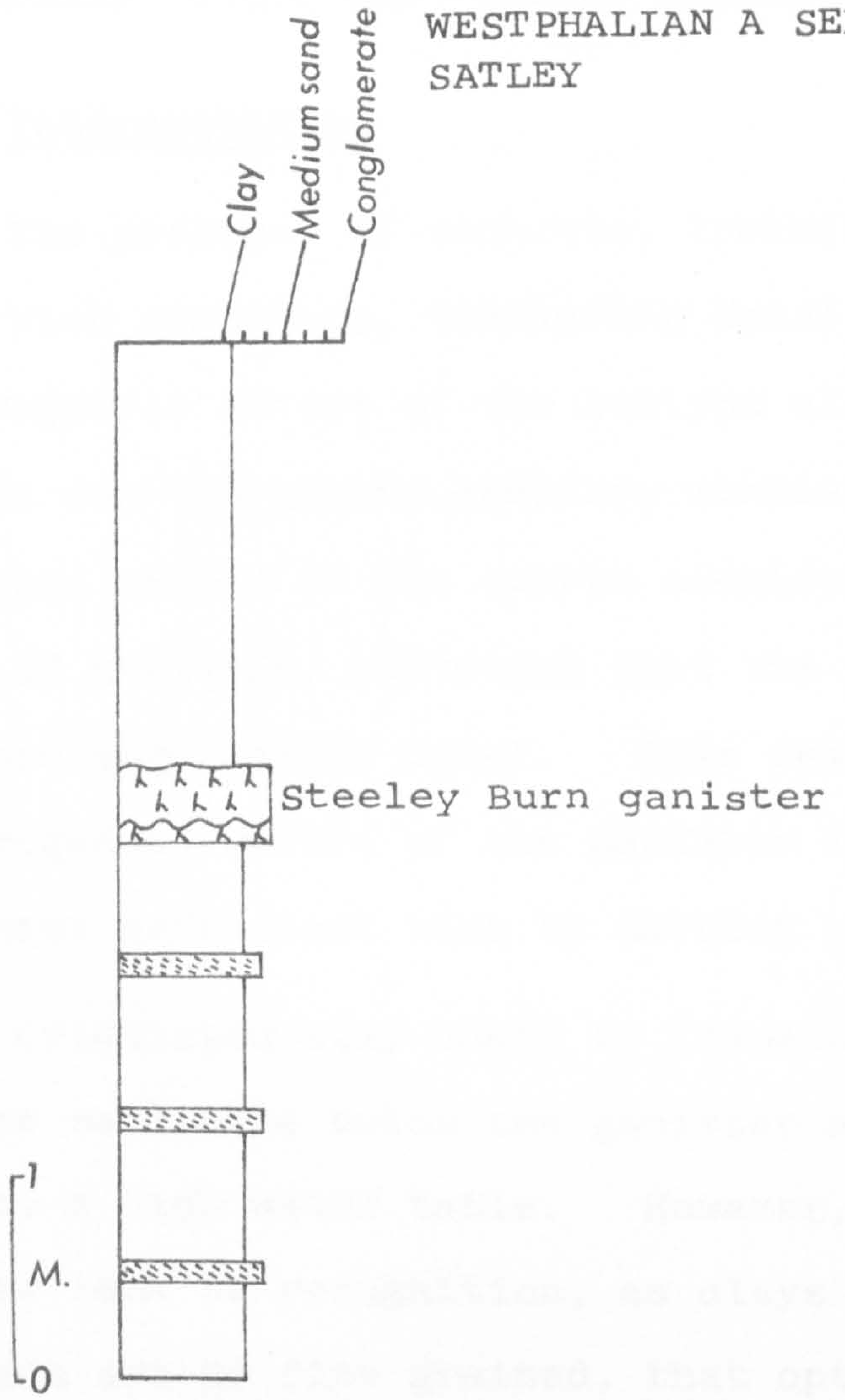
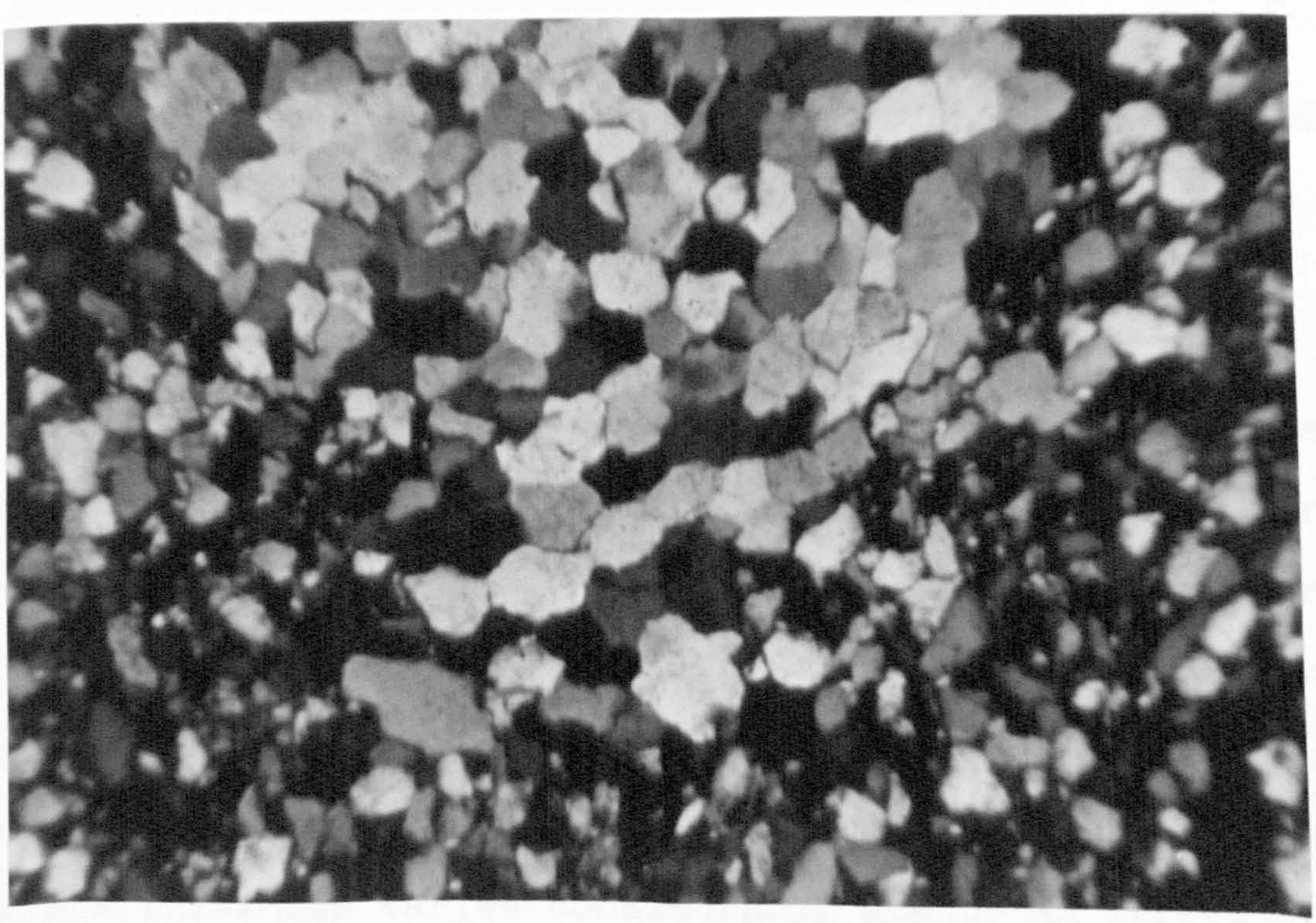


Fig.36



End of rootlet infilled with coarser grained moderately well sorted quartz arenite(top centre),base of Steeley Burn ganister,Satley.Length of photomicrograph 2.95mm. (crossed polarized light).

Fig.37

(generally < 0.032 mm.) quartz cement.

(c) Interpretation

The presence of rootlets, transition into less mature clay rich sandstone, undulating basal contact, and the very heterogenous nature of the horizon all suggest a pedogenic origin for the quartz arenite, similar to previous examples. The thin nature of the quartz arenite, and the poor development of horizons, indicates that the period of pedogenesis was probably fairly brief. This resulted in the very heterogenous nature of the ganister A_2-horizon, which did not have sufficient time to develop completely.

Orientated clay coats to framework grains are absent in the sandstone below the ganister and may not have developed due to a high water table. However, their absence may be due to lack of recognition, as clays present in this B-horizon are so fine grained, that optically it is difficult to determine any preferential orientation.

(iv) Lower ganister, Bessy's Bank Quarry, Castleside, Consett (NZ 07654940)

(a) Description

A disused and overgrown quarry at Bessy's Bank, Castleside exposes 2 fine grained quartz arenites. These are of Westphalian A age, occurring at the top of the Third Grit, which is well exposed in an old moulding sand quarry downslope (NZ 07654950). The 2 quartz arenites are fairly similar in appearance and are separated by 2.6 m. of grey shale (Fig.38). The upper horizon is up to 72 cms. thick, but its thickness varies considerably due to an irregular

MEASURED VERTICAL SECTION THROUGH THE THIRD GRIT AND OVERLYING STRATA, BESSY'S BANK, CASTLESIDE

Fig.38

'knobbly' base. Towards the N.W. it appears to thin and deteriorates in quality, becoming softer and more clay rich.

The lower horizon is exposed along the quarry floor and consists of up to 70 cms. of irregularly based fine grained quartz arenite, lying on a kaolinitic clay. Evidently this as the main horizon worked and towards the E. it deteriorates in quality and passes into less mature, fine grained sandstone (Collins, 1925).

Sedimentary structures are absent from this lower quartz arenite, probably due to destruction by the abundant rootlets which penetrate this horizon and pass down into the underlying clays. Rare, burrows may have aided in this respect.

The basal contact of the quartz arenite contains large undulations up to 20 cms. deep into the underlying clays. Roots, rootlets and possibly burrows infilled with quartz arenite occur along this surface, causing further irregularities. The top surface of the quartz arenite is also irregular, with undulations up to several cms. deep.

In thin section quartz grains are subrounded -rounded and well sorted, and the quartz arenite averages 98.5-99.5% quartz (Fig.25). At the top the quartz content decreases due to an increase in the percentage of goethite, kaolinite and occasionally mixed layer clays (Fig.25).

(b) Diagenesis

Quartz cementation has been the main diagenetic event, predominantly as overgrowths to framework grains, but also as grained quartz cement in clay rich zones. Locally minor amounts of pore filling kaolinite has formed.

Often, particularly at the top, there has been a late stage influx of iron which has resulted in replacement of both quartz grains and overgrowths. At present this iron occurs as goethite and is preferentially developed in carbonaceous rich areas. During diagenesis such carbon rich zones would have formed local reducing environments. Goethite is unlikely to form in such a setting, and is more likely to be an oxidation product of an earlier mineral, such as pyrite.

(c) Interpretation

The presence of roots, lateral passage into less mature fine grained sandstone, and the undulating basal contact all suggest a pedogenic origin for the quartz arenite. The underlying kaolinitic clay is too thick (50 cms. or more) to be of purely pedogenic origin, and is considered to be an original sedimentary deposit. Development of the ganister appears to have taken place in an originally coarser grained layer overlying these clays, similar to that envisaged for the Sheffield Blue Ganister (p. 45). The subrounded -rounded, well sorted nature of the ganister, suggests that the parent material of this horizon was fairly mature.

The upper quartz arenite exhibits very similar characteristics to this lower ganister, and probably developed in a similar manner. The occurrence of fresh muscovite may suggest fairly rapid formation. However, this mineral can persist in soils at an advanced stage of weathering (Young, 1976) and thus its presence does not necessarily indicate only a short period of pedogenesis.

D. Conclusions

Thin quartz arenites penetrated by fossil rootlets are present throughout the Carboniferous succession of the Northern Pennines, and are particularly common within lowermost Westphalian A deposits. Most of these quartz arenites are poorly exposed and elucidation of their origin is difficult. Some show features more indicative of pedogenesis than sedimentation and may be true ganisters; others are purely sedimentary in origin. Often both processes have contributed. This is probably the most common case in the formation of ganisters as they will tend to develop most rapidly on parent materials already enriched in quartz by sedimentary processes. Such cases are likely to be the most difficult to interpret as pedogenesis commonly results in destruction of sedimentary structures, dissolution of fossils and alteration in lithology. Unless some parent material is preserved, it is often virtually impossible to deduce its origins, and the extent to which quartz enrichment has taken place by pedogenesis.

The majority of ganisters within the Carboniferous succession of the Alston Block form fairly localized lenses. Such occurrences are more likely to have developed as a result of local depressions in the water table relative to the land surface, rather than regional falls in base level. Extensive horizons of ganister occurrence such as the top of the Firestone Sill probably formed due to the parent material having been deposited as a regional topographic high above the water table. There is therefore no evidence from the foregoing to suggest that regional falls in base level were important in the development of many of the ganisters of the Alston Block. However, during the Westphalian A, deposition commonly took place at or below the water table, and freely drained conditions were rare. Occurrences of ganister in Westphalian A strata may therefore require some external cause for their formation such as a fall in base level. The implications these horizons have for Westphalian deposition are discussed at greater length in Chapter 8.

CHAPTER FIVE

QUARTZ ARENITES OF BARRIER ISLAND ORIGIN

A. Barrier island systems and their deposits

(i) Introduction and origin of barrier islands

Barrier islands are long narrow, emergent sand or gravel accumulations separated from land by a lagoon (Elliott, 1978b) (Fig.39). They occur mainly on coastal plain shorelines located on the trailing edges of continents, and on marginal seas, and vary in morphology in response to tidal range, and wave energy (Hayes, 1979).

Most barrier islands consist of sand, and are confined to mesotidal (2-4 m. tidal range), and microtidal (<2 m. tidal range) coastlines. Microtidal barriers tend to be long linear features with abundant storm washovers, whereas mesotidal barriers tend to be short and stunted due to numerous tidal inlets (Hayes, 1979). However, barrier island morphology is also affected by wave energy levels, and where they are extremely low tidal inlets and tidal deltas can be important components of microtidal barriers (McCann, 1979).

The origin of barrier islands has been the subject of considerable debate (Price, 1963; Fisher, 1967, 1968; Hoyt, 1967, 1968; Otvos, 1970, 1979; Bruun, 1978). Basically 3 main theories have been proposed (Wanless, 1976):-

(a) Build up and emergence of offshore bars

(b) Longshore spit accretion across bays

(c) Drowning of coastal sand ridges.

BLOCK DIAGRAM ILLUSTRATING THE VARIOUS SUBENVIRONMENTS IN A BARRIER ISLAND SYSTEM

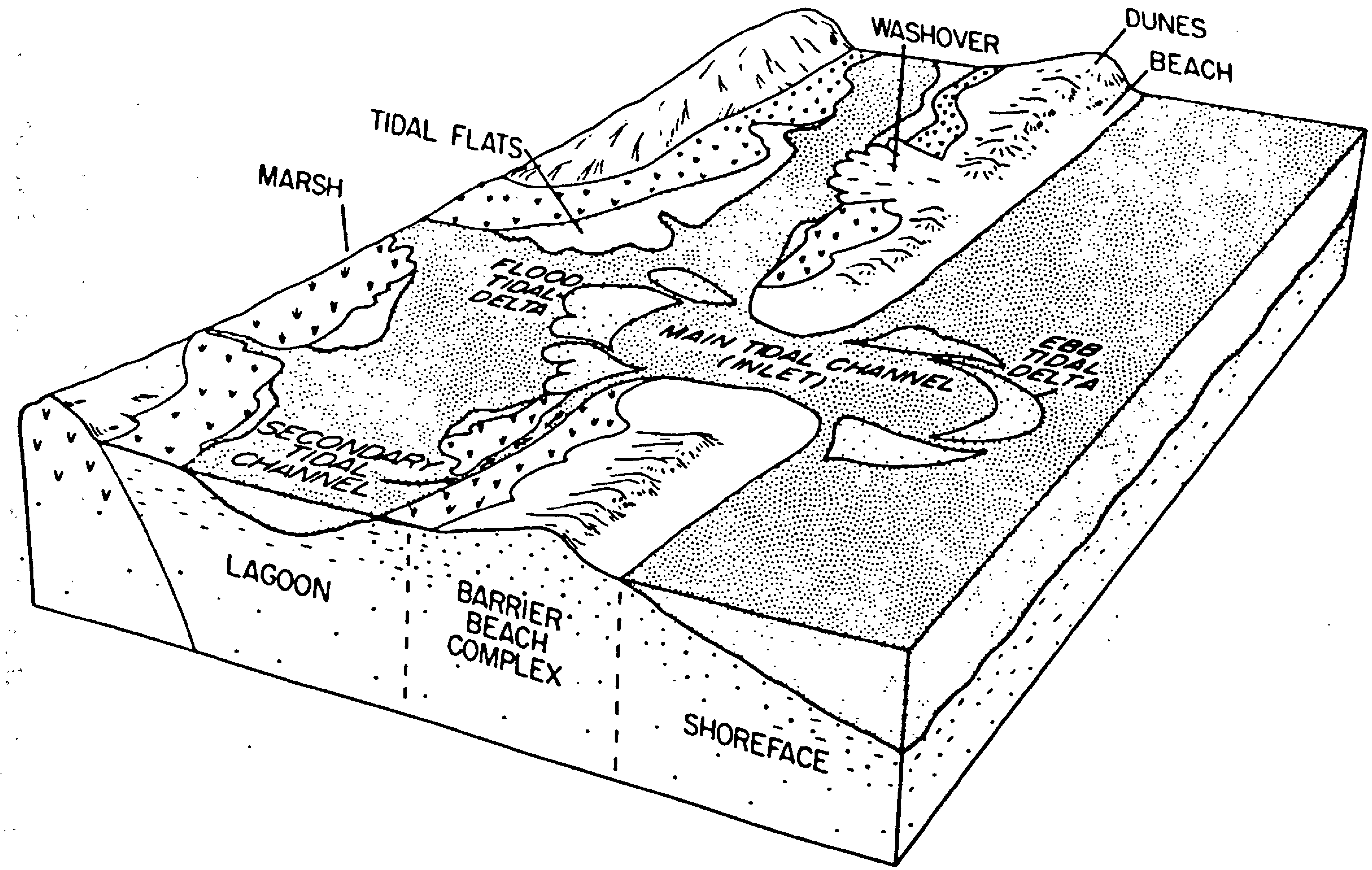


Fig.39

After Reinson(1979)

Most present day barrier islands formed along shorelines of submergence in response to the post-glacial rise in sea level. Consequently the drowning of coastal sand ridges is their most likely origin, and indeed most large barrier chains are thought to form in this way (Hoyt, 1969). Other less important occurrences of barriers formed by offshore bar aggradation (Price, 1963; Otvos, 1970, 1979). and by spit growth (Fisher, 1967, 1968) are known, and thus barriers can be considered polygenetic in origin.

(ii) Deposits of barrier island systems

Depositional environments within a barrier island system are varied, but fall into 3 main groups (Reinson, 1979):-

(a) Barrier Beach and related subenvironments

This consists of a number of subenvironments which parallel the shoreline. From seaward to landward these subenvironments are shoreface → foreshore → backshore - dune → washover flats (Figs. 40 and 41).

(1) Shoreface

This is defined as the area seaward of the barrier, from low tide mark to a depth of about 10-20 m. The lower limit corresponds to the position at which waves begin to affect the sea bed. On prograding shorelines lower shoreface deposits consist of dominantly bioturbated, parallel laminated very fine to fine grained sands. These pass landward into fine to medium grained sands displaying ripple cross lamination, parallel lamination and trough cross-bedding (Reinson, 1979). Storm deposition in the shoreface environment may be important in terms of preservation potential,

PLAN VIEW OF A BARRIER BEACH, PADRE ISLAND TEXAS

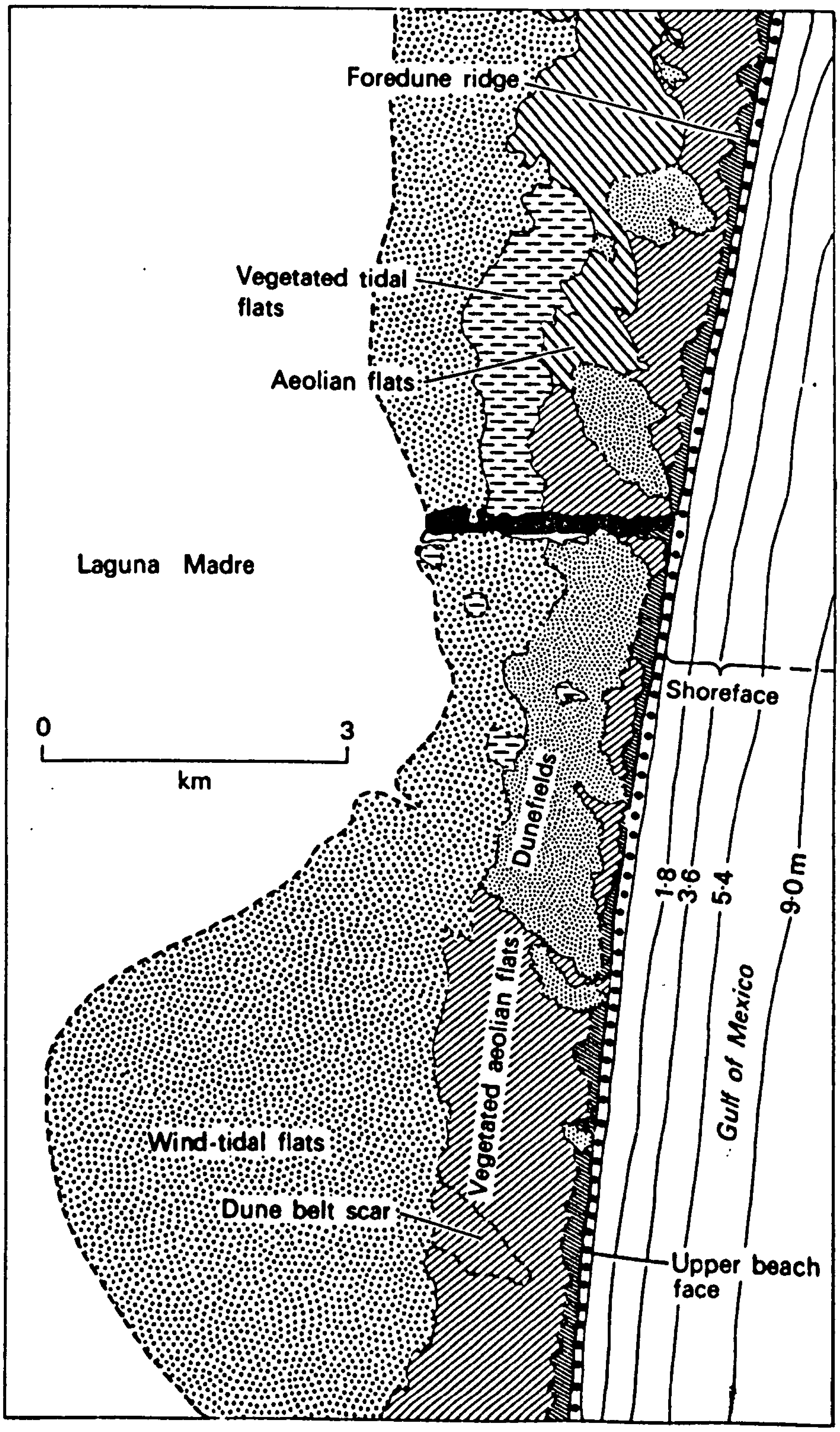


Fig.40

After Dickinson(1971)

GENERALIZED PROFILE OF A BARRIER BEACH AND RELATED SUBENVIRONMENTS

Fig.41

and may include hummocky cross-stratified sands in the lower shoreface zone (Harms *et al*, 1975).

On transgressive shorelines where relative sea level rise is small and transgression takes place principally by shoreface erosion, shoreface deposits consist of a coarse lag containing shell debris overlying a ravinement surface. This results from erosion by wave action of barrier beach and older underlying sediments (Fischer, 1961; Swift, 1968).

(2) Foreshore

This constitutes the intertidal zone, and is dominantly a region of wave swash which gives rise to low angle seaward dipping laminations (Clifton, Hunter and Phillips, 1971). Higher angle landward dipping laminae develop when longshore/oblique bar forms are present (Davidson-Arnott and Greenwood, 1974; Hunter, Clifton and Phillips, 1979).

(3) Backshore-dune

This is a subaerial zone above normal high water level, which is dominated by wind deposition. Backshore deposits consist of horizontal or landward dipping plane beds. Storm deposition may be important in this zone, and commonly results in parallel laminated sands containing abundant faunal remains, and occasional large rock fragments.

Dune deposits consist of trough cross-stratified sands commonly in sets up to several metres high. Foresets are commonly steeply dipping (up to 42^{o}), and highly variable in direction (Land, 1964). Plant roots extensively disturb dune beds. In humid tropical areas abundant vegetation stabilizes sand in emergent areas, and dune deposits are not well developed. In these zones soil horizons may begin to form. Preservation potential of backshore-dune deposits is very low due to their topographically high position.

(4) Washover flats

These consist of subaerial lobate or sheet-like deposits of sand, which are formed largely of sediment carried across a barrier island and dumped by catastrophic storms such as hurricanes (Andrews, 1970). Each washover sand has an erosive base, shell placer, and grades up into parallel laminated clean sand (Andrews, 1970; Morton, 1978). Laterally washover sands may pass into the lagoon where they become interbedded with quieter water deposits. In this distal zone, where washovers enter the lagoon, high angle ($<30^{o}$) landward directed delta foreset strata are often developed. These pass laterally into low angle ($<4^{o}$) bottomset beds which terminate the washover (Schwartz, 1975). Subaerial washover flats dip landward at angles of 1^{o} to 4^{o}, and may become colonized by plants giving rise to rootlet beds. Washover channels commonly exhibit scour and fill sequences capped by mud drapes (Morton, 1978).

Washover deposits are important reservoirs of sediment in barrier island systems, forming up to 50% of some barriers (Morton, 1978; Fisher and Simpson, 1979). Their abundance together with the fact that they infill topographically low areas and commonly occur low in the depositional sequence results in a high preservation potential.

(b) Lagoon

Lagoons tend to accumulate fine grained sediment deposited from suspension. These deposits may contain a fauna which is generally brackish water in nature due to the restricted circulation and fresh water river influx. Fine grained or heterolithic facies may form in adjacent tidal flats, and occasionally peats may accumulate in marshes and swamps (Elliott, 1978b; Reinson, 1979). Higher energy environments bordering lagoons often introduce coarser material, resulting in interbedded and interfingering sands, silts and muds. These neighbouring higher energy environments include washover fans, flood tidal deltas, tidal channels and small scale river deltas. Both the topographically low position of lagoonal sediments and their occurrence towards the base of the sedimentary sequence in transgressive situations results in a high preservation potential.

(c) Tidal inlet - Tidal delta system

Tidal inlets are narrow relatively deep channels through which tidal currents flow as water enters and leaves the backbarrier lagoon (Kumar and Sanders, 1974). Tidal deltas are broad sand accumulations produced at the inlet mouths as water enters the relatively quieter conditions of the lagoon (flood tidal delta) or open sea (ebb tidal delta). Often wave energy is high on the seaward side of the barrier and ebb tidal deltas do not form.

Tidal inlet deposits may form by inlet abandonment and *in situ* aggradation, or by lateral migration of the inlet commonly in response to longshore drift (Bruun, 1978). The latter is the most common case and results in reworking of previously deposited barrier sands, and formation of erosively based sequences which underlie many barrier islands. Tidal inlet deposits are thus important reservoirs of sediment in many barrier island systems (Hayes, 1980), and due to their topographically very low position exhibit excellent preservation potential (Kumar and Sanders, 1974).

Sequences formed by laterally migrating tidal inlets contain some of the following characteristics (Kumar and Sanders, 1974; Oomkens, 1974; Barwis and Makurath, 1978; Hayes, 1980).

(1) Erosive base with coarse grained lag containing shell debris;
(2) Upward decrease in cross-stratification size;
(3) Upward decrease in grain size;
(4) Mixed fauna of washed in brackish and marine species;
(5) Poor trace fossil assemblage;
(6) Bipolar palaeocurrents;
(7) Palaeocurrents at oblique to high angles to sand body trend.

Tidal deltas are intimately associated with tidal inlets and thus their deposits should be associated in ancient sequences. Flood tidal deltas consist of dominantly landward directed cross-bedded sands forming a bar like morphology (Hayes, 1976; Hobday and Horne, 1977). Abandonment may lead to colonization by plants and formation of thin coals (Reinson, 1979). Ebb tidal deltas are subject to both tidal and wave energy and thus internal structures can be varied depending on the balance between these processes. Tidal processes tend to predominate in the centre of the delta, whilst wave processes are most effective on the flanks. This gives rise to seaward directed dunes flanked by landward directed swash bars (Hine, 1976).

Both flood and ebb tidal delta deposits have textures and sedimentary structures similar to inlet sequences, and their recognition in ancient sediments may depend on their geometry and position relative to surrounding facies (Reinson, 1979).

(iii) Barrier island models

Sedimentary sequences formed by barrier islands tend to fall into 3 main groups (Fig.42) (Reinson, 1979):-

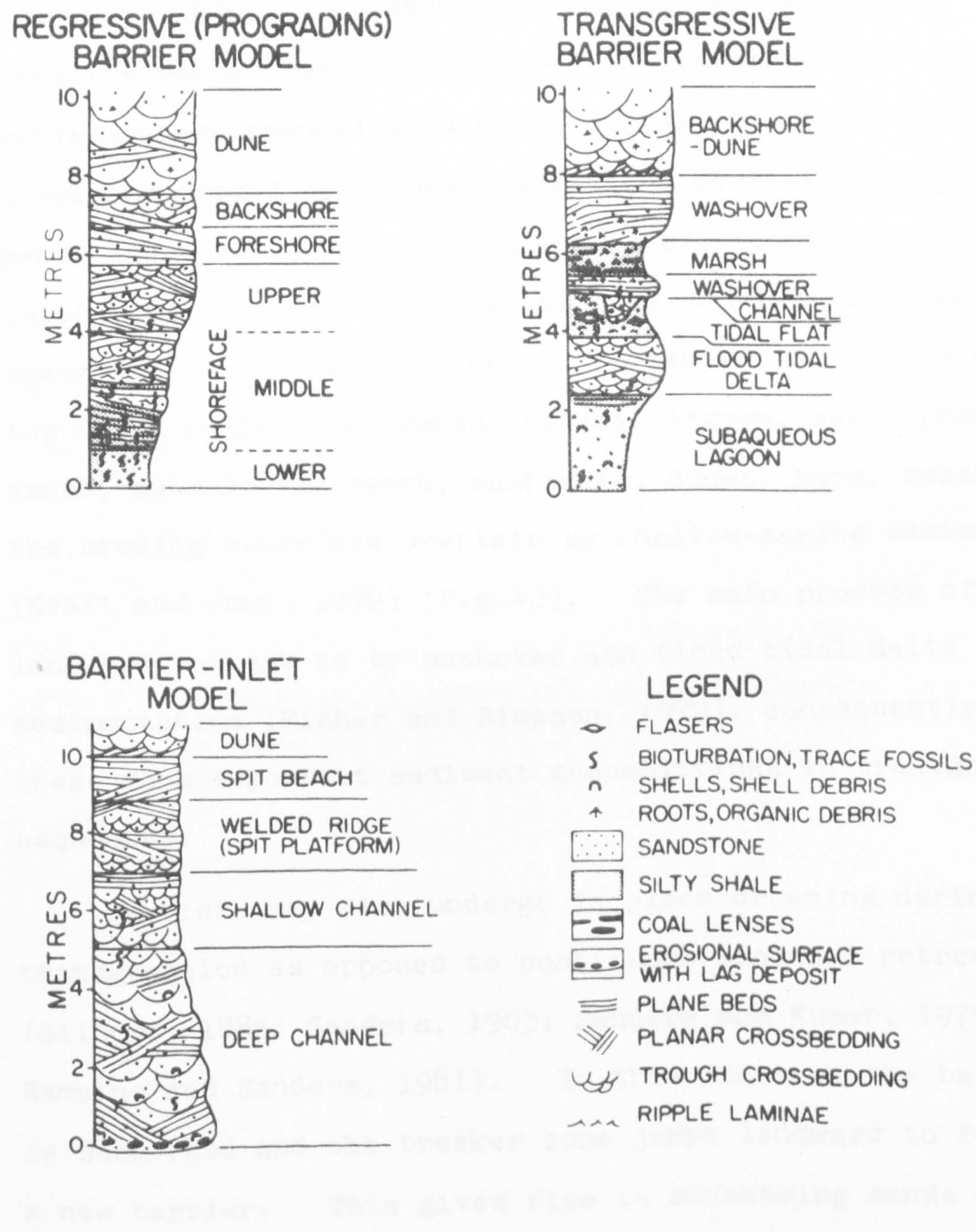
(a) Regressive model

This was the original depositional model for barrier islands. Progradation of the barrier results in a coarsening upward sequence showing a transition from truly marine to truly terrestrial conditions, overlain by backbarrier deposits (Bernard, Le Blanc and Major, 1962; Davies, Ethridge and Berg, 1971) (Fig.42). The thickness of the coarsening upward sequence commonly reflects the depth of water into which the barrier prograded (Klein, 1974). During progradation the lagoon is commonly infilled, unless a relative sea level rise or tidal scouring of the backbarrier area is sufficient to maintain this feature. The infilling of the lagoon results in the development of a prograding beach complex at the expense of the barrier island system.

(b) Transgressive model

The preservation of transgressive barrier island deposits has been the subject of debate (Bass, 1934; Bass *et al*, 1937; Fischer, 1961; Swift, 1968; Kraft, 1971; Kraft and John, 1979). The amount of preservation depends on a variety of factors, the most important of which appears to be the rate of sea

THE THREE "END MEMBER" FACIES MODELS OF BARRIER ISLAND STRATIGRAPHIC SEQUENCES



After Reinson (1979)

Fig.42

level rise relative to the rate of coastal erosion (Kraft, 1971; Belknap and Kraft, 1981). With rapid sea level rise a barrier sequence may be almost totally preserved. Shoreline and nearshore erosion, however, often results in reworking of at least the upper part of the sequence (Kraft and John, 1979). Consequently transgressive barrier deposits range from a thin veneer of residual sands and gravels where reworking is almost total, to fairly thick sequences formed by landward migrating barrier subenvironments where retention is complete (Kraft, 1971). The latter sequence generally passes from non-marine to marine upwards. An idealised vertical sequence from bottom to top might be fringing marsh, coastal lagoon, sub lagoonal sands, backbarrier marsh, washovers, dunes, berm, beach and the eroding shoreface overlain by shallow-marine sediments (Kraft and John , 1979) (Fig.42). The main process of landward retreat is by washover and flood tidal delta sedimentation (Fisher and Simpson, 1979), consequently these form important sediment accumulations in transgressive sequences.

Barriers may also undergo in place drowning during transgression as opposed to continuous landward retreat (Gilbert, 1885; Sanders, 1963; Sanders and Kumar, 1975; Rampino and Sanders, 1981). In this instance the barrier is submerged and the breaker zone jumps landward to form a new barrier. This gives rise to shoestring sands parallel to the shoreline (Sanders and Kumar, 1975).

(c) Tidal inlet model

This model is based upon the fact that many tidal inlets migrate laterally, reworking previously deposited barrier sediments. The extent to which this takes place, depends on the rate of inlet migration relative to shoreline transgression or regression. With rapid inlet migration it is possible that the only entry into the geologic record of a former barrier island complex would be tidal inlet sediments (Kumar and Sanders, 1974). These may form continuous sheet sands whose internal structures have been described previously (p.127) (Fig.42).

These 3 models are end members of a continuous spectrum, and any ancient barrier island deposit may contain varying proportions of each. In simple ideal cases only one model may be applicable, but generally situations tend to be more complex.

Within the Carboniferous succession of the Alston Block there has been only one previously described barrier island sand body (Elliott, 1974, 1975). Several others have been identified and will be described in the following pages.

B. Low Brig Hazle[1]

(i) Description

The Low Brig Hazle is a fine grained sandstone occurring in the Scar Limestone cyclothem of Brigantian (Dinantian, D_2) age (George *et al*, 1976). It outcrops

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1. The type locality of the Low Brig Hazle is in Teesdale. In Weardale this horizon is known as the Slaty Hazle.

extensively on the Alston Block, and can be traced southwards into the Stainmore Trough, where it is well exposed in the Brignall Banks Inlier. Throughout this area it has only been worked for the manufacture of refractory bricks at Thringarth in Lunedale (NY 93252350), (Strahan, 1920; Smith, 1974). Owing to its thickness, and lack of overburden it was worked as recently as 1973.

Within the confines of the Alston Block the Low Brig Hazle is divisible into 2 facies associations. A third association is developed in the Stainmore Trough.

(a) Facies Association A

In Teesdale Facies Association A is widely developed, and the quarries at Thringarth worked part of this sequence. At its simplest, Facies Association A consists of an erosively based quartz arenite up to 18 m. thick, overlain by interbedded sandstones and shales directly beneath the Five Yard Limestone. Typical exposures occur in many of the streams draining the N. side of Teesdale, with perhaps the best being in Bow Lee Beck South (NY 90702855) where the whole Scar Limestone cyclothem, and overlying Five Yard Limestone is exposed (Fig.43).

At this locality fossiliferous shales above the Scar Limestone pass up into unfossiliferous shales, which are overlain erosively by a fine grained sandstone approximately 9 m. thick (Figs. 43 and 44). At the base this contains abundant intraformational shale clasts up to 20 cms. long, and tends to be slightly coarser grained. This passes up into fine grained sandstones which are dominantly trough cross-bedded throughout (sets generally <1 m. thick). Planar

MEASURED VERTICAL SECTION
THROUGH THE CLASTIC INTERVAL
OF THE SCAR LIMESTONE CYCLOTHEM,
BOW LEE BECK SOUTH

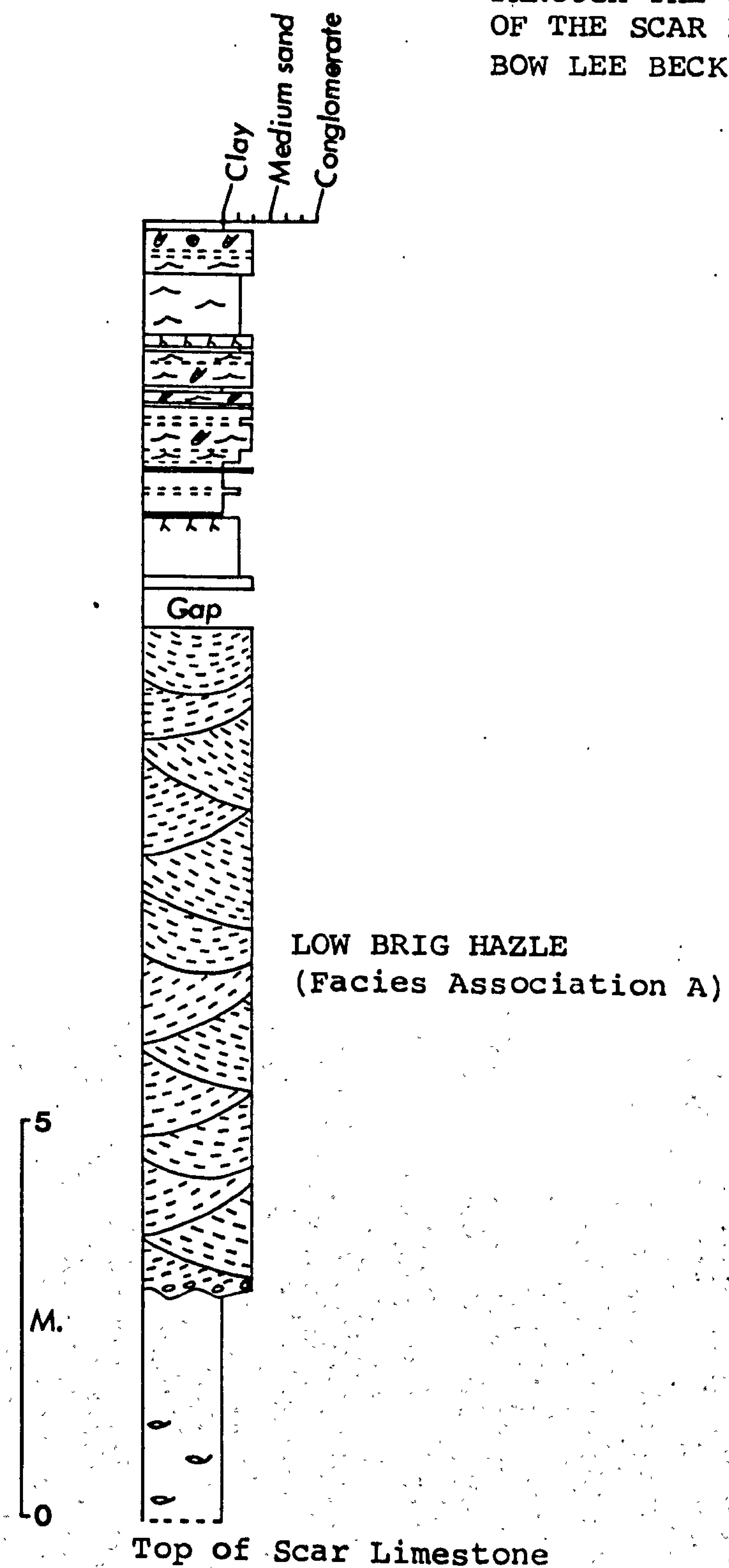
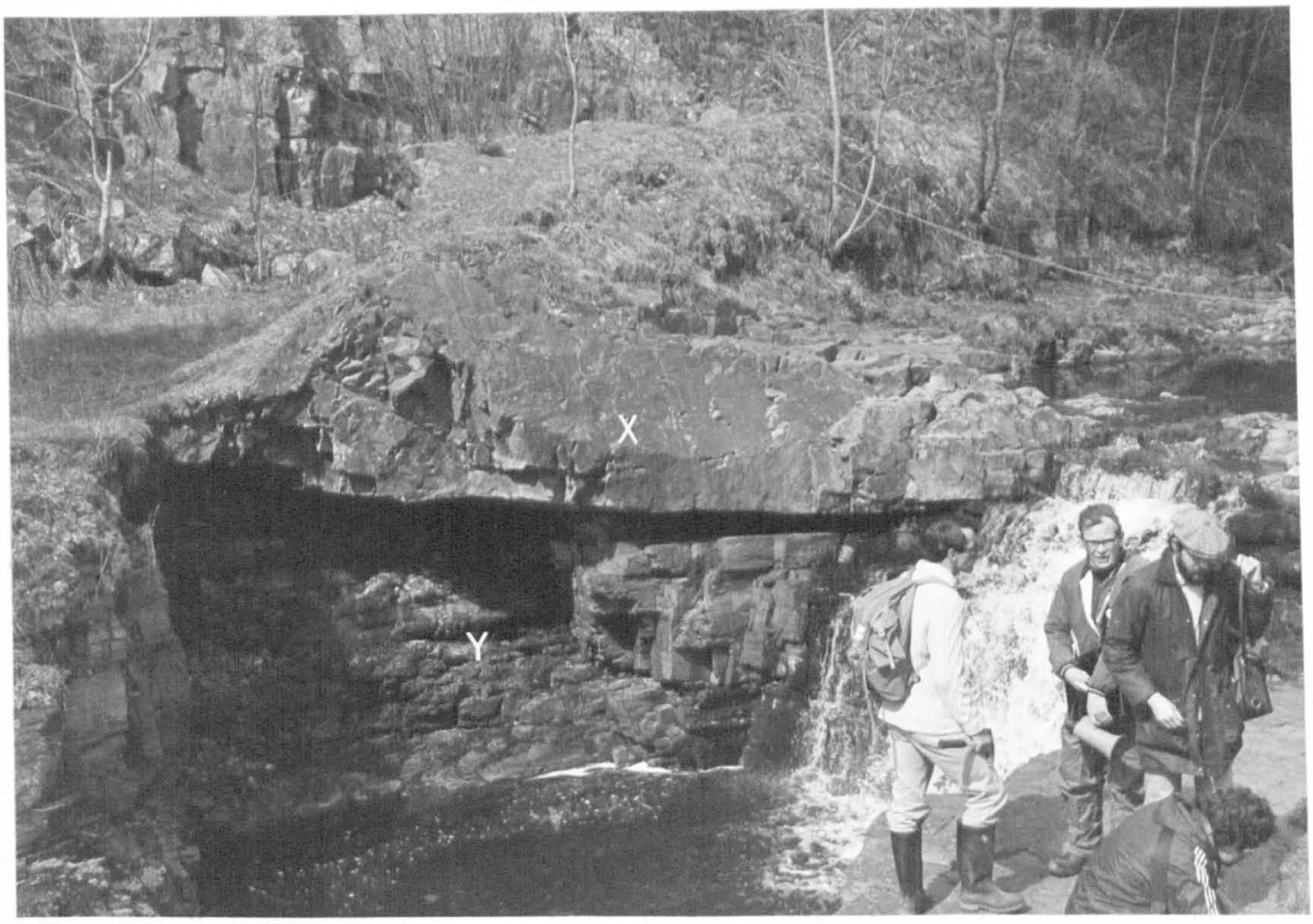
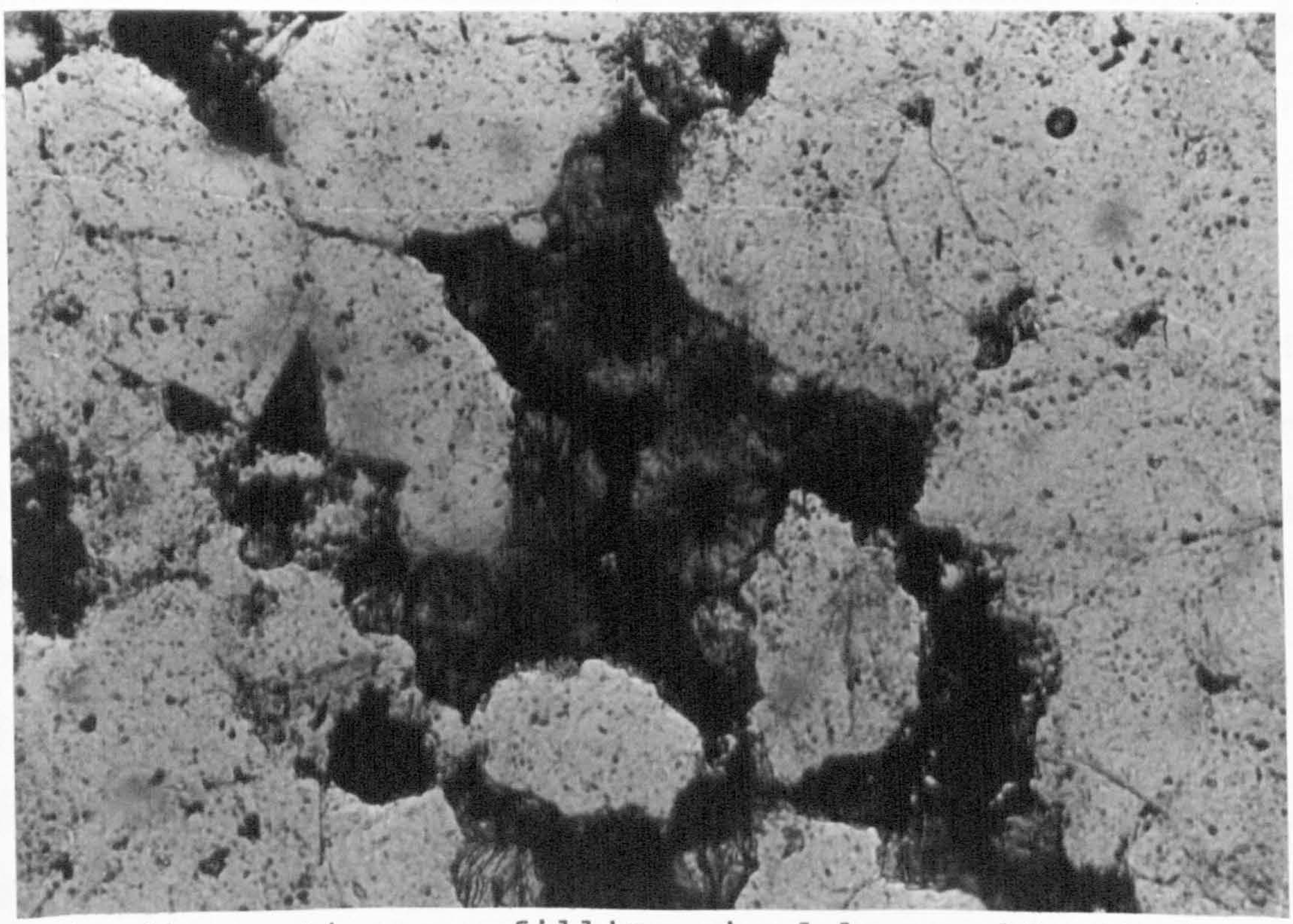


Fig.43



Erosively based quartz arenite(X) overlying shales(Y) above the Scar Limestone,Low Brig Hazle,Facies Association A, Bow Lee Beck South. Fig.44



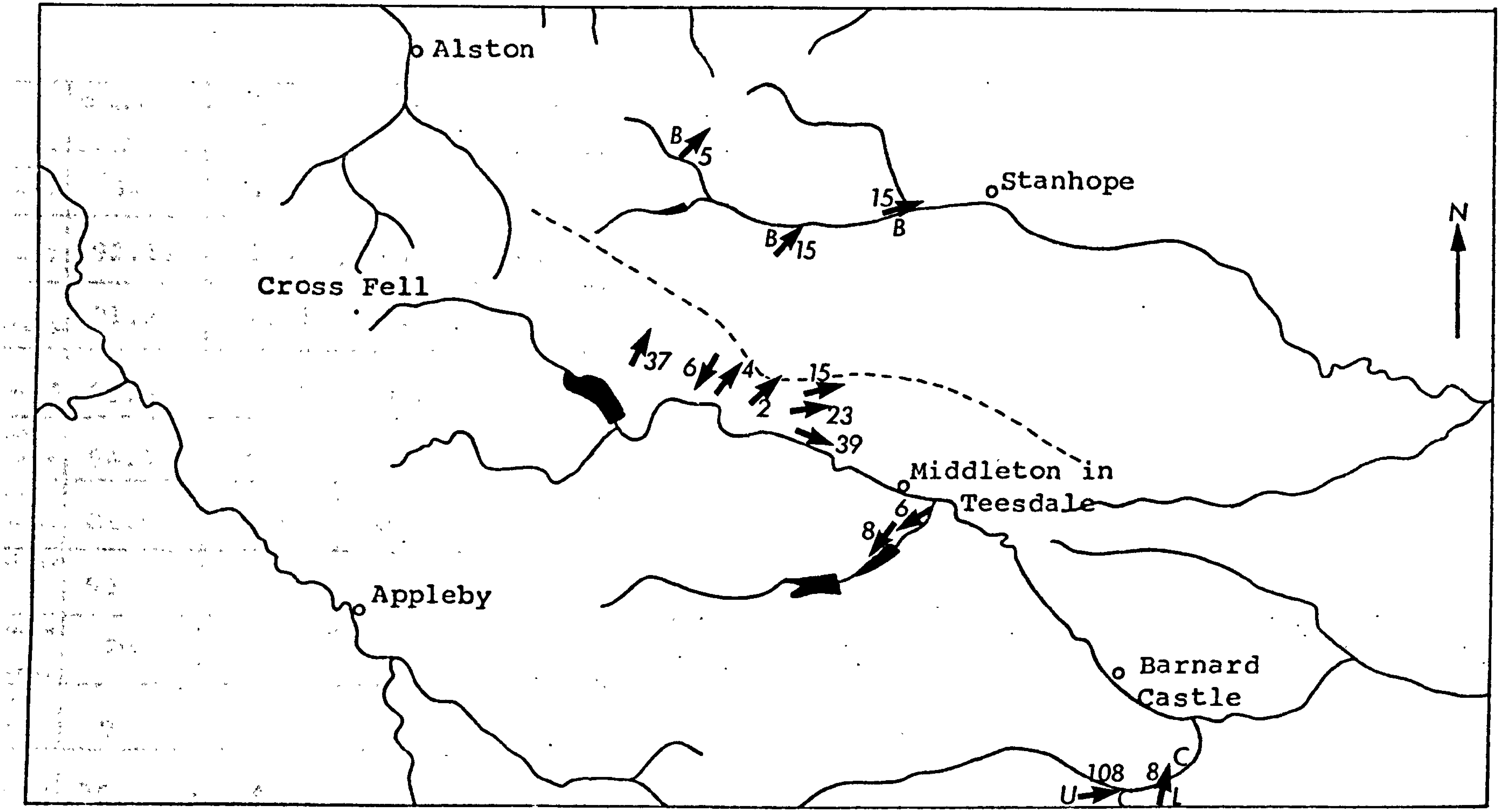
Late diagenetic pore filling mixed layer chlorite/vermiculite replacing adjacent quartz grains and showing well developed spherulitic texture,Low Brig Hazle,Facies Association A, Greengates Quarry,Lunedale(Length of photomicrograph 0.8mm.). Fig.45

cross-bedding and parallel lamination are occasionally present, and sometimes there is an upward decrease in cross-stratification size. Individual sandstone beds are lenticular in profile and display erosive bases which are occasionally accentuated by loading. Clasts derived from thin interbedded shales, and driftwood fragments are common, particularly towards the base of beds.

Palaeocurrents at any one locality are relatively unidirectional, but variations of 120° about the vector mean do occur, and rare herringbone cross-bedding has been observed. On a regional scale palaeocurrents show a trend towards the N.E. with a minor reverse trend towards the S.W. (Fig.46). Petrographically the sandstones are well sorted fine grained quartz arenites containing a small amount of sericite, kaolinite, and occasionally feldspar (Fig.47). Original detrital grains are subrounded to rounded, and very occasionally display multiple and abraded overgrowths indicating reworking of older sediments in the source area.

The thickness of this sandstone unit is variable, generally being in the range of 6-12 m., but reaches its maximum of at least 18 m. in Greengates Quarry, Thringarth. At the top it passes into a series of interbedded fine grained sandstones and shales. Rootlet horizons occur, and thin coals may be present. Rarely as in Newbiggin Beck (NY 91452793), and the River Tees at Breckholme Pool (NY 94002555) some of the shales contain a marine fauna. Bioturbation is common within this uppermost strata, and may be sufficiently intense to cause poorly sorted muddy sandstones due to the admixing of finer and coarser grained

LOW BRIG HAZLE PALAEOCURRENTS



=Vector mean at each locality
6=Number of palaeocurrent measurements at each locality
U/L=Upper or lower leaf where applicable
=Approximate line of junction between Facies Associations A and B
All localities Facies Association A except where stated

Fig.46

POINT COUNT ANALYSES OF BARRIER ISLAND QUARTZ ARENITES AND ASSOCIATED STRATA

Horizon/ Facies	Quartz %	Mixed Layer Clay/Sericite %	Kaolinite %	Feldspar %	Muscovite %	Carbonaceous Material %	Heavy Minerals %	Goethite %	Chert %	Calcite (C) Biotite (B) %	N
Low Brig Hazle Facies Association A	94	4.5	0.5				0.5	0.5			200 (1)
Low Brig Hazle Facies Association B	92.17	2.5	0.83	0.33	0.17			1		3(C)	500 (2)
Low Brig Hazle Facies Association C	91.25	1.25	5.25	1.25			0.25	0.75			400 (2)
High Brig Hazle Facies Association A	96.5	2.41	0.17	0.17	0.25	0.17		0.25	0.08		1200 (6)
High Brig Hazle Facies Association B	94.5	4.5					1				200 (1)
High Brig Hazle Facies Association C	81.5	8.5	0.5	0.5				9			200 (1)
Sandy Carr Ganister Facies A	93.75	0.25	3.25		0.5			2.25			400 (2)
Sandy Carr Ganister Facies B (Rootlet Penetrated)	79	14.5	3.5		1.5	1.5					200 (1)
Millstone Rigg Quartz Arenite	97	2	0.25				0.25	0.5			400 (2)
Sandstone Above Sandy Carr Ganister	75.5	14	5.5	0.5	1.5	2.5				0.5(B)	200 (1)

N=Total number of point count measurements(number in top right hand corner refers to the number of thin sections analysed)

Fig.47

material. Trace fossils include *Aulichnites*, *Cosmorhaphe*, *Crossopodia*, *Muensteria* and indeterminate horizontal and vertical burrows.

Shales within this uppermost strata are occasionally sandy, and contain wavy and lenticular bedding. Wave ripples exhibit crestal trends of approximately N.E.-S.W. Other sedimentary structures are restricted to parallel lamination within sandstone beds. This interbedded sandstone and shale sequence tends to be less than 6 m. thick, and is overlain directly by the Five Yard Limestone. Locally the top of the sequence has been reworked by the transgression which preceded deposition of the limestone.

In Greengates Quarry, this upper part of Facies Associaton A is much thicker than normal (11 m. or more), and includes several highly convolute fine grained quartz arenites. Towards the top of the sequence a large scale truncation plane is present between an upper horizontal set of strata and a lower set dipping at 4°, 64°. This dies away as it is traced towards the S.W. along the quarry face. In the horizontal strata above, several small channels (several 10's cms.-1m. or more deep) trending N.N.W.-S.S.E. are present.

(b) <u>Facies Association B</u>

Facies Association B outcrops extensively in Weardale, particularly in the lower reaches of streams draining into the River Wear in the Eastgate - St. Johns Chapel region. In this area the Low Brig Hazle consists of interbedded fine grained sandstones and shales, overlain by thicker erosively based sandstones. A particularly good exposure occurs in Harthope Burn (NY 88153770) where the Low Brig Hazle forms the top of an approximately 20 m. thick coarsening and thickening upward sequence capped by the Five Yard Limestone (Fig. 48).

Shales above the Scar Limestone are overlain by a series of interbedded fine grained sandstones and shales which dominate the sequence, and give rise to the local name of Slaty Hazle for this horizon. Individual sandstone beds are generally < 30 cms. thick and have sharp bases and tops. Petrographically they consist of moderately well sorted quartz arenites containing subrounded to rounded detrital grains. A small percentage of clay is often present, particularly as pore fills. Occasionally texturally less mature sandstones occur towards the base of the section, but are generally of minor importance.

Many sandstone beds are laterally persistent within an individual exposure (generally < 100 m. in length). Internally they display parallel lamination or occasionally low angle lamination through their middle and lower portions, and commonly current, wave, or interference rippled upper surfaces. Wave ripples are very common, and may show variations in crestal trend of 70° from successive beds. Overall, however, there is a dominance of N.-S. orientations. Bioturbation is fairly common, particularly on the top surface of sandstones, and includes *Aulichnites*, *Gyrochorte*, *Muensteria*, *Pelycypodichnus*, *Planolites*, and indeterminate horizontal and vertical burrows.

Interbedded shales are often micaceous and carbonaceous, and drape over the top surface of underlying sandstones. Internally they may contain thin sandstone lenses and ripples

MEASURED VERTICAL SECTION THROUGH THE CLASTIC INTERVAL OF THE SCAR LIMESTONE CYCLOTHEM, HARTHOPE BURN, ST.JOHNS CHAPEL

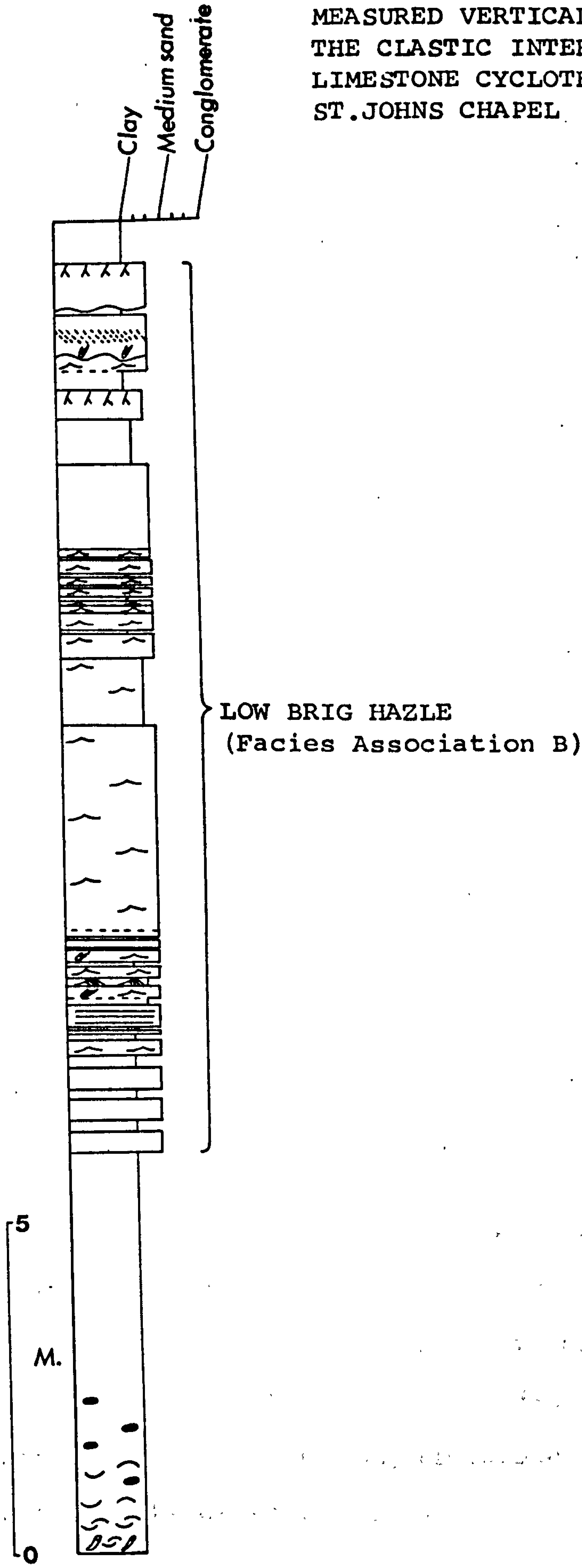


Fig.48

giving rise to lenticular and wavy bedding. Rootlet beds occur towards the top of the sequence, and are overlain by thicker erosively based fine grained quartz arenites. In Rookhope Burn, (NY 95253890) these are up to 3.5m. thick, and display abundant trough and occasionally planar cross-bedding in sets up to 1.25 m. thick. Intraformational shale clasts and driftwood fragments are common. Occasionally wave ripples are present and may occur superimposed on foresets, often with their crests trending down dip at high angles. Palaeocurrents from these sandstones trend in a dominantly N.E. direction (Fig.46). Bioturbation is occasionally present, and consists of obscure horizontal burrows commonly at the base of beds.

Petrographically the quartz arenites are well sorted, and original detrital grains range from subrounded to rounded in outline. Rare quartz grains from this and the underlying sandstones exhibit multiple overgrowths indicating recycling from older sediments. Occasional chert grains are also present. Sericite and kaolinite make up the small percentage of clay minerals present (Fig.47).

The top of Facies Association B often consists of a sandstone or shale penetrated by rootlets. Locally, however, reworking has taken place prior to deposition of the overlying Five Yard Limestone. This has resulted in the destruction of any rootlets present, and incorporation of marine fossils into the top of the Low Brig Hazle. In these areas the contact with the overlying limestone is transitional, elsewhere this tends to be sharp.

Slight variations of Facies Association B occur in the River Nent at Alston (NY 72104675), and the core from the Rookhope borehole. At the former locality the Low Brig Hazle forms the top of a 15 m.+ coarsening upward sequence above the Scar Limestone. Thin laterally persistent beds of quartzarenite interbedded with shales pass up into thicker bioturbated, parallel laminated (with associated streaming lineation) and trough cross-laminated fine grained quartz arenites. Bioturbation includes *Cosmorhaphe* and *Muensteria*. In the core from the Rookhope borehole, the clastic interval of the Scar Limestone cyclothem consists of 2 coarsening upward sequences approximately 12 m. thick separated by a fossiliferous marine shale. These are very similar in sedimentary structures and lithologies to the River Nent exposure.

(c) Facies Association C

Facies Association C consists of a series of thick sandstone units (generally <12 m. thick), and interbedded shales, and thin conglomerates forming a sequence approximately 36 m. thick. It is restricted to the Stainmore Trough, where it is well exposed in the Brignall Banks Inlier (NZ 05551140). At this locality over 30 m. of sandstone are exposed in a series of cliffs alongside the River Greta when it transects the Middle Tyas - Sleightholme anticline.

Lateral variations in bed thickness and lithology do occur along this 5 km. long discontinuously exposed section, but a generalized sequence can be ascertained (Fig.49). The lowest exposed strata consist of a 6 m. thick coarsening

GENERALIZED VERTICAL SECTION THROUGH THE EXPOSED CLASTIC INTERVAL OF THE SCAR LIMESTONE CYCLOTHEM, BRIGNALL BANKS

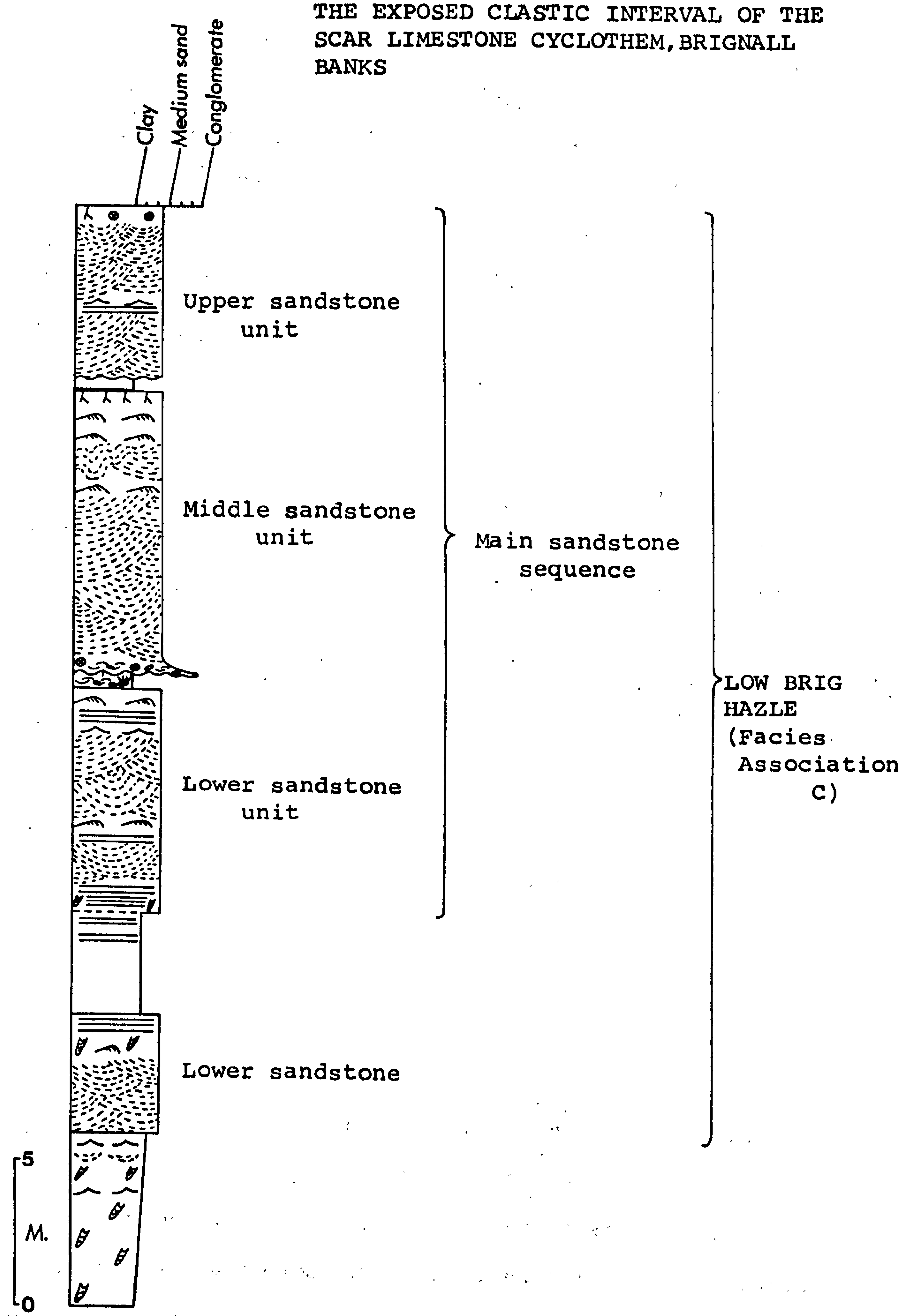


Fig.49

upward sequence of dark grey silty mudstone with thin sandstone laminae, thought to lie close above the Scar Limestone (Mills and Hull, 1976). The thin sandstones display superb trough cross-lamination, parallel lamination, and low amplitude wave ripples. Thin clay drapes give rise to flaser bedding, and bioturbation consists of obscure horizontal and vertical burrows.

These sandstones and shales are overlain erosively by a fine to medium grained sandstone generally < 4 m. thick. This displays trough cross-bedding, current ripple cross-lamination, and parallel lamination with palaeocurrents towards the N. (Fig.46). Individual beds are sharply or erosively based, and intraformational shale clasts are common. Several large scours up to 1.5m. deep and several metres wide are present; these trend towards the N.E. Bioturbation includes *Pelycypodichnus* and *Skolithos* which may locally be very abundant.

This sandstone is overlain by a series of sandy and silty shales approximately 3.5m. thick. These are generally unfossiliferous, but at NZ 04451140 a series of shales at approximately the same horizon contain gastropods, and fenestellid bryozoa. At this locality the top few cms. of the underlying sandstone has been reworked, and contains broken and abraded shell debris. Overlying these shales is the main sandstone sequence which forms virtually the whole of the remaining Scar Limestone cyclothem. (Fig.49). This sandstone sequence can be subdivided into 3 units based on the presence of a marine band, and a thin coal and associated seatearth. Where these are locally absent it is often difficult to distinguish between units due to their similar lithology and structures.

The basal sandstone unit is transitional or locally erosive into the underlying shales, and consists of a series of fine to medium grained sandstones 6-10 m. thick. At NZ 05601145 the base is transitional, and thin (up to several cms. thick) parallel laminated, wave and current rippled fine grained sandstones pass up into erosively based trough cross-bedded sandstones in sets up to 2 m. thick. Bioturbation is common towards the base, and includes *Pelycypodichnus*, *Cochlichnus* and obscure vertical burrows.

A marine band commonly overlies this sandstone unit. This varies markedly in lithology, and may locally be absent due to erosion at the base of the overlying sandstone. At its simplest the marine band consists of a thin shale up to a few 10's cms. thick containing brachiopods, bivalves, crinoid ossicles and fenestellid bryozoa. Often, however, it consists of a series of sandstones, shales and conglomerates. The conglomerates consist of intraformational shale clasts, and broken and abraded fossils (bivalve, brachiopod and crinoid debris) in a coarse grained sandstone matrix. The conglomerate commonly occurs in small channel-like bodies, but is also present in fining upward units approximately 0.5 m. thick. Interbedded sandstones and shales display parallel lamination, herringbone cross-bedding, wave ripple cross-lamination and bioturbation. Occasionally the shales are contorted, and more rarely small slumped blocks of laminated sandstone and small synsedimentary faults are present.

This marine band is overlain erosively by the 10-12 m. thick middle sandstone unit. The basal few cms. of this sandstone are often conglomeratic containing abundant intraformational shale clasts, broken and abraded fossils, and large driftwood fragments. This passes upward into dominantly trough cross-bedded fine to medium grained sandstone in beds up to several metres thick. Cross-laminated horizons occur, and appear to increase in abundance near the top. This is accompanied by a decrease in bed thickness. Convolute lamination is present, and suggests both vertical and lateral movement of sand.

The top of this sandstone unit is rarely exposed, but when seen consists of a rootlet penetrated muddy micaceous sandstone overlain by a 2 cm. thick coal. A thin plant rich shale (approx. 32 cms. thick) separates this from the overlying upper sandstone unit. This topmost sandstone is approximately 6m. thick, and consists of a sharply based fine to medium grained sandstone with occasional thin silty shale laminae up to a few cms. thick. The top is often reworked by the transgression which preceded deposition of the Five Yard Limestone, and contains broken and abraded shell fragments and crinoid ossicles. Locally this reworking was not so effective and rootlets are present. Trough cross-bedding is the dominant sedimentary structure in the upper sandstone unit, and tends to decrease in set thickness near the top where sets are commonly <15 cms. thick. Wave ripples, parallel lamination and reactivation surfaces occur at various levels, and occasional bioturbation consists dominantly of obscure horizontal burrows.

Palaeocurrents from this main sandstone sequence are fairly variable, but show a dominant trend towards the E.N.E./E. (Fig.46). In thin section the sandstones are dominantly moderately well sorted quartz arenites, and original detrital grains exhibit subrounded to rounded outlines. Feldspar and clay minerals (dominantly sericite and kaolinite) occur in minor amounts, and occasionally chert grains are present (Fig.47).

(d) Relationship between facies associations

(1) Facies Associations A and B

The junction between Facies Associations A and B is never seen in the field. Certain exposures, however, show varying developments of each, and it is thought that the contact is probably both transitional and erosive, occurring somewhere across the Weardale-Teesdale watershed (Fig.50).

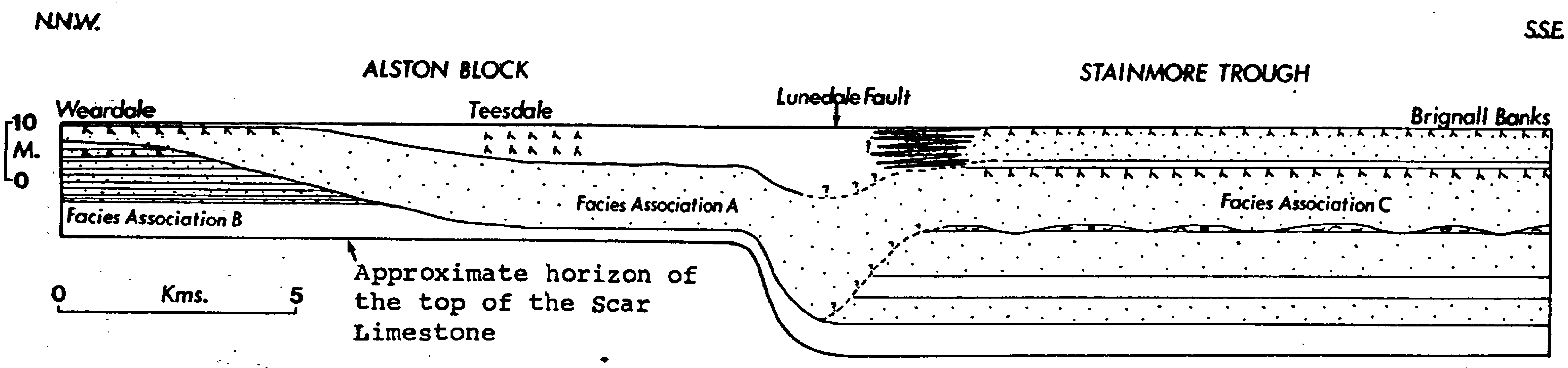
(2) Facies Associations A and C

Southwards Facies Association A passes into Facies Association C, the contact again being unexposed. As Facies Association A is traced southwards it appears to thicken in the vicinity of the Lunedale-Butterknowle Fault. It is therefore suggested that the contact between the 2 facies associations is transitional, in part at least and occurs in proximity to this hinge line. The greater subsidence in the Stainmore Trough allowing accumulation of the thick clastics which are characteristic of Facies Association C. A possible relationship between Facies Associations A and C is shown in Fig.50. This is based upon lithological similarities between sandstones across the Lunedale Fault, and correlation constraints imposed by the interpreted depositional environments of the sandstone units.

(3) Facies Associations B and C

These are never juxtaposed in the field, being separated in all cases by Facies Association A (Fig.50).

DIAGRAMMATIC N.N.W.-S.S.E. SECTION THROUGH THE CLASTIC INTERVAL OF THE SCAR LIMESTONE SHOWING THE FACIES VARIATION OF THE LOW BRIG HAZLE



☐ =Sandstone

☐ =Shale(with occasional interbedded sandstone)

Correlation of strata across the Lunedale Fault is uncertain

Lateral continuity of beds in the Stainmore Trough is unknown

The horizontal line forming the top of the section represents the base of the Five Yard Limestone

Fig.50

(ii) Diagenesis

The diagenetic histories of sandstones from all 3 facies associations are very similar, and they are therefore treated together. Cementation and porosity reduction has been achieved mainly by the formation of authigenic overgrowths on detrital quartz grains. Prior to this the sandstones had undergone some compaction resulting in slight distortion of large detrital mica grains.

Occasionally a late stage influx of carbonate rich solutions has occurred resulting in replacement of quartz grains and overgrowths by coarse grained poikilotopic calcite cement. This is most common directly beneath the Five Yard Limestone, but does occur lower down in Facies Association B in conjunction with thin calcite veins. Commonly in these areas the proportion of calcite is very small, and occurs as pore fills. Such small quantities of calcite may have originated within individual sandstone beds by dissolution of shell material.

Feldspars, when present, often show alteration to sericite, and most pore filling clay minerals appear to represent the end products of this process. Very occasionally sericite occurs as incipient, apparently diagenetically formed clay coats to framework grains, and mixed layer chlorite/ vermiculite is sporadically present as late diagenetic pore fills. The latter exhibits well developed spherulitic texture and commonly replaces adjacent quartz grains and overgrowths (Fig.45).

Siderite is occasionally present, and varies from fairly early diagenetic coatings to grains, to late stage pore linings.

Infrequently there are local developments of late stage pyrite which replaces quartz grains. Its patchy development suggests an association with regional mineralization, although small occurrences may have formed around decaying organic matter. Stylolites are moderately common in all the quartz arenites and indicate late diagenetic pressure solution of quartz.

(iii) Interpretation

(a) Facies Association A

In the Middleton-in-Teesdale area Jones (1956) concluded that the erosively based quartz arenite of Facies Association A was of distributary mouth bar origin. However, the erosive base, mature nature of the sandstone, palaeocurrent reversals, and cross cutting relationship between palaeocurrents and sand body trend argue strongly against such an origin (Fisk *et al*, 1954; Fisk, 1961; Gould, 1970). Quartz arenites with similar palaeocurrent trends are common amongst tidal deposits (Hobday and Horne, 1977; Klein, 1977; Tankard and Hobday, 1977). The erosive base, fining upward trend, lack of bioturbation, palaeocurrent pattern, and occasional decrease upward in the scale of cross-stratification suggest the thick (> 5 m.) quartz arenites were deposited by laterally migrating tidal inlets along a barrier island coastline. Occasional thinner quartz arenites showing similar features probably represent associated tidal channel deposits (Fig.51).

The geometry and orientation of the sand body suggests that the barrier island system was orientated in a W.N.W.-E.S.E. direction. This was cut by a series of tidal inlets which reworked all previously deposited barrier sands. The thickness of the quartz arenites formed suggest that these inlets were generally <10 m. deep, but occasionally reached 18 m. or more, which is well within the range of modern examples (Kumar and Sanders, 1974). Palaeocurrents suggest that flood tides were dominant and their relationship to sand body trend indicates that littoral drift and inlet migration was probably towards the W.N.W. The lack of any fauna is attributed to the inhospitable nature of the environment, and perhaps due to the post depositional leaching of shell material.

Tidal inlets are most common along mesotidal barrier coastlines (Hayes, 1979). The abundance of inlet deposits in Teesdale may suggest similar conditions during formation of Facies Association A.

The overlying deposits up to the base of the Five Yard Limestone represent a series of environments ranging from marine to non-marine. The abundance of shale, degree of bioturbation, lack of large scale sedimentary structures, and poorly sorted nature of many sandstones indicates formation under low energy conditions. These features, together with their position above tidal inlet sandstones suggest deposition in backbarrier/lagoonal environments during barrier progradation (Fig.51). Thin coals and rootlet beds may have formed on emergent backbarrier flats (p. 125), whereas bioturbated sandstones and shales, and lenticular and wavy bedded horizons are lagoonal and intertidal in origin. Thin convolute laminated quartz arenites indicate rapid deposition, and probably represent washover sands emplaced during storm events. Associated small channels may be feeders to this system or are possibly tidal in origin. The abundance of tidal inlets could lead to complete circulation of marine waters into the lagoon, resulting in the formation of fossiliferous marine shales in quiet water areas.

The large scale truncation plane present in Greengates Quarry overlies a series of strata dipping to the E.N.E. These low angle dips do not appear to be due to synsedimentary tectonism, and suggest deposition took place on the S.S.W. flank of a large topographic hollow. It is tentatively suggested that this feature may have been a backbarrier lagoon, and that the low angle surfaces represent the S.S.W. sloping margin of this feature at successive points in time.

Facies Association A is thus interpreted to have formed by southward progradation of a mesotidal barrier island system, which resulted in deposition of backbarrier and lagoonal sediments over previously formed tidal inlet sands (Fig.51).

(b) Facies Association B

This lies N. of Facies Association A, which implies formation in a more landward position. The paucity of marine fossils, and the presence of several rootlet beds, and occasional thin coals tends to support this. On general considerations, therefore, Facies Association B might be expected to have formed in a backbarrier/lagoonal or coastal plain environment. The textural maturity of the sandstones, presence of abundant wave ripples, and landward directed palaeocurrents suggest backbarrier/lagoonal deposition.

The lower thin quartz arenite and shale facies indicates fluctuating energy conditions. Periods of rapid sand emplacement giving rise to sharply based quartz arenites are interspersed with quieter water shale deposition. Similar sequences are known from modern barrier islands where storm washovers rapidly deposit sand eroded from the front of the barrier. If emplaced subaqueously these are liable to wave and current reworking, bioturbation and deposition of thin clays during quiet water periods. Subaerially deposited washovers may become colonized by plants (p.125). This lower facies is thus thought to represent a series of dominantly subaqueously emplaced washover sands and interbedded lagoonal muds (Fig.51).

Thicker erosively based quartz arenites form the upper half of this facies association. The degree of scouring at the base of some beds, and the size of bedforms suggest fairly high energy conditions. Superimposed wave ripples on trough cross-beds often have their crests oriented subparallel to palaeocurrent trend. This suggests no relationship between wind driven wave direction and the direction of migration of larger bedforms, thus the currents operating during formation of the latter were probably tidal rather than wind driven in origin (Levell, 1980a). These characteristics together with the onshore directed palaeocurrents (Fig.46), and association with lagoonal deposits suggest a flood tidal delta and probably associated flood tidal channel origin for these thicker quartz arenites (Fig.51). Flood tidal deltas form topographic highs in lagoons, consequently their deposits may overlie previously deposited lagoonal and backbarrier sediments as in this facies association. The occurrence of rootlet beds beneath flood tidal delta deposits at several localities suggests that a relative rise in sea level (possibly due to subsidence) took place during barrier migration.

Well developed coarsening upward sequences within Facies Association B probably also represent flood tidal delta deposits. The occurrence of 2 such sequences in the Rookhope borehole core suggests 2 separate periods of flood tidal delta progradation. This may reflect the lateral migration of 2 discrete tidal inlets and their associated deltas during a relative sea level rise, or 2 episodes of barrier migration. The thickness of the coarsening upward sequence in the R. Nent suggests progradation of a flood tidal delta into a lagoon at least 15 m. deep (Barwis and Hayes, 1979).

The topmost sandstone of Facies Association B occasionally contains rootlets. This probably represents abandonment of flood tidal deltas during inlet migration and barrier progradation, with resultant colonization by plants of emergent areas. If sufficient time was available thin coals developed. Often, however, these topographically high areas were reworked by the transgression which preceded deposition of the overlying limestone.

Wave ripples throughout the sequence vary in crestal trend, but N.-S. and N.E.-S.W. orientations predominate. These may represent forms produced by winds blowing along the length of the lagoon, or oceanic waves refracted through tidal inlets.

Facies Association B thus represents deposition in a backbarrier environment which was dominated by the processes of washover and flood tidal delta sedimentation. Progradation of flood tidal deltas into the lagoon and over previously deposited washover sands gave rise to coarsening and thickening upward sequences up to 20 m. thick.

(c) Facies Association C

Due to the thick complex nature of this facies association, and the lack of sufficient data on facies changes, and sand body geometry and trend, a detailed environmental reconstruction is not attempted. Faster rates of subsidence and sedimentation and subsequent stacking of sandstones in the Stainmore Trough makes correlation with events on the Alston Block difficult. However, the presence of fossiliferous conglomeratic horizons, and marine shales within the sequence, suggests that southwards one was passing into a more open marine area.

The lowest exposed sandstone exhibits no diagnostic criteria for any particular depositional environment. Its position low in the sequence, however, indicates that it was probably forming while the barrier island complex lay to the N. on the Alston Block. The presence of *Skolithos*, fairly large bedforms, northward directed palaeocurrents, and the lack of evidence of emergence can tentatively be taken to suggest a shallow subtidal origin (Fig.51).

The main sandstone body represents a stacked sequence of approximately 3 sandstone units. The presence of erosional bases to beds, coarse grained conglomeratic horizons and fairly large scale sedimentary structures in these units suggests high energy conditions during deposition. Palaeocurrent reversals occasionally occur within individual sandstone units indicating that tidal currents were probably active.

The middle sandstone unit displays all these features together with convolute lamination indicating rapid deposition. It erosively overlies a marine band, contains marine fossils at the base, displays an upward decrease in the scale of cross-stratification, and becomes penetrated by rootlets and overlain by a thin coal at the top. All these features are similar to those formed by laterally migrating tidal inlets (p. 127). It is thus suggested that this unit has a similar origin and reflects in part southward progradation of the barrier island system into the Stainmore Trough (Fig.51).

The marine band beneath this sandstone unit consists of interbedded conglomerates, sandstones and shales, indicating highly fluctuating energy levels during deposition. The occurrence of herringbone cross-bedding in the sandstones suggests that tidal currents may have been responsible, at least in part.

The remaining 2 sandstone units are fairly poorly exposed. However, in grain size, roundness and sorting they are very similar to the middle unit, and thus probably underwent a similar degree of reworking. This together with the sedimentary structures present, and the E.N.E. palaeocurrents tentatively indicates a shallow subtidal-intertidal origin. The presence of occasional rootlets at the top of the upper sandstone suggests that final deposition of this unit took place supratidally (Fig.51). The transitional base to the lower sandstone unit at NZ 05601145 and its coarsening upward nature suggests a tidal delta origin, possibly flood-dominated (Fig.51).

It is thus suggested that Facies Association C formed in a series of dominantly shallow subtidal-intertidal environments. These were connected, at least in part. with southward progradation of a barrier island system into the Stainmore Trough. The stacking of sandstone units reflects fairly rapid subsidence in the depositional basin (Horne and Ferm, 1977).

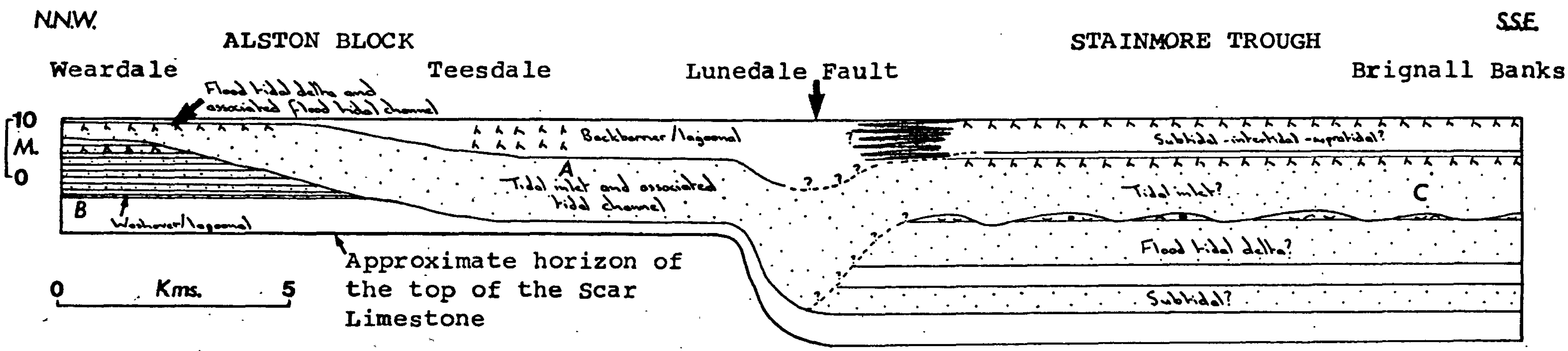
(d) Overall depositional environment

The Low Brig Hazle throughout most of the Alston Block is interpreted to represent the deposits of a former meso-tidal barrier island system (Fig.51). The lack of tidal inlet deposits below the backbarrier deposits of Weardale indicates that the barrier always lay to the S. Conversely the tidal inlet deposits of Teesdale suggest that the barrier once lay across this area. The northern limit of the barrier must therefore have originally been in the vicinity of the present Teesdale-Weardale watershed. Exposures of back-barrier deposits in Teesdale with no underlying tidal inlet sediments suggest a position on the Teesdale side of the watershed. The barrier may have originated in this position, but as with many modern examples is more likely to have migrated into this area during a transgressive event.

From this position the barrier prograded southwards across the Alston Block and probably into the Stainmore Trough. During progradation a backbarrier lagoon was maintained, as overlying lagoonal and backbarrier deposits are preserved. The persistence of a lagoon during progradation probably reflects a small continuous relative rise in sea level, as during stillstands or falls in relative sea level lagoons often become infilled. Progradation in this situation is due to sediment supply to the front of the barrier outpacing relative sea level rise. Occasionally this balance was changed, and periods of *in situ* accretion and landward migration took place.

The abundance of tidal inlet deposits in Teesdale, and the absence of beach, foreshore and shoreface sediments

DIAGRAMMATIC N.N.W-S.S.E. SECTION THROUGH THE CLASTIC INTERVAL OF THE SCAR LIMESTONE CYCLOTHEM SHOWING THE SUGGESTED DEPOSITIONAL ENVIRONMENTS OF THE THREE FACIES ASSOCIATIONS OF THE LOW BRIG HAZLE



⊡ =Sandstone

□ =Shale(with occasional interbedded sandstone)

A=Facies Association A
B=Facies Association B
C=Facies Association C

The horizontal line forming the top of the section represents the base of the Five Yard Limestone

Fig.51

reflects rapid inlet migration relative to shoreline progradation. The preservation of abundant flood tidal bedforms must reflect the dominance of this tide during deposition. Together with the scarcity of herringbone cross-bedding this suggests time velocity asymmetry of the tidal currents (Klein, 1977). However, palaeocurrent reversals between localities indicate that the lack of herringbone cross-bedding is due in part at least to the infilling of discrete ebb or flood-dominated tidal channels (Levell, 1980b).

The Low Brig Hazle is never seen in lateral contact with less mature fluvio-deltaic sandstones, and thus probably formed as a strike fed system downdrift from a major delta, rather than by reworking of an abandoned delta lobe (Hobday and Horne, 1977). The direction of littoral drift (p.151) suggests that this delta probably lay towards the E.S.E. The presence of quartz grains with multiple overgrowths, and chert grains in the Low Brig Hazle suggests that the river supplying this delta was eroding a source area containing at least some sedimentary rocks.

The degree to which wave action affected the barrier system is hard to deduce in the absence of any barrier beach deposits. Nevertheless, the apparent absence of ebb tidal deposits may indicate that wave energy was fairly high.

C. High Brig Hazle

(i) Description

The High Brig Hazle occurs in the Five Yard Limestone cyclothem of Brigantian (Dinantian, D_2) age (George, *et al* 1976). It is thus the next major sandstone above the previously described Low Brig Hazle. In the field it consists of fine to medium grained sandstones which outcrop extensively on the Alston Block, and can be traced southwards into the Stainmore Trough where they are well exposed in the Brignall Banks Inlier. On the Alston Block, the High Brig Hazle has been worked at several localities for the manufacture of refractory bricks, e.g. Billing Hills (NY 94753795), Burnhope Burn (NY 85303925), Harthope Burn (NY 87853745), Lanehead (NY 83654190) and Westgate (NY 90653855). A large quarry at Stripe Head (NY 83953930) worked the High Brig Hazle for construction material for the Burnhope Reservoir Dam.

Within the confines of the Alston Block the High Brig Hazle is divisible into 2 facies associations; a third association occurs in the Stainmore Trough.

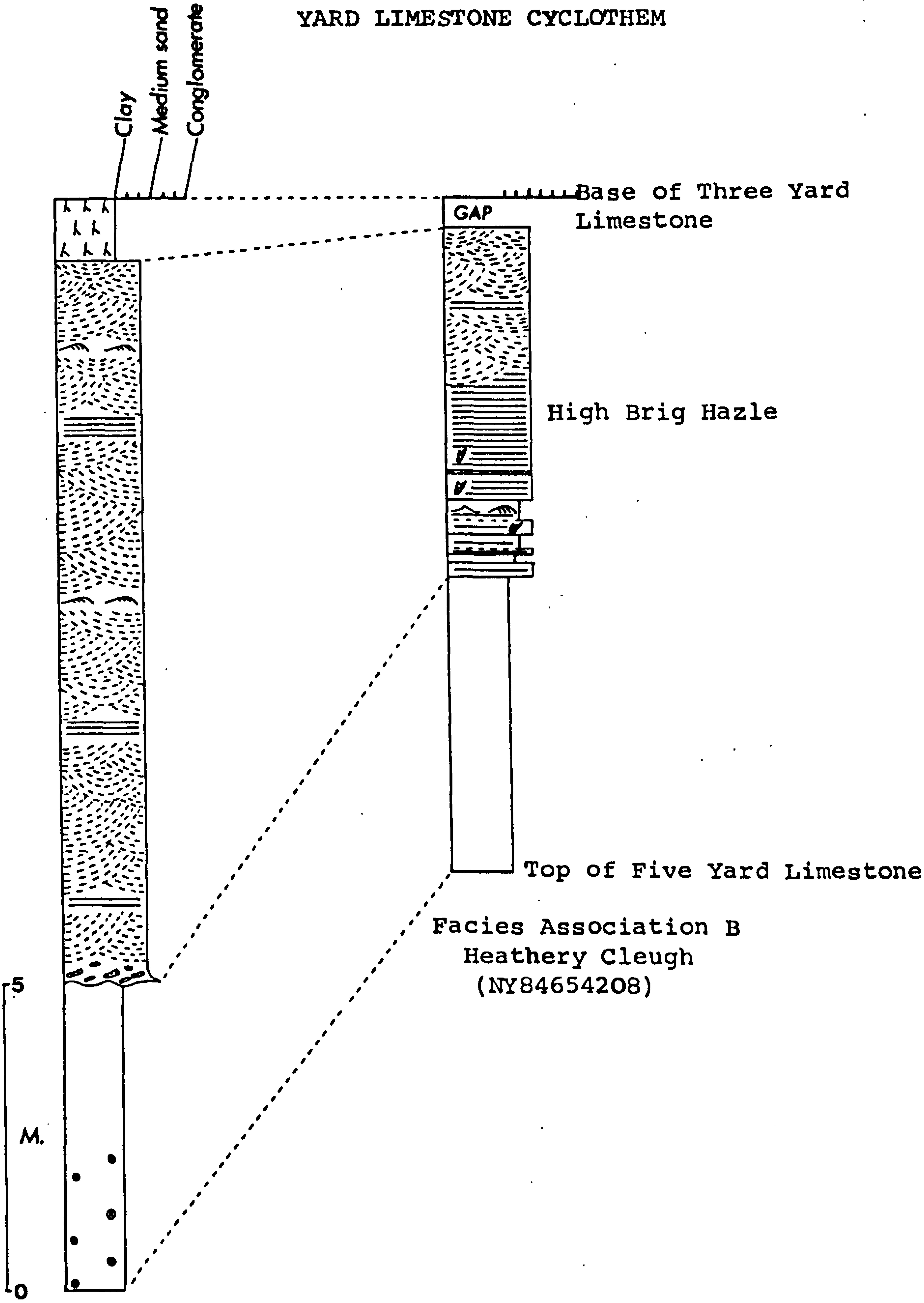
(a) Facies Association A

Volumetrically and economically this is by far the most important. All the workings mentioned above are within this facies association, and it forms the vast majority of exposures on the Alston Block, to which it is confined. At its simplest, Facies Association A consists of erosively based fine to medium grained quartz arenites containing up to 98% quartz, (Fig.47), and occasional interbedded shales. Commonly only one quartzarenitic sand body is present. This often has a highly erosive basal contact, and overlies fossiliferous shales directly above the Five Yard Limestone (Fig.52). In the basal 15-20 cms. it contains abundant intraformational shale clasts in a coarse grained sandstone matrix, but rapidly fines upward, and consists dominantly of well sorted, fine grained quartz arenites up to approximately 18 m. thick (in Weardale, the High Brig Hazle is known as the Six Fathom Hazle due to its massive, thick nature). In thin section detrital quartz grains show subrounded to well rounded outlines.

Trough cross-bedding is the dominant sedimentary structure, with troughs generally several metres wide and several 10's cms. deep. Planar cross-bedding and parallel lamination occasionally occur in interbedded units. Current ripples, and rarely wave ripples are present, and often occur superimposed on cross-beds with their crests orientated down the foreset dip direction. Current ripples are commonly seen in this situation, indicating a 90° change in palaeocurrent direction. Palaeocurrents from cross-beds at any one locality also indicate varying current directions with spreads of 160° common, and occasional herringbone cross-bedding present. Regionally palaeocurrents are highly variable and tend to box the compass (Fig.53).

Sedimentary structures appear to occur asequentially, and although there is sometimes an upward decrease in the scale ofcross-stratification, this tends to occur fairly abruptly near the top. Deformed cross-bedding and convolute lamination commonly occur and indicate both down current and vertical movement of sand. Bioturbation is rare, being restricted to sporadic horizontal burrows at the base of some beds.

MEASURED VERTICAL SECTIONS THROUGH THE CLASTIC INTERVAL OF THE FIVE YARD LIMESTONE CYCLOTHEM

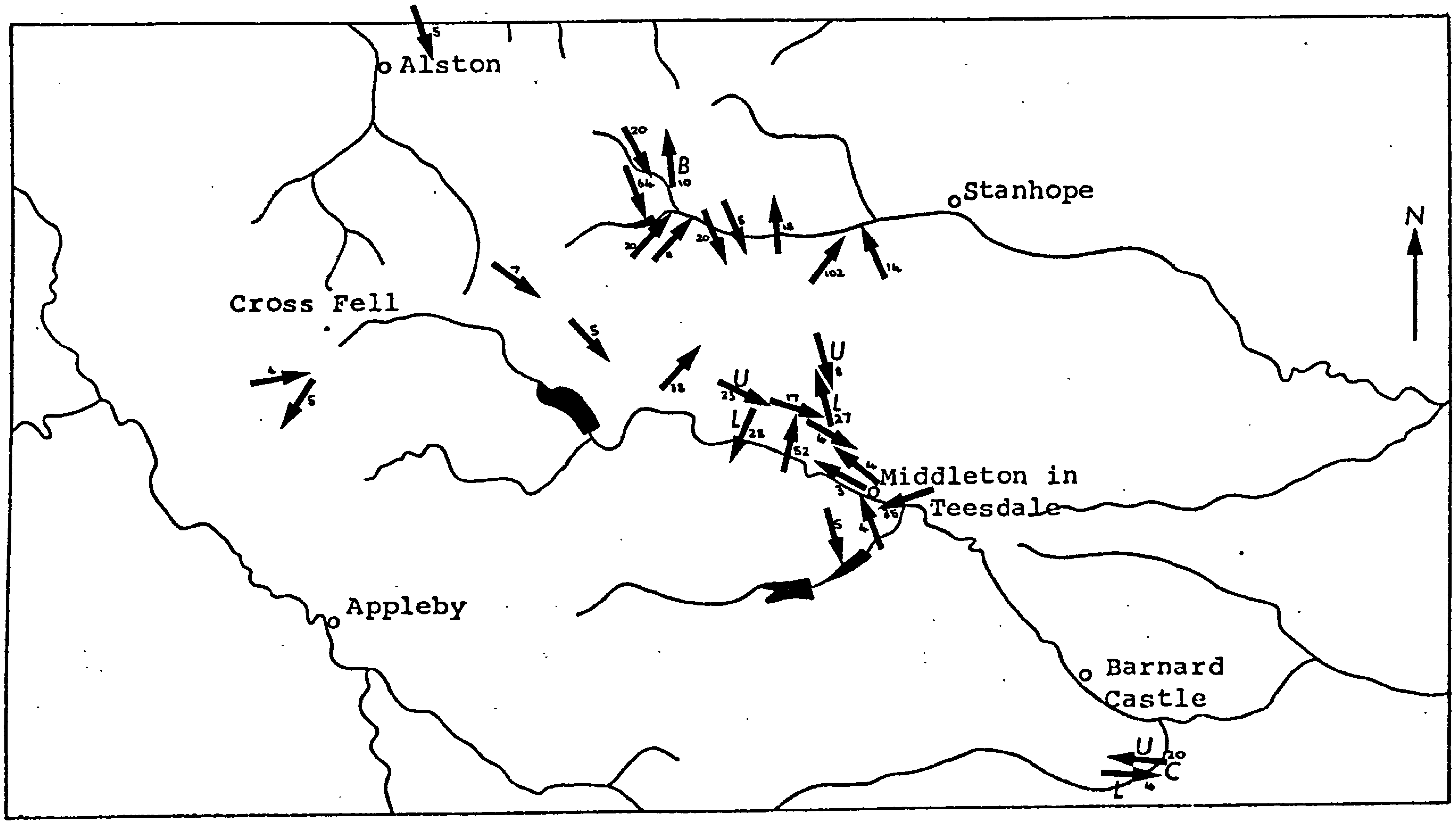


Facies Association A
Westernhope Burn
(NY93423730)

Facies Association B
Heathery Cleugh
(NY84654208)

Fig.52

HIGH BRIG HAZLE PALAEOCURRENTS



= Vector mean at each locality
U/L = Upper or lower leaf where applicable
All localities Facies Association A except where stated
17 = Number of palaeocurrent measurements at each locality

Fig.53

Interbedded thin shales are often lenticular due to erosion beneath overlying sandstones. Commonly they drape underlying bedforms, and may display wave bedding due to the presence of thin rippled sandstone lenses. The top of the sand body is commonly penetrated by rootlets, or overlain by a mudstone containing rootlets which lies beneath the Three Yard Limestone.

In Burnhope Burn, Facies Association A contains a series of dessication cracks approximately 1 m. below its rootlet penetrated top. Individual cracks are generally 1-1.5 cms. wide, but may rarely reach 2.5 cms. These outline a series of polygons up to 26 cms. across (average = 12-15 cms.). Exposure does not allow the cracks to be seen in section, and thus their depth is unknown.

Variations from the above description of Facies Association A occur, the most notable being the splitting of the sand body into 2 leaves. This occurs in Etters Gill (NY 88553040) where two 6 m. thick erosively based quartz arenites are separated by approximately 3.5m. of rootlet penetrated silty shales containing a thin coal. Palaeocurrent vector means from the 2 leaves vary by 93°. The upper leaf contains thin interbedded sandstones and shales at the top, which are penetrated by rootlets and overlain by the Three Yard Limestone.

In Flushiemere Beck, (NY 90952985) Facies Association A again consists of 2 leaves, both penetrated by rootlets at the top and separated by 4 m. of silty shales. The upper leaf is approximately 5 m. thick and has a slightly gradational base with the underlying shales. It tends to contain more clay laminae than the slightly thicker lower leaf, which consists of an erosively based quartz arenite, of the type characteristic of this facies association. Palaeocurrents between the 2 leaves vary by 159°.

Incipient separation into 2 leaves is seen in Ireshope Burn (NY 86253847) where highly bioturbated fine grained sandstones, and interbedded plant rich 'coaly' shales occur between 2 quartz arenites. These quartz arenites are very similar in lithology and sedimentary structures, and consist of erosively based units up to several metres thick. When present as one sandstone body, the High Brig Hazle of Facies Association A occasionally passes up into a series of interbedded thin (up to several 10's cms. thick) fine grained sandstones and shales beneath the Three Yard Limestone. The sandstones tend to be clay rich, micaceous and dominantly current rippled whereas the shales tend to be silty and contain plant debris. Rarely thin clay layers consist of intraformational mud chip conglomerates up to several cms. thick. Fossils are absent and bioturbation consists of obscure horizontal burrows in some of the sandstone units.

Locally a coal is present within Facies Association A. This generally occurs towards the top of the sequence. In the Langdon Beck area of Teesdale (NY 85353120)a coal up to 56 cms.in thickness (including shale partings) was formerly worked from just above the main sandstone body (Smith, 1912).

(b) Facies Association B

Exposures of Facies Association B are confined to a small stream section in Heathery Cleugh, (NY 84654208), although undoubtedly other minor developments occur elsewhere. At this locality the clastic interval of the Five Yard Limestone cyclothem consists of an 11 m. thick coarsening upward sequence (Fig.52). This begins in shales, and passes up through interbedded sandstonesand silty shales into parallel laminated and finally trough cross-bedded sandstones. The lowest sandstones are fine to medium grained and contain abundant clays and micas. Beds are up to several 10's cms. thick, have sharp bases, and display parallel lamination and wave, current, and interference ripples occasionally in flaser bedded units. Bioturbation consists of indeterminate horizontal and vertical burrows.

The overlying parallel laminated sandstones contain some clay, and a moderate amount of mica, but are generally more mature than the sandstones below. They occur interbedded with occasional thin silty shales, and contain sporadic vertical burrows and horizontal traces, including *Cosmorhaphe*.

The topmost sandstones are quartz arenitic in composition (Fig.47) and occur interbedded with very thin silty and sandy shales. Sedimentary structures include trough cross-bedding, parallel lamination, and current ripple cross-lamination. The visible top to the sandstones contains no rootlets. However, there is a small gap in the section before the Three Yard Limestone is exposed, and the possibility of a rootlet bed cannot therefore be excluded.

Palaeocurrents from this locality trend towards the N. (Fig.53), but are rather variable particularly within the trough cross-bedded sandstones where spreads of over 180^{o} occur.

(c) Facies Association C

Facies Association C is confined to the Stainmore Trough where it is well exposed in the Brignall Banks Inlier. In this area the clastic interval of the Five Yard Limestone cyclothem consists of a 30 m. succession of interbedded thick sandstones and shales, with a marine horizon approximately 9 m. from the top. Lateral facies changes occur, and thus no general succession exists.

A good section is exposed in the River Greta from above St. Mary's Church (NZ 07721220) down to Scotchmans Stone (NZ 08071245). At this locality 2 main sandstone units[1] are exposed beneath the Three Yard Limestone (Wells, 1955; Mills and Hull, 1976). The lowest sandstone is approximately 11 m. thick, and separated by a gap in the succession from the underlying Five Yard Limestone. It consists of interbedded fine grained occasionally micaceous sandstones (Fig.47) and shales. Individual sandstone beds are commonly a few 10's cms. thick, and occasionally highly bioturbated due to the presence of abundant horizontal burrows. Sedimentary structures consist of trough cross-bedding in the thicker units, and parallel lamination, current and interference ripples in the thinner flaser bedded members. Towards the top shales become more abundant, and occasional rootlet beds are present. Palaeocurrents from cross-beds trend towards the E. (Fig.53) which is at a high angle to the W.N.W. to N.W. directions obtained from associated trough cross-lamination. Towards the base of the sandstone there is a reversal in palaeocurrent direction and trough cross-beds trend towards the S.W.

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1. A third sandstone unit may occur towards the base of the cyclothem, but is unexposed at this locality (Mills and Hull, 1976).

The top of the lower sandstone consists of a rootlet bed, this is overlain erosively by the upper sandstone which contains a discrete fossiliferous horizon at the base.[2] This consists of a 50 cm. thick erosively based accumulation of shell debris and crinoid ossicles. This is overlain by approximately 9 m. of sandstone displaying abundant trough and planar cross-bedding with palaeocurrents towards the W. (Fig.53). Palaeocurrent variation within this unit is quite high and rare herringbone cross-bedding is present. The topmost sandstone is occasionally current ripple cross-laminated, and contains rootlets. Commonly, however, it has been reworked into a calcareous sandstone containing shell fragments and crinoid ossicles by the transgression which preceded deposition of the overlying limestone.

At NZ 07821244 an apparently 3 m. high set of planar cross-bedding occurs within this upper sandstone which can be traced over 100 m. along outcrop. Foresets dip northwards at angles up to 35°, and display parallel lamination, current, wave, and interference ripples, and occasional horizontal burrows. Palaeocurrents from current ripples trend towards the S.W.

Internally small angular discordances appear to occur between cross-strata. This suggests that several small (up to 1.5m. thick) rather than one large set of cross-strata are present. Petrographically this unit contains more mica and clay than the rest of the upper sandstone which tends to be a fairly mature quartz arenite.

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2. Wells (1955) recorded a 2m. thick shale approximately 1 m. below this horizon, and took this as the dividing line between the 2 sandstone units.

(d) Relationship between facies associations

The contacts between any 2 facies associations are never seen in the field.

1. Facies Associations A and B

These occur in close proximity to each other at Lanehead. The petrography and sedimentary structures of the topmost portion of Facies Association B are very similar to the erosively based quartz arenites of Facies Association A, and it seems probable that these are transitional with each other. The lower part of Facies Association B is very different from Facies Association A and the contact is considered likely to be erosional. It is therefore suggested that the thick erosively based quartz arenites of Facies Association A lie with erosive contact against the lower portions of Facies Association B, but the upper zones of both facies associations are transitional (Fig.54).

On the Alston Block, these 2 facies associations combine to give the High Brig Hazle a sheet-like geometry. Only rarely, as on Meldon Hill (NY 77162908) is it absent being replaced locally by siltstones (Burgess and Holliday, 1979).

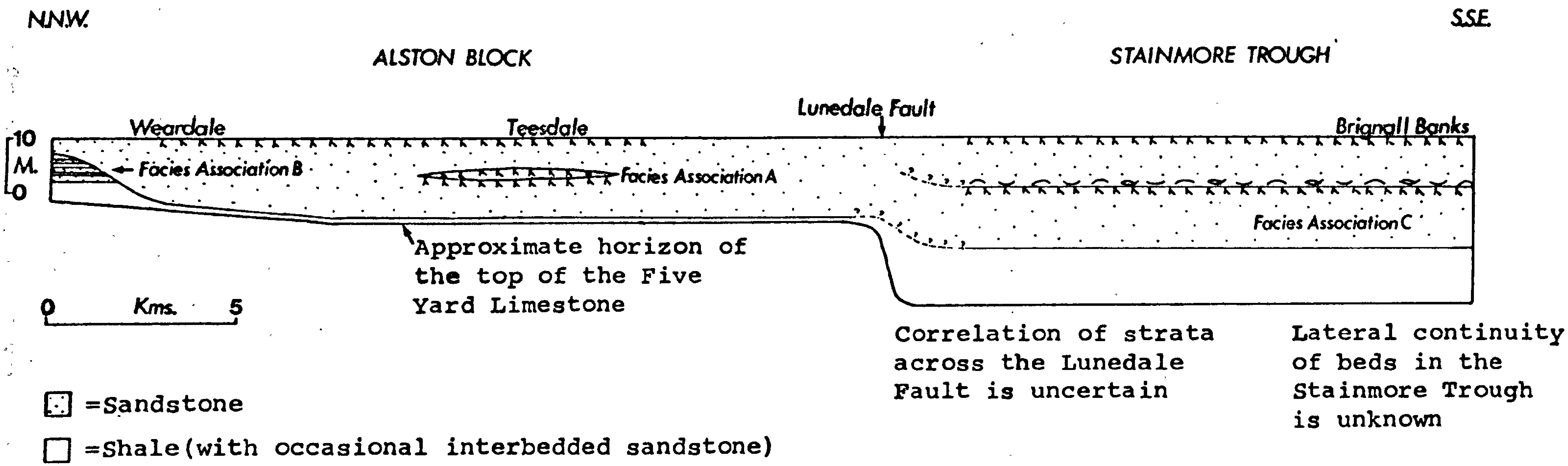
2. Facies Associations A and C

The thicker clastics of Facies Association C are confined to the Stainmore Trough, and presumably pass into Facies Association A across the Lunedale-Butterknowle Fault Line. The actual nature of the contact is unknown (Fig.54).

3. Facies Associations B and C

These are never seen in close proximity to each other in the field, always being separated by Facies Association A. (Fig.54).

DIAGRAMMATIC N.N.W.-S.S.E. SECTION THROUGH THE CLASTIC INTERVAL OF THE FIVE YARD LIMESTONE CYCLOTHEM SHOWING THE FACIES VARIATION OF THE HIGH BRIG HAZLE



The horizontal line forming the top of the section represents the base of the Three Yard Limestone

Fig.54

(ii) Diagenesis

The diagenetic histories of sandstones from all 3 facies associations appear very similar. Compaction has resulted in distortion of mica flakes, and shale clasts. Subsequently cementation has taken place principally by the formation of interlocking quartz overgrowths. Locally a late stage introduction of carbonate rich fluids has resulted in replacement of quartz grains by poikilotopic calcite cement. Thin calcite vein fills have also developed. This is particularly common when carbonate rich horizons occur in close proximity.

Pore filling chlorite, sericite and kaolinite are present, and represent degradation products of unstable grains and redistributed original detrital clays. The process of diagenetic formation of clay minerals is visible in detrital feldspar grains. These commonly exhibit alteration to sericite along cleavage traces.

Siderite is occasionally present, often lining pores later infilled by calcite. Infrequently a late stage influx of iron rich fluids has resulted in replacement of quartz grains by pyrite.

The effects of pedogenesis tends to be minimal and confined to the top few 10's cms. of the sand body. Locally it has resulted in the topmost sandstone containing a higher than usual percentage of clays due to incorporation of finer grained material by rootlets. This gives rise to a heterogeneous texture of quartz rich and clay rich areas. Occasionally the presence of this clay has inhibited quartz overgrowth formation, and cementation has taken place by the precipitation of abundant microquartz.

(iii) Interpretation

(a) Facies Association A

Harbord (1962) concluded that the erosively based quartz arenite which characterises this facies association was fluvial in origin. The mature, well sorted nature of the sandstones, large palaeocurrent dispersion, presence of herringbone cross-bedding, and the relationship between cross-beds and superimposed current ripples argue strongly against a fluviatile mode of formation, and suggest deposition in a tidal environment (Klein, 1970a, b, 1972, 1977; de Raaf and Boersma, 1971). The erosive base, coarse grained basal lag, fining upward trend, occasional upward decrease in the scale of cross-stratification, and the presence of a rootlet penetrated top indicates deposition in a series of laterally migrating tidal inlets along a barrier island coastline (p.127) (Fig.55).

In Etters Gill where this facies association consists of 2 erosively based quartz arenites separated by shales containing rootlets, both quartz arenites exhibit many of the above features. This suggests a stacking of tidal inlet deposits. Palaeocurrent variations between the 2 leaves reflect changes in inlet orientation and ebb or flood tidal dominance. Alternatively one or both of the quartz arenites may represent backbarrier tidal channel fills. Modern tidal inlets are completely transitional with associated tidal channels. Consequently absolute distinction between the two in ancient sedimentary sequences may be difficult. However, the thickness of the quartz arenites, and the lack of lateral accretion surfaces and rotational slump blocks tends to support the idea of a tidal inlet origin.

The stacking of 2 tidal inlet (or even tidal channel) sequences requires explanation. The most obvious solution is that 2 periods of barrier progradation were separated by a marine transgression probably due to subsidence outpacing sediment supply. Evidence of a transgression is lacking, as the shales separating the 2 inlet sequences are unfossiliferous and contain rootlets. Consequently either a marine transgression did not take place or its deposits were eroded prior to deposition of the overlying quartz arenite.

If a marine transgression did not take place, an alternative method of formation is necessary. *In situ* accretion of a barrier complex keeping pace with rising sea level could superimpose inlet sequences. However, it would be rare for the whole of a previous inlet sequence to be preserved, and normally the next inlet migrating alongshore would erode much of its upper portions. Similarly 2 separate periods of short life tidal inlet formation could cause superimposition of inlet sequences, but complete preservation of the deposits of the first period of inlet formation is unlikely. Another possibility is that the lower quartz arenite represents a progradational phase, and the upper quartz arenite a transgressional one. Complete inlet sequences capped by rootlet beds are, however, unlikely to be produced and preserved during a transgression, even if *in situ* drowning of the barrier took place. All 4 theories have their drawbacks, and none explains the facts fully. The first 3 ideas do seem more plausible in terms of the actual sequences preserved. All 4 theories require a relative rise in sea level during formation of Facies Association A.

The presence of a marine horizon towards the base of the upper sandstone in Facies Association C may indicate that a transgression did occur during formation of the High Brig Hazle, but its deposits were not preserved on the Alston Block. However, the actual timing of deposition of this marine horizon relative to events on the block, and its significance and original lateral extent remain highly speculative. It is therefore suggested that a barrier island system prograded southwards during a relative rise in sea level. Progradation was dependant on a positive balance between sediment supply and relative sea level rise. Variations in this balance led to alternate periods of transgression, *in situ* accretion, and progradation. Periods of progradation subsequent to transgressive events, or *in situ* accretion resulted in the preservation of 1 or 2 tidal inlet sandstones depending on the depth of reworking of the last inlet to migrate across the area.

The occurrence of current ripples superimposed on cross-bed foresets with their crests orientated down dip in sandstones of Facies Association A is important. These commonly form during falling water level as water becomes restricted to the troughs between bedforms. Flow then takes place along these troughs often at high angles to the original current direction. Consequently ripples migrate at right angles to the slip face of earlier formed dunes (Klein, 1977). Such features are common in intertidal settings. Furthermore their presence at the base of Facies Association A in such places as Ireshope Burn argue against a true tidal inlet origin for this basal quartz arenite, and it probably therefore represents an intertidal channel deposit. The bioturbated sandstones and plant rich shales above suggest quieter water conditions and are probably of tidal flat origin. The presence of further quartz arenites above these again suggests stacking of sequences.

Superimposition of such tidal channel deposits could give sequences broadly similar to tidal inlet deposits providing intervening fines were removed. However, one might expect wider palaeocurrent dispersion, and more emergent phenomena within such a sand body.

The erosively based quartz arenites of Facies Association A thus represent tidal inlet and associated tidal channel deposits (Fig.55). These formed during a relative sea level rise which led to superimposition of sequences in certain areas.

In Flushiemere Beck the upper quartz arenite of Facies Association A exhibits a slightly transitional base with the underlying shales. This together with the S.S.E. directed palaeocurrents, overall environmental setting, thickening upwards of sandstone beds, and presence of rootlets at the top suggests a shallow water probably ebb tidal delta origin. The occurrence of ebb tidal deposits above the lower quartz arenite of tidal inlet origin suggests 2 separate periods of barrier progradation.

Occasionally an interbedded sequence of fine grained sandstones and shales occurs at the top of Facies Association A. These suggest fluctuating energy conditions, and probably represent backbarrier lagoon, and intertidal deposits. Coals which are particularly common in the Langdon Beck area probably formed in backbarrier swamps.

Facies Association A thus represents a series of prograding barrier island deposits. The abundance of tidal inlet sediments suggests a mesotidal regime, and high rates of inlet migration relative to barrier progradation. The absence of washover deposits reflects both the abundance of tidal inlets, and reworking of washover deposits by tidal channels during progradation. Palaeocurrents from this facies association are highly variable, and reflect a complex progradational history, and its associated changes in barrier island and inlet orientation, overprinted on a complicated tidal sediment distribution pattern (Klein, 1967). This has resulted in a regional distribution which boxes the compass (Fig.53).

(b) Facies Association B

The presence of quartz arenites, occurrence of flaser bedding and wide palaeocurrent dispersion with a vector mean against the regional palaeoslope suggests deposition in a tidal environment (de Raaf and Boersma, 1971; Klein, 1977). The less mature nature of some of the sandstones, smaller size of bedforms, and the larger proportion of shale indicates quieter water conditions than those experienced during deposition of Facies Association A.

The coarsening upward nature of Facies Association B resembles sequences produced by modern river deltas. Similar sequences can, however, be formed by tidal deltas along barrier coastlines. The northerly directed palaeocurrents together with the already interpreted tidal environment suggest deposition in a flood tidal delta (Fig.55). Progradation of the delta into the lagoon would give rise to a coarsening upward sequence beginning with lagoonal muds and thin sands overlain by parallel laminated and cross-bedded sands of the delta itself. Laterally these would pass into closely associated tidal inlet and channel deposits.

(c) Facies Association C

The lower sandstone of this facies association displays palaeocurrent reversals, and an orthogonal relationship between cross-bed palaeocurrents and those from associated current ripples which suggests a tidal origin. Extreme variation in the degree of bioturbation of sandstone beds, together with the presence of interbedded thin shales indicates fluctuating energy levels and rates of deposition (Howard, 1978). Lack of exposure inhibits detailed analysis of this horizon, but the above criteria together with the presence of rootlet beds suggests a shallow subtidal-intertidal-supratidal origin (Fig.55).

The fossiliferous sandstone at the base of the upper sandstone represents a washed in accumulation, possibly a storm lag deposit. Towards the W. shales containing *Lingula* occur at the same level (Mills and Hull, 1976), and this horizon may therefore represent a true transgressive deposit. The upper sandstone contains rootlets at the top and thus displays a marine to non-marine transition. The textural maturity of the sandstones of this unit together with the large palaeocurrent dispersion and rare herringbone cross-bedding indicates a tidal origin. The thickness of the sand body, and the marine to non-marine transition suggests subtidal, intertidal and occasionally supratidal deposition along a prograding shoreline (Fig.55).

The 3 m. thick coset of cross-strata in this sandstone body is obscure in origin. Foresets dip at right angles to the palaeocurrent vector mean and are commonly rippled. This suggests reworking of original avalanche laminae or formation by accretion of smaller bedforms. The high angle dip of some foresets argues against accretion, and suggests an avalanche origin. These higher angle foresets are commonly parallel laminated rather than ripple cross-laminated which tends to support an avalanche origin. Ripple cross-lamination occurs associated with low angle ($<20^{o}$) cross-strata towards the base of the unit, and suggests an accretionary origin. Similar lateral accretion surfaces have been described from both intertidal and fluvial environments where they form due to growth of point bars (Bridges and Leeder, 1976; Collinson, 1978).

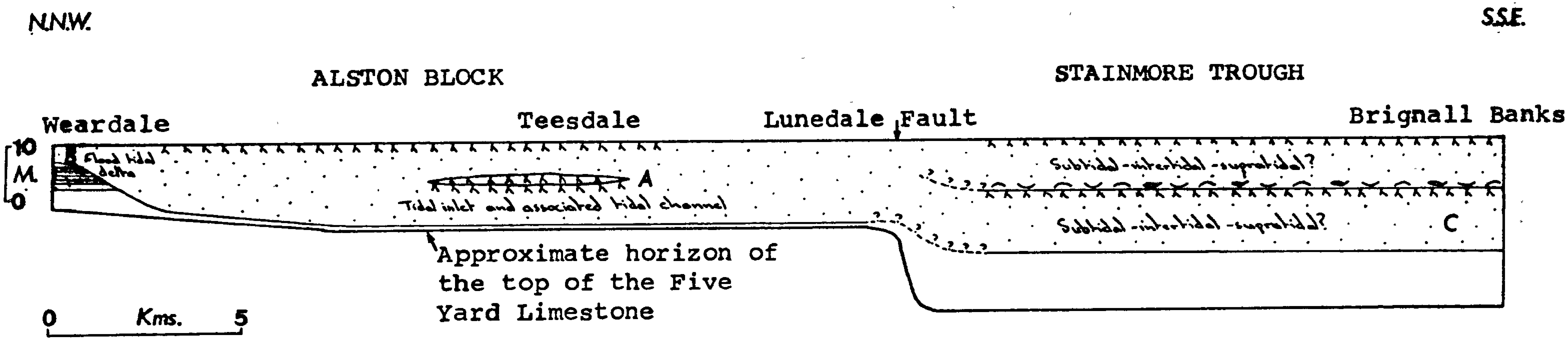
The overall environmental setting, together with the orientation of the foresets relative to the palaeocurrent vector mean therefore suggests that the cross-strata represent the side infilling of a tidal channel/tidal channels, initially by lateral accretion, and subsequently by avalanching.

Facies Association C thus represents a series of dominantly subtidal and intertidal deposits probably associated with southward progradation of a mesotidal barrier island system.

(d) Overall depositional environment

The High Brig Hazle within the Alston Block, and parts of the Stainmore Trough represents the deposits of a former mesotidal barrier island system and associated tidal environments (Fig.55). The presence of flood tidal delta deposits

DIAGRAMMATIC N.N.W.-S.S.E. SECTION THROUGH THE CLASTIC INTERVAL OF THE FIVE YARD LIMESTONE SHOWING THE SUGGESTED DEPOSITIONAL ENVIRONMENTS OF THE THREE FACIES ASSOCIATIONS OF THE HIGH BRIG HAZLE



[∴]=Sandstone

[ ]=Shale(with occasional interbedded sandstone)

A=Facies Association A
B=Facies Association B
C=Facies Association C

The horizontal line forming the top of the section represents the base of the Three Yard Limestone

Fig.55

and intertidal channel sequences in Upper Weardale with no underlying tidal inlet sediments suggests the main barrier island system never lay across this area. However, tidal inlet deposits do occur closely associated with these occurrences. This suggests that the landward margin of the barrier island probably lay in the Upper Weardale region. The barrier island system may have originated in this area, but is more likely to have migrated into part of Upper Weardale during a transgressive event. From this position it began a general southwards progradation across the Alston Block during a relative rise in sea level. Progradation was not a single continuous event, and appears to have been interspersed with periods of *in situ* accretion and landward migration. The orientation of the barrier system and its exact direction of progradation are unknown, and may well have varied with time. The paucity of washover sediments may reflect the abundance of tidal inlets along the barrier system, but is also probably due to reworking by tidal channels in the backbarrier zone.

The absence of any closely associated less mature fluvio-deltaic sandstones suggests formation as a strike fed system downdrift from a delta, rather than reworking of an abandoned delta lobe. The source area of the river supplying this delta appears to have been very similar to that previously described for the Low Brig Hazle.

D. Sandy Carr ganister[1] and associated strata

(i) Description

A series of quarries at Sandy Carr (NZ 08703865) expose a quartz arenite of Marsdenian (Namurian, R_{2c}) age (Ramsbottom *et al*, 1978). This forms the lower unit of the Second Grit which westwards unites with the upper unit to form a single sandstone body in the vicinity of Collier Law (NZ 01624179). Quartz arenites are not commonly exposed in the latter area, and good sections tend to be restricted to the Sandy Carr region, where a 5 m. thick quartz arenite is almost continuously exposed for over 600 m. along outcrop. In the field this quartz arenite is divisible into 2 facies.

(a) Facies A

Facies A forms the basal and middle portion of the sandstone (Fig.56), and appears to have been the main horizon worked for refractory purposes. It consists of a series of low angle (9^{o}-14^{o}) northerly dipping sandstone beds up to 1 m. thick (Figs. 57 and 58). Occasional thicker beds are present, but weathering generally shows these to be composite. Bed contacts are sharp, and internally most beds appear structureless. However, parallel lamination is occasionally present, and rare wave ripples with crests trending 60^{o}-240^{o} occur at the top of beds. Bioturbation is restricted to rare inclined burrows.

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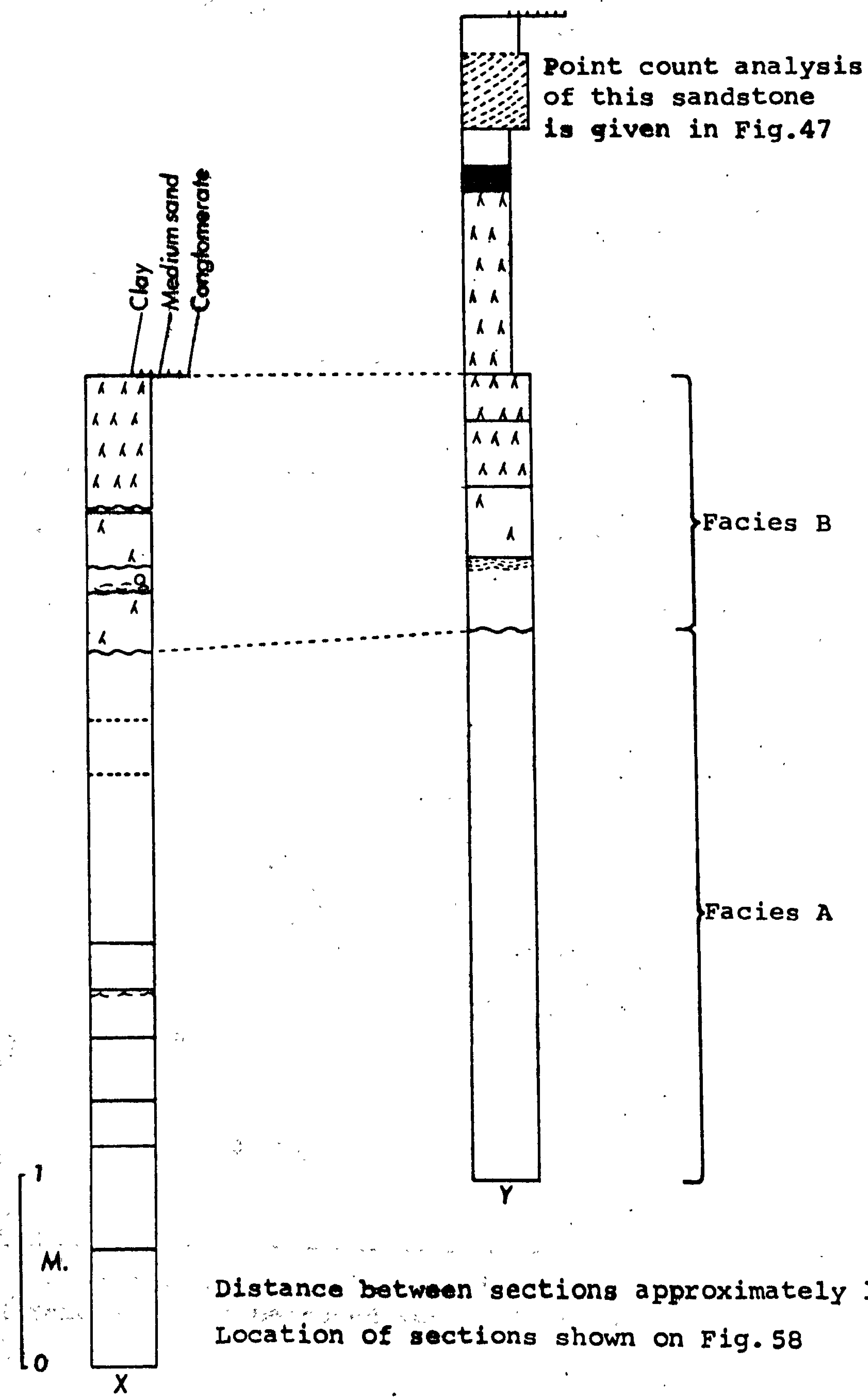
1. This horizon was worked as the raw material for refractory bricks, and thus became termed a ganister. It is not a true ganister as previously defined (p. 5).

MEASURED VERTICAL SECTIONS THROUGH THE SANDY CARR GANISTER AND OVERLYING STRATA

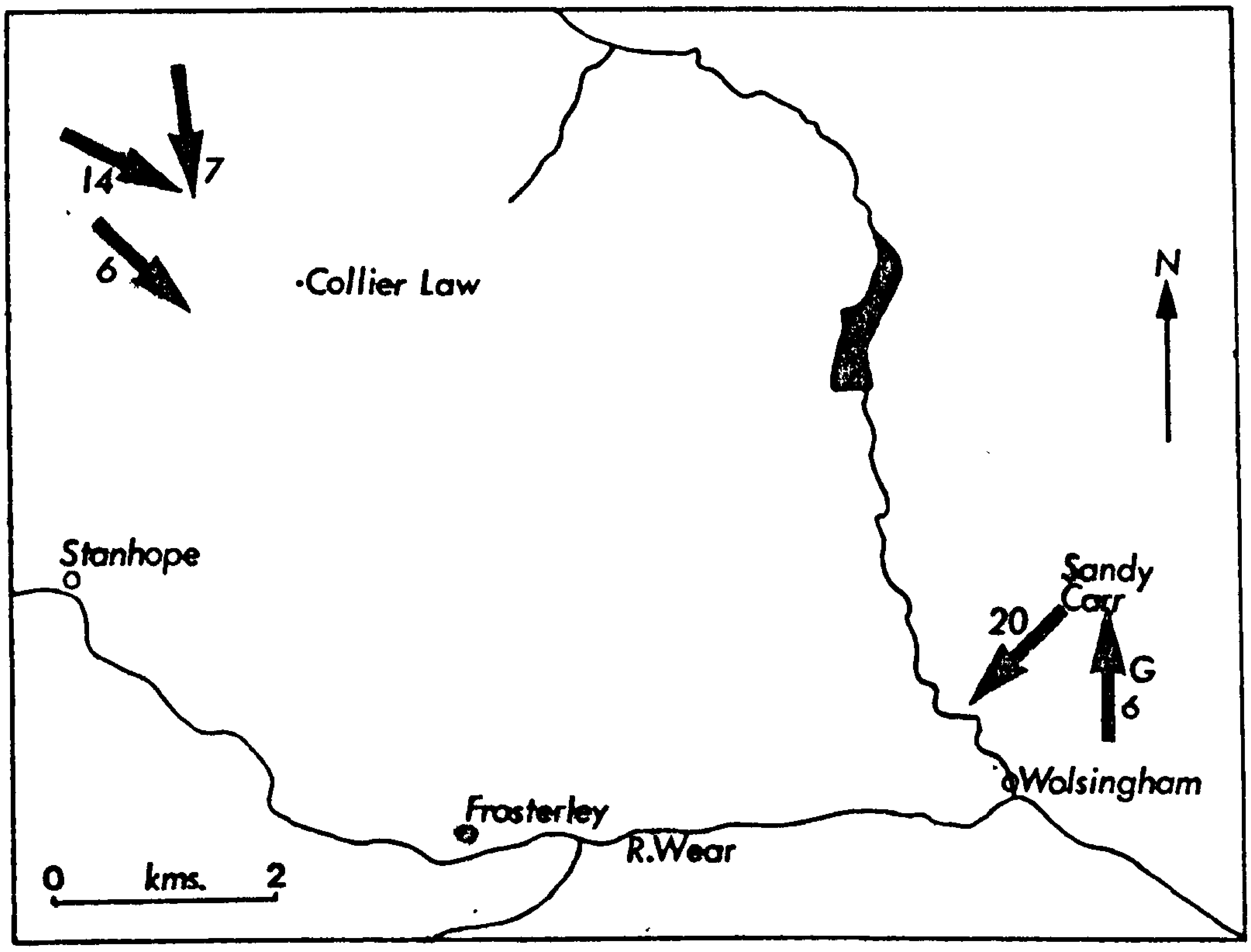


Distance between sections approximately 100m.

Location of sections shown on Fig. 58

Fig.56

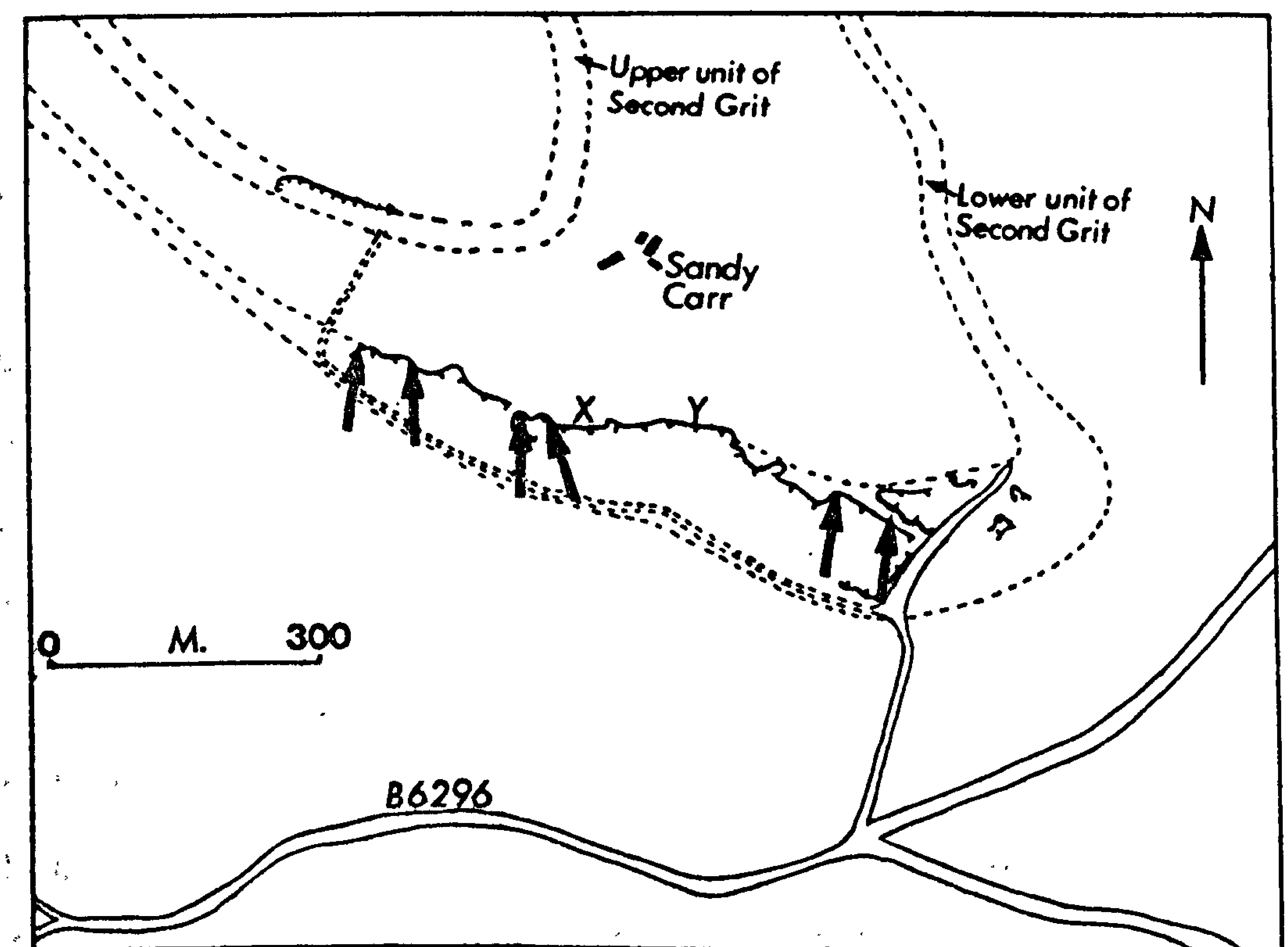
SECOND GRIT PALAEOCURRENTS



6 =Palaeocurrent vector mean and number of palaeocurrent measurements
G=Low angle depositional dips from the Sandy Carr ganister

Fig.57

SECOND GRIT EXPOSURES IN THE VICINITY OF SANDY CARR



=Individual low angle depositional dip directions
X&Y=Location of measured vertical sections in Fig.56

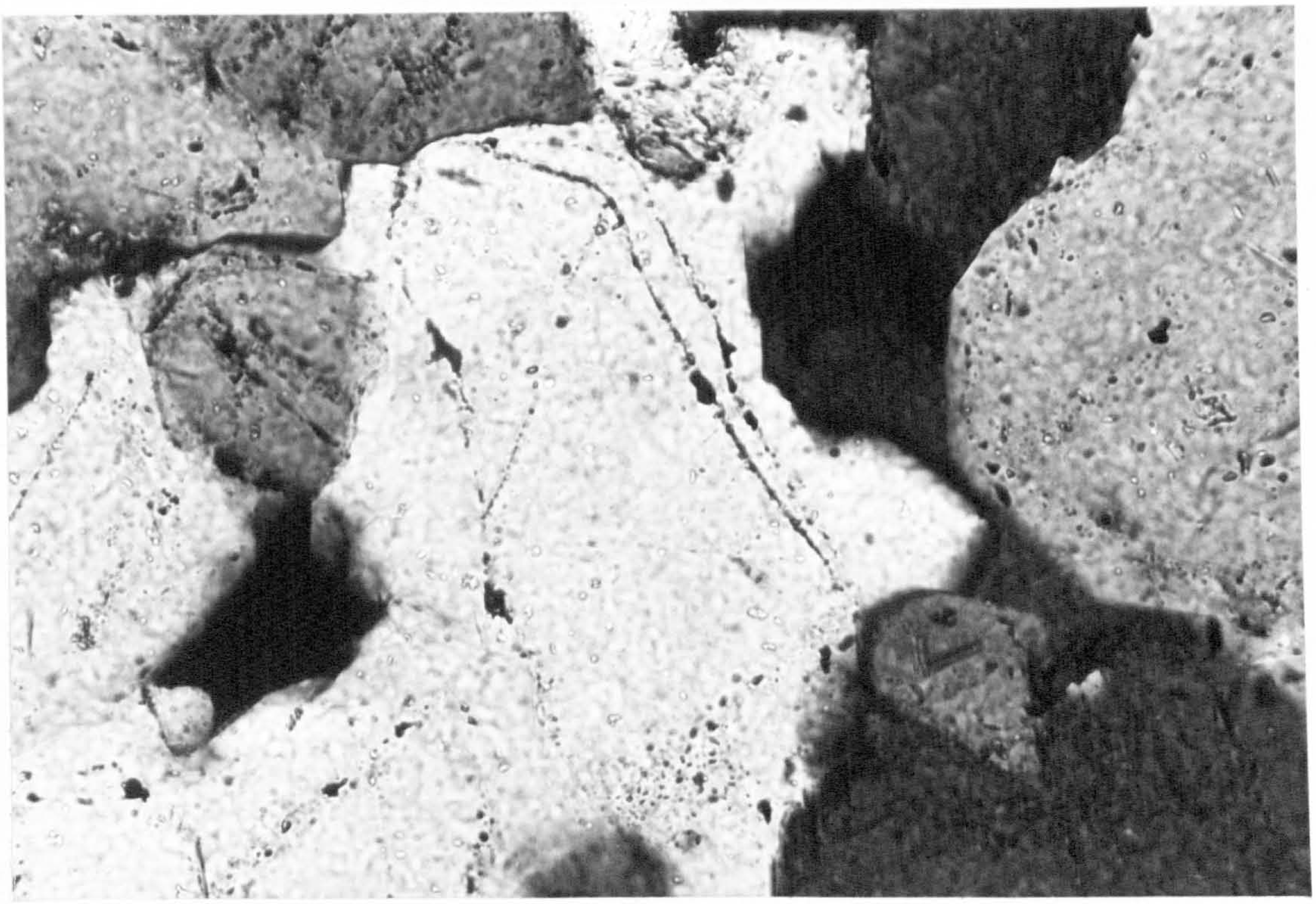
Fig.58

Petrographically the sandstones are moderately well sorted, fine to medium grained quartz arenites. They contain a small percentage of clay minerals and micas, rare feldspar and chert grains, and very fine grained quartz arenite rock fragments (Fig.47). Original detrital grains show subroundedto rounded outlines, and occasionally grains with multiple overgrowths are present (Fig.59).

(b) Facies B

Facies A is overlain by Facies B which forms the upper 50 cms. - 1.5 m. of the sandstone (Fig.56). The contact with Facies A is commonly erosive and contains small channel-like features. These tend to be orientated S.W.-N.E. and contain abundant driftwood fragments at the base. Above occurs a series of erosively or sharply based fine grained sandstones with occasional interbedded thin shale laminae. Rootlets are common, and increase in abundance towards the top. Very occasionally thin washed-in shell accumulations are present. One such horizon occurs towards the base and consists of broken and abraded shell debris, plant fragments and rare small vein quartz pebbles. Preservation of the shell material is poor, but identifiable genera include *Myalina sp. Conocardium sp*., and possibly *Nucula sp*.

Petrographically Facies B is variable, mainly due to differences in the intensity of rootlet penetration which has incorporated fine grained material into the sandstones. It thus ranges from a texturally mature quartz arenite where rootlets are absent to a less mature, muddy fined grained sandstone where they are abundant (Fig.47). The latter occasionally exhibits incipient formation of orientated sericite coats to framework grains.



Quartz grain showing 2 dust rims with subrounded outlines, probably indicating recycling from an older sedimentary source, Sandy Carr ganister, Sandy Carr Quarry, Wolsingham. Length of photomicrograph 0.53mm. Fig.59

Sharply based rootlet free quartz arenite overlying rootlet bed, base of the Second Grit, Millstone Rigg. Hammer 33cms. long.

Fig.60

Overlying Facies B is a shale containing rootlets, and an associated thin coal, followed by a series of interbedded fine grained sandstones and shales (Fig.56). The sandstones contain abundant clay minerals and micas (Fig.47) and palaeocurrents trend towards the E. Southwards in the Barnard Castle district a marine band is present at approximately this horizon (Mills and Hull, 1976).

(ii) Diagenesis

Diagenesis has principally resulted in compaction, and cementation by the formation of interlocking quartz overgrowths. Incorporation of clays into parts of Facies B has inhibited overgrowth formation, and consequently the rock is fairly friable. Pore filling clay minerals, particularly kaolinite occur in both facies.

Locally, there has been a late diagenetic development of iron minerals, particularly at the top of Facies B. These replace both quartz grains and overgrowths. The preferential occurrence of these iron minerals (now principally goethite) at the top of the sandstone suggests that ascending iron rich fluids probably became trapped beneath the overlying impermeable shale. Former rootlet channels are commonly unaffected.

(iii) Interpretation

(a) Facies A

The sharp bases and tops of beds together with the low angle dips suggest periodic rapid deposition of sand down the northern side of a gently sloping topographic feature. The constant nature of these northerly dips for over 600 m.

in an E.-W. direction indicates the crest of this topographic high lay to the S. and had a similar E-W. orientation.

The presence of a thick texturally and compositionally mature sandstone suggests formation by reworking in a high energy environment. However, the absence of large scale cross-stratification argues against similar conditions at the site of deposition. The lack of evidence of emergence together with the presence of rare wave ripples indicates subaqueous deposition. It is therefore suggested that clean quartz arenite sands were produced in a high energy environment to the S., and were subsequently emplaced across the top of a topographic high which protected a shallow water zone on its northern side.

The presence of rootlets in the directly overlying Facies B sandstones suggest that this topographic feature was emergent, and consequently a likely origin for Facies A is by washover deposition along a barrier island coastline. Barrier orientation was E.-W., and during storms sand was eroded from the beachface and rapidly emplaced in the protected backbarrier zone. The lack of any *in situ* fauna, together with the paucity of bioturbation suggest that this backbarrier area was fairly inhospitable to most life forms.

The low angle dips in Facies A reflect the local slope of part of the backbarrier area. The angle of these dips (approx. 10°) together with the thickness of Facies A suggests that such slopes only extended for a few 10's of m. in a N.-S. direction.

(b) Facies B

The scoured bases of many beds, and the presence of marine fossils closely associated with rootlets indicates rapid deposition of marine sand in an emergent area. The presence of channel-like features, large pieces of driftwood and occasional small pebbles suggests fairly high energy confined flows during deposition. These characteristics together with the occurrence above washover sediments suggests deposition of Facies B in a series of backbarrier washover channels which supplied sand to adjacent washover flats (p.125). Following storms these channels became abandoned, plant colonization took place in emergent areas, and thin shales formed in zones of stagnant water.

(c) Overall depositional environment

The quartz arenite exposed at Sandy Carr appears to have formed as a series of backbarrier washover flats and associated washover channels. The presence of overlying non-marine strata suggests formation along a prograding barrier island shoreline. However, the occurrence of washover channel deposits erosively overlying washover flat sediments in the quartz arenite suggests a transgressive situation existed. Both of these features can be explained by washover fan progradation and *in situ* aggradation of the lagoon, which probably took place during a stillstand in sea level. Subsequent to this the shoreline may have prograded southwards.

The lack of any tidal deposits associated with the washover flat sands indicates that tidal range was fairly low during deposition. This together with the abundance of washover deposits which are most common along microtidal barrier island coastlines suggests a microtidal regime during deposition of the Sandy Carr quartz arenites.

(iv) Laterally equivalent strata in the Collier Law area

(a) Description

In the vicinity of Collier Law, the Second Grit consists of a single thick sandstone. This contains fine grained quartz arenites at the base, and one such horizon at least 3.65 m. thick was formerly worked at Weatherhill Quarry (NZ 00404278). This is no longer exposed, but approximately 930 m. to the S. at Millstone Rigg (NZ 00404185) a series of thin quartz arenites are exposed at roughly the same horizon. These are separated by a thin coal and shale from the overlying coarse to very coarse grained sandstones of the true Second Grit.

The topmost quartz arenite forms a bed approximately 1 m. thick, and appears to have been quarried on a small scale. It contains rootlets and abruptly overlies thin (up to several 10's of cms. thick) quartz arenites which are bioturbated and occasionally penetrated by rootlets. These consist of sharply based beds which occasionally overlie rootlet horizons or thin shale laminae (Fig.60). Mineralogically these lower quartz arenites tend to be less mature than the topmost bed which locally reaches 99% quartz (Fig.47). In thin section the latter consists of subrounded to rounded detrital grains, and is moderately well sorted.

The overlying sandstones are poorly cemented due to the abundance of interstitial clays, and as a result they have been extensively worked in the Collier Law area for moulding sand. These display trough and planar cross-bedding in sets up to 1.5m. high, with unidirectional palaeocurrents towards the S.E. (Fig.57). Individual beds are commonly erosively based with a coarse grained basal lag of small vein quartz pebbles, and occasional driftwood fragments. Petrographically the sandstones are immature containing approximately 80% quartz, the remainder being mainly clay minerals with a small amount of feldspar.

(b) Interpretation

The sharp bases to beds, presence of rootlets and the lack of visible physical sedimentary structures within the quartz arenites suggests rapid deposition of sand in an emergent area. The mature nature of the quartz arenites relative to associated strata suggests reworking in a high energy environment. This coupled with the occurrence at a similar horizon to Sandy Carr suggests deposition took place on a series of backbarrier flats. Sand was rapidly introduced during storms by washover, and inundated former zones of plant colonization giving rise to sequences such as that seen in Fig. 60.

The coarse grain size, erosive bases of many beds and the large scale of preserved bedforms in the overlying sandstones suggest high current velocities during deposition. The south easterly unidirectional nature of these currents together with the immature character of the sandstones, and the lack of any marine fossils indicates a fluvial origin (p. 69). These sandstones therefore reflect the type of detritus being supplied to the depositional basin.

The underlying quartz arenites probably formed by reworking of similar less mature sandstones. The increase in quartz content of approximately 15% in the quartz arenites reflects the amount of reworking these sandstones underwent.

(c) Relationship to the Sandy Carr ganister

The occurrence of the Millstone Rigg quartz arenites at the same stratigraphical horizon as the Sandy Carr deposits, and their apparently similar modes of origin suggests that both formed as part of a single barrier island system. It is therefore suggested that the base of the Second Grit formed during a period of low to moderate sand supply. This resulted in the formation of an E.-W. orientated microtidal barrier island system in the Stanhope-Wolsingham district. Sedimentation along this system was dominated by washover deposition which resulted in washover fans prograding into the backbarrier lagoon. Eventually the barrier became abandoned and overlain by the deposits of a high energy fluvial system flowing towards the S.E.

E. Conclusions

Barrier island sandstones seem moderately common within the Carboniferous succession of the Alston Block, and tend to be dominated by tidal inlet and washover deposits. Dinantian barrier islands appear to have formed along mesotidal coastlines whereas Namurian examples suggest a microtidal origin. The deposits of the former are very occasionally more quartz rich, probably due to the increased reworking the sediments underwent by tidal currents. In many instances, however, the quartz content between the sandstones of the two types is similar (Fig.47). This may reflect lower rates of deposition in the microtidal examples, allowing more time for reworking by wave action. The significance of the change in tidal regime which appears to occur across the

Dinantian-Namurian boundary is unknown, but probably reflects a local change in basin morphology.

Throughout the Dinantian and Namurian sediment was supplied to this basin by fluvial systems draining a land-mass to the N./N.E. In zones of high sediment input deltas formed, elsewhere fluvial sediment supply was lower, reworking took place, and occasionally barrier island systems developed. Progradation of these systems over offshore muds or trans-gression over lagoonal deposits occasionally gave rise to coarsening upward sequences. Together with the presence of erosively based tidal inlet sands many of these deposits vaguely resemble fluvial and deltaic Yoredale cyclothem deposits.

A result is that many previous authors have misinterpreted these deposits and arrived at the conclusion that all Yoredale sequences can be explained in terms of a fluvial-dominated delta model; often the Mississippi delta is cited. Although some barrier island deposits may have formed as delta destructive facies, e.g. Elliott (1975), many appear to have formed as strike fed systems. It is now apparent that the Mississippi delta model has been overused in interpretation of clastic Yoredale sequences, particularly in the Dinantian where the model was originally applied (Moore, 1955).

Examples of Carboniferous barrier island deposits are rare within the British Isles, but many have been described within the United States (Ferm, 1974; Horne, Ferm and Swinchatt, 1974; Hobday and Horne, 1977; Horne and Ferm, 1977; Hobday, 1979; Milici, 1979). This probably reflects a lack of detailed attention to such deposits within this country rather than their absence, as broadly similar quartz arenites to those described in this chapter occur in other Carboniferous sequences in Britain, e.g Namurian Basal Grits of S. Wales (Heward, 1976), Cefn-y-Fedw sandstone of N. Wales.

CHAPTER SIX

QUARTZ ARENITES OF SHALLOW-MARINE ORIGIN

A. Shallow siliciclastic seas and their deposits

(i) Introduction

Shallow seas ranging in depth from 10-200 m., are divisible into 2 main types (Heckel, 1972; Johnson, 1978; Walker, 1979):-

1. Marginal or pericontinental seas, such as those which cover the present day continental shelves. These extend between the zone dominated by nearshore processes and the edge of the continental shelf.

2. Epeiric or epicontinental seas, which cover continental regions and form partially enclosed shallow basins with low bottom slopes, e.g. Hudson Bay, North Sea.

At the present time shelf seas are dominant and consequently most work on recent shallow-marine sedimentation has been done in these areas (Walker, 1979). Although modern shelves should provide a basis for reconstructing the processes which were operative in ancient shallow-marine seas, at the present no universally acceptable facies models exist (Johnson, 1978). This has resulted in few detailed sedimentological studies of ancient shallow-marine sandstones. The lack of modern shallow-marine siliciclastic facies models can be attributed to:-

1. Lack of detailed studies of modern continental shelves, partly resulting from inaccessibility. Knowledge of sediment transport paths, storm depositional processes, internal structure of bedforms, sedimentary sequences, etc. is therefore poor.

2. The former idea that most sediment on the shelf is relict, except at the shoreline. Sediments on the present continental shelf were thought to have formed during a Pleistocene low stand of sea level (Emery, 1968). Deposition took place in fluvial, deltaic and occasionally glacial environments; gradually with the Holocene rise in sea level these sediments became abandoned with only slight reworking. As a result the present distribution of sediments bore little relationship to the present processes operating.

Swift , Stanley and Curray (1971), concluded that the idea that all shelf sediment was relict was invalid. Although the sediment had originated in an earlier environment, in most cases it was being modified in response to the present processes operating, especially the hydraulic regime, with which it was gradually approaching a state of equilibrium. The amount of reworking is variable and depends on the available energy, but in high energy areas may be almost complete.

Most modern shelf deposits have therefore been reworked subsequent to the Holocene transgression, but many still show some signs of disequilibrium with the present environment. Thus although they may provide valuable transgressive models, they are not applicable to ancient regressive or equilibrium situations (Johnson, 1978).

3. The extreme variability of physical and biogenic processes operating on the shelf. This results in a wide variety of possible facies and facies sequences. Different processes may also result in similar sequences, causing particular problems in developing models for use in determining the

dominant depositional process in the ancient (Walker, 1979).

Physical processes operating in the shallow-marine environment include (Swift, *et al*, 1971; Walker, 1979):-

1. Intruding ocean currents, e.g. Agulhas Current of the Indian Ocean (Flemming, 1980)
2. Tidal currents
3. Meteorological currents (wind, wave and storm currents)
4. Density currents due to variations in temperature, salinity or concentration of suspended sediment (Johnson, 1978). Studies of recent sediments suggests that storm and tidal currents are the most important (Swift, 1970; Swift *et al*, 1971), resulting in the concept of storm-dominated and tide-dominated shelves (Johnson, 1978; Walker, 1979). Although this division is easily recognizable in recent deposits, applying it to the ancient is difficult unless diagnostic crieria are present.

(ii) <u>Tide-dominated shelf sedimentation</u>

(a) <u>Recent tide-dominated sand bodies</u>

Studies of present day sedimentation in tide-dominated shallow-marine seas include those of Houbolt (1968), Kenyon and Stride (1970), McCave (1971), and Caston (1972) in the North Sea, and Belderson and Stride (1966) in the Celtic Sea. Both these regions experience a large tidal range (> 3-4 m.) and high current velocities, and as a result most sediment has been reworked, and is in virtual equilibrium with the present operative processes. They are fairly representative of other tide-dominated shallow-marine seas and typically show the development of 5 major types of sand accumulation:-

1. Sand ridges

Tidal sand ridges are large scale, linear bedforms aligned parallel with the direction of strongest tidal currents (Houbolt, 1968; Caston, 1972, 1979; Johnson, 1978). Commonly they occur associated together in sand ridge fields e.g. Norfolk ridges, which are analogous to the shoal-retreat massifs of storm-dominated shelves (Swift, 1975). Individual ridges as exemplified by those of the southern North Sea are commonly 10-40 m. high, 1-2 kms. wide, up to 65 kms. long with their crests spaced at intervals of 4-12 kms. (Houbolt, 1968; Caston, 1972; Johnson, 1978). They are commonly asymmetric in profile and have dunes superimposed on their surface which face towards the ridge crest. Migration of the ridges is generally in the direction of the steepest face, and results in the development of large, low angle internal bedding planes, often with thin clay drapes (Houbolt, 1968).

Generally ridge deposits consist of cross-bedded, well sorted, medium grained sands which tend to coarsen upwards. These overlie a coarse basal lag conglomerate formed by erosion of the intervening trough floor.

2. Sand ribbons

These consist of longitudinal zones of sand accumulation developed parallel with the main sediment transport direction (Belderson and Stride, 1966; Kenyon, 1970a). They range in morphology from ribbons of shelly sand up to 15 kms. long, 200 m. wide and 1 m. thick to trains of transverse bedforms with similar overall dimensions (Kenyon, 1970a). Individual bedforms are up to 1 m. in height and 150 m. in wavelength. Occasionally the top surface of the sand ribbons contains current ripples. Generally sand ribbons form in areas of low sand content, and are interspersed with areas of underlying immobile gravel. Occasionally these gravel areas are partially covered by a thin surficial layer of shell debris (Kenyon, 1970a).

3. Sand sheets

These consist of extensive deposits of smooth surfaced, but probably rippled, well sorted, fine sand, which may grade vertically and laterally into unbedded, poorly sorted muddy sand. The latter is up to 10 m. thick, and rests upon an irregular surface of older material (Belderson and Stride, 1966).

4. Sand patches

These consist of patches of fine to medium grained, commonly ripple cross-laminated sand which often overlies gravel (Belderson and Stride, 1966; Kenyon and Stride, 1970). In the Celtic Sea sand patches are either elongate forms only a few cms. thick, orientated parallel to the dominant transport direction, or sinuous to crescentic forms generally up to 2 m. thick, which are commonly symmetrical in profile and orientated transverse to the dominant transport direction (Belderson and Stride, 1966; Kenyon, 1970b, Kenyon and Stride, 1970). In certain areas transverse forms may have been confused with true sand waves (Caston, 1979).

5. Sand waves

Sand waves are large, transverse bedforms, 1.5-15 m. high with wavelengths of 30-500 m., occasionally forms >5 m. high, have superimposed megaripples (McCave, 1971). Generally sand waves are straight crested, and asymmetric in profile. Migration is in the direction of the steepest face, and commonly results in the development of low angle (<10^{o}) foresets (Johnson, 1978). Occasionally well developed avalanche faces may be present, giving rise to large scale foresets, with intervening thin mud drapes and bioturbated zones (Allen, 1980).

Symmetrical forms develop in areas of zero net sand transport during a tidal cycle. Internally these are thought to consist of small, intricately related herringbone or climbing cross-bedding sets (Allen, 1980). Although sand waves are most common in tide-dominated regions, they may also form in other shallow-marine settings due to intruding ocean currents (Flemming, 1980).

Sediment dispersal patterns in present day tide-dominated shallow-marine seas are generally parallel to the coastline (Johnson, 1978). Preserved palaeocurrents may be unimodal or bimodal depending on the time-velocity asymmetry of the tidal cycle (Klein, 1967).

(b) Ancient tide-dominated sandstones

According to Johnson (1978) ancient tide-dominated shallow-marine sandstones can be classified into 3 main groups:-

1. Blanket sandstones

These are laterally extensive (several hundred kms.) often thick (up to several kms.), texturally and mineralogically mature sandstones. Cross-bedding is generally abundant and often indicates 180° reversals in current direction (herringbone cross-bedding)(Swett *et al*, 1971; Anderton, 1976; Johnson, 1978; Levell, 1980b). Interbedded tidal flat sediments are occasionally present (Swett and Smit, 1972).

2. Sand wave deposits

These commonly form during transgressive events and consist of cross-bedded sandstones with foreset heights up to 20 m. Reactivation surfaces, clay drapes to foresets, and low angle surfaces are abundant (Nio, 1976). Sand wave deposits may occur as separate sandstone bodies, or as part of blanket sandstone accumulations (Narayan, 1971; Johnson, 1978; Levell, 1980b).

3. Linear sand bar deposits

These form isolate, elongate sand bodies which coarsen upwards and are similar in scale to modern linear sand ridges. Cross-bedding is abundant and palaeocurrents are commonly at right angles to the dip of large-scale inclined surfaces produced on the bar flanks (Hobday and Reading, 1972; Johnson, 1977, 1978).

(iii) Storm-dominated shelf sedimentation

(a) Recent storm-dominated sand bodies

Present day shelf seas affected mainly by meteorological currents, e.g. wave, storm, include the Middle Atlantic Bight of the eastern seaboard of the U.S.A. This typically shows the development of 2 major morphological features due to sand accumulation:

1. Shoal-retreat massifs:

These consist of broad (up to 21 kms. wide), shelf transverse sand bodies up to 72 kms. long, and 10-30 m. thick, which mark the retreat paths of coastal depocentres associated with littoral drift convergences (Swift, 1975; Walker, 1979). Preserved sedimentary structures are produced by superimposed smaller features such as linear sand ridges.

2. Linear sand ridges

These are developed both on and between shoal-retreat massifs and consist of elongate sand accumulations 3-12 m. high, 1-3 kms. wide, and up to several 10's of kms. long (Johnson, 1978; Walker, 1979; Field, 1980; Swift and Field, 1981). These transect the shelf diagonally, with average spacings between ridge crests of 3 kms. The ridges are generally asymmetric in profile, the direction of asymmetry often varies according to their position on the shelf (Swift and Field, 1981). Dips of the ridge flanks are up to a few degrees at maximum. Internally sand ridges display large low angle surfaces, and commonly show a coarsening upward sequence overlying a coarse basal lag (Stubblefield *et al*, 1975; Stubblefield and Swift, 1976). Thus apart from their smaller amplitude, they are very similar to the previously described tidal sand ridges (p.197). However, dunes and sand waves are rare on storm-dominated ridges, and suspension deposition is often equally if not more important. As a result internally they should show less cross-bedding, and a wider range of sedimentary structures than their tidal counterparts (Johnson, 1978).

Besides these major types of sand accumulation, deposition in storm-dominated shallow-marine seas also takes the form of thin (approximately 5-30 cm. thick) laterally extensive, sharply based sands. During storms sand is eroded from the coastal zone, and emplaced by turbidity currents associated with storm-surge return flow (Hayes, 1967a,b). These deposits extend seaward for at least 15 kms. and form important pathways by which sand is transported out onto the shelf (Walker, 1979). Internally these beds may be graded, or show evidence of decreasing current velocities with time.

(b) Ancient storm-dominated sandstones

Examples of ancient storm-dominated sandstones fall into 4 main groups:-

1. Sublittoral sheet sandstones

These consist of thin (<70 cms. thick), laterally persistent sandstones interbedded with shales. Individual sandstone beds often have solemarked bases and show evidence of rapid deposition from currents of waning flow strength (Goldring and Bridges, 1973; Brenchley, Newall and Stanistreet, 1979; Bhattacharyya, Soumen and Chanda, 1980). Internally beds display parallel lamination hummocky cross-stratification (Harms *et al*, 1975) and ripple cross-lamination and are thought to form by deposition from density currents of storm-surge ebb origin.

2. Sand bar deposits

Of the documented cases of ancient sand bar sequences, most appear to have been affected by both tides and storms e.g. Brenner and Davies (1974); Spearing, (1975, 1976). As a result purely storm-dominated examples are rare.

Those described by de Raaf, Boersma and Van Gelder (1977) are essentially wave-dominated and consist of sandstones up to 10 m. thick which grade laterally and vertically into shale. Wave ripples are common, particularly in the peripheral heterolithic units, and sections through the centre of the bar commonly coarsen upwards, and are occasionally overlain by a minor fining upward sequence. Sedimentary structures vary vertically and laterally, and reflect variations in water depth both across the bar, and due to bar aggradation with time.

3. Thick sandstone accumulations

These consist of sandstone sequences from a few 10's to a few 100's m. thick which represent stacked sandstone units, or accumulations of smaller morphological features in actively aggrading sand areas. Parallel lamination, hummocky cross-stratification, ripple cross-lamination and cross-bedding are common, and often there is a simple orthogonal relationship between wave ripple crestal trends and palaeocurrents (Bourgeois, 1980; Levell, 1980a). Occasional thin granule lags occur at the tops of beds and represent periods of winnowing and sand removal (Levell, 1980a).

4. Coquinoid sandstone lags

These comprise winnowed accumulations of shells, shell debris and coarse siliciclastic materials (Brenner and Davies, 1973).

(iv) Criteria for recognizing ancient shallow-marine sandstones

(a) General criteria

According to Johnson (1978), the recognition of ancient shallow-marine sandstones depends on the presence of one or more of the following features:-

1. Open marine fauna
2. Marine trace fossil assemblage
3. Interfingering of sandstones with fully marine deposits
4. Glauconite, chamosite or phosphatic accessory mineralogy
5. High textural and mineralogical maturity of sandstones
6. Laterally extensive, low relief erosion surfaces, and a lack of deep channeling.

Trace elements which are salinity dependent e.g. boron also provide a means of differentiating between marine and non-marine sediments.

(b) Tide-dominated

Tide-dominated deposits commonly contain abundant cross-bedding which may show reversals in current direction (herringbone cross-bedding). Palaeocurrent patterns are variable and include unimodal, bimodal-bipolar, bimodal-90^{o} and multimodal types. Other features common in tidal environments include mud drapes and reactivation surfaces. In some cases an association with tidal flat deposits may prove diagnostic.

(c) Storm-dominated

Storm-dominated deposits commonly show evidence of rapidly emplaced sandstone beds separated by quieter water sediments. Other diagnostic features include abundant wave ripples, parallel lamination, and hummocky cross-stratification. The latter is thought to form mainly in between storm and fairweather wave base by the action of large scale storm waves (Harms, *et al*, 1975; Hamblin, Duke and Walker, 1979; Hamblin and Walker, 1979; Bourgeois, 1980).

B. Harthope Ganister[1]

(i) Description

This was the last horizon to be worked for refractory purposes on the Alston Block, being extensively quarried in a limited region along the Teesdale-Weardale watershed above St. Johns Chapel (Fig.61). The Harthope Ganister is restricted to this area and consists of up to 8.8 m. of bedded quartz arenite. As a result of the negligible tectonic dip it outcrops along the 2000' (610 m.) contour, and due to its hard resistant nature forms a slight topographic feature. The original mapping of the Geological Survey must have relied heavily on this feature as natural outcrops are rare because of extensive peat cover. Towards the N.W. this feature dies away and as a result the Harthope Ganister is thought to thin, and eventually may be completely replaced by shales. A similar relationship appears to hold as the Harthope Ganister is traced south-eastwards.

Lying directly above the Harthope Ganister are a series of fossiliferous shales and thin lenticular limestones which Dunham (1948) correlated with the Coalcleugh Marine Band. Stratigraphically this means the Harthope Ganister forms the top of the Lower Felltop Limestone cyclothem of Namurian, E_2 (Arnsbergian) age (Hull, 1968), and correlates with the Coalcleugh Transgression Beds[2] (Carruthers, 1937; Dunham, 1948).

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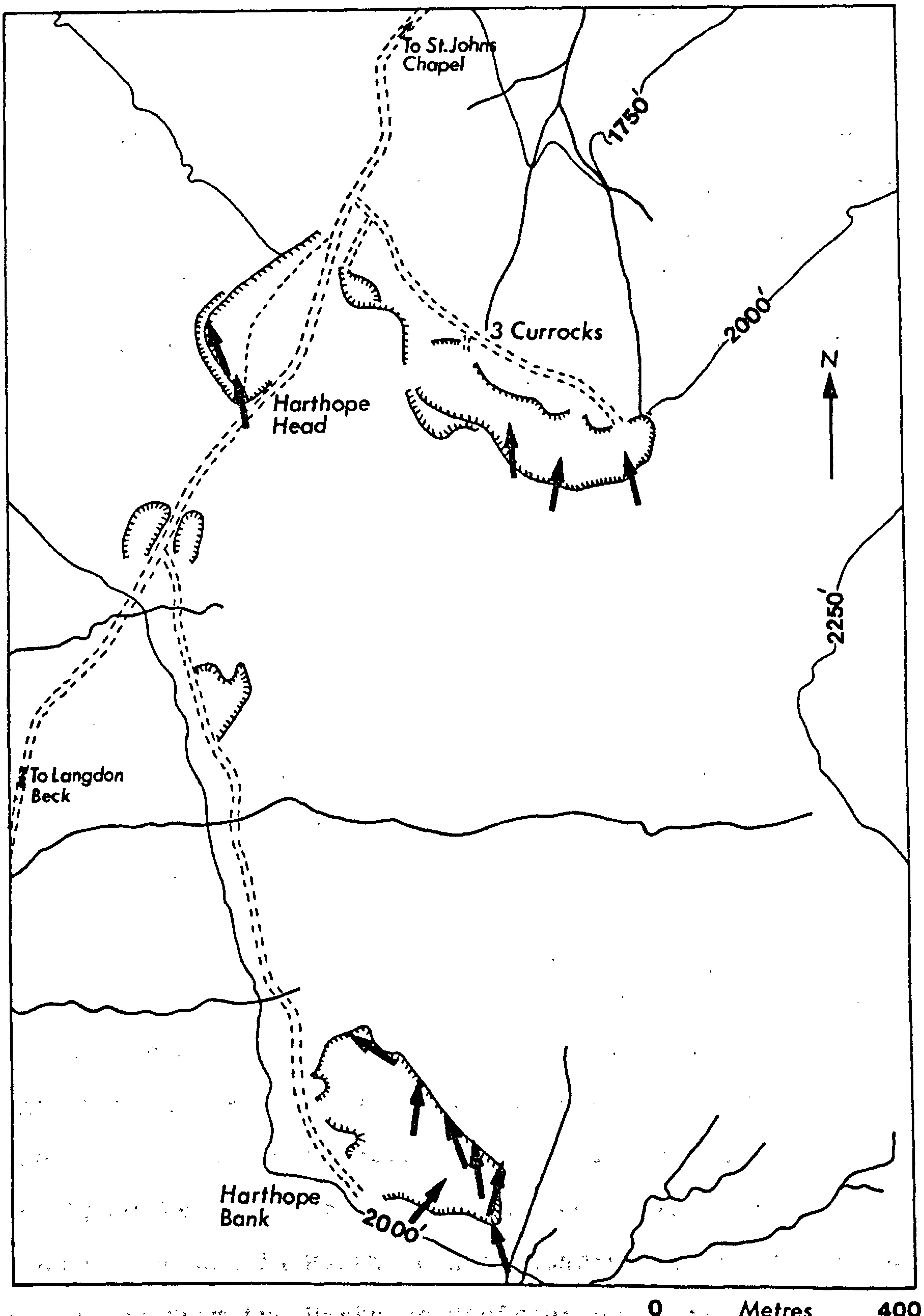
1. The term Harthope Ganister arose from the rock being quarried for refractory purposes. It was introduced into the literature by Dunham (1948), who used it in a stratigraphical sense for the local equivalent of the Coalcleugh Transgression Beds. Due to widespread usage the term Harthope Ganister is retained even though the rock is not a true ganister.

2. The term Transgression Beds refers to horizons which have a widespread highly erosive basal contact. It does not refer to deposits formed during a marine transgression.

LOCATION MAP OF THE MAJOR HARTHOPE GANISTER QUARRIES



=Dip direction of low angle(< 10°)bedding planes within the Harthope Ganister.Each arrow represents a single measurement.

Contours in feet.

Fig.61

Although the marine band above the Harthope Ganister contains no diagnostic fauna, the occurrence of the Upper Felltop Limestone approximately 13 m. above supports this correlation.

The Coalcleugh Transgression Beds are divisible into 2 main facies (Dunham, 1948; Pattinson, 1964), the first of which outcrops in East and West Allendale and the headwaters of the River Wear, and consists of interbedded sandstones and shales. Eastwards these are replaced by a highly erosively based coarse-very coarse grained sandstone (High Grit Sill), which fines upwards and is thought to be fluvial in origin (Pattinson, 1964).

Both facies are commonly overlain by a thin coal (Coalcleugh Coal), and its associated seatearth. Typical exposures of these 2 facies, and the overlying strata can be seen in the valley of Rookhope Burn (Fig.62). Southwards the Coalcleugh Coal and associated seatearth appear to die away. At Harthope Head (NY 86253502) both are completely absent, their place being taken by the uppermost beds of the Harthope Ganister.

The sequence above the Harthope Ganister in the region of Harthope Head shows little variation and consists of an approximately 10 m. thick coarsening upward sequence into the Hipple Sill, which contains a rootlet horizon at the top. This is overlain by a shale and sandstone beneath the Upper Felltop Limestone. The best exposure of this sequence occurs in Harthope Head Quarry (NY 86203515) where a section from the Harthope Ganister up to the base of the Upper Felltop Limestone is visible (Fig.63).

COMPARATIVE SECTIONS THROUGH THE COALCLEUGH COAL AND ASSOCIATED STRATA IN THE VALLEY OF ROOKHOPE BURN

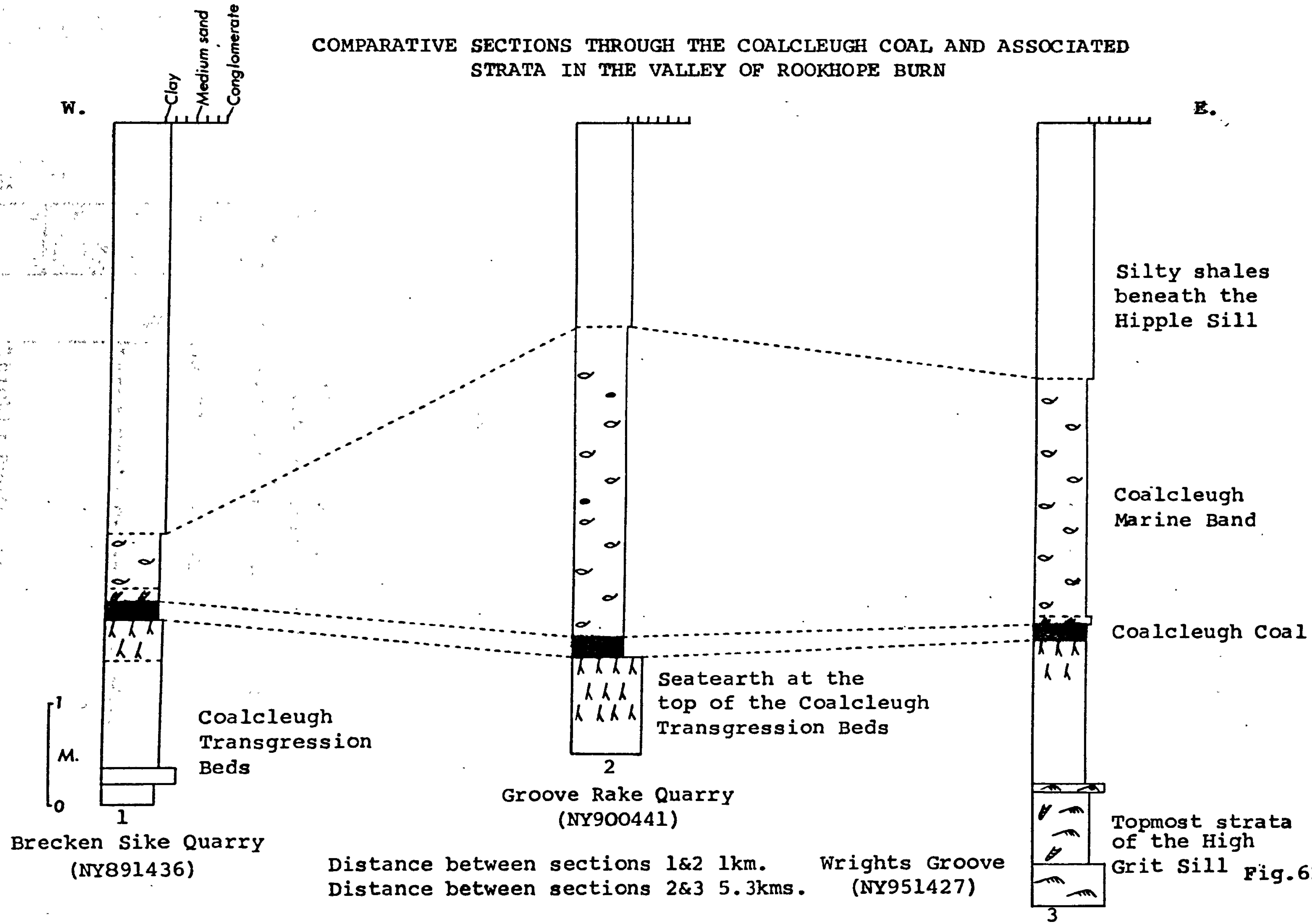


Fig.62

MEASURED VERTICAL SECTION IN HARTHOPE HEAD QUARRY

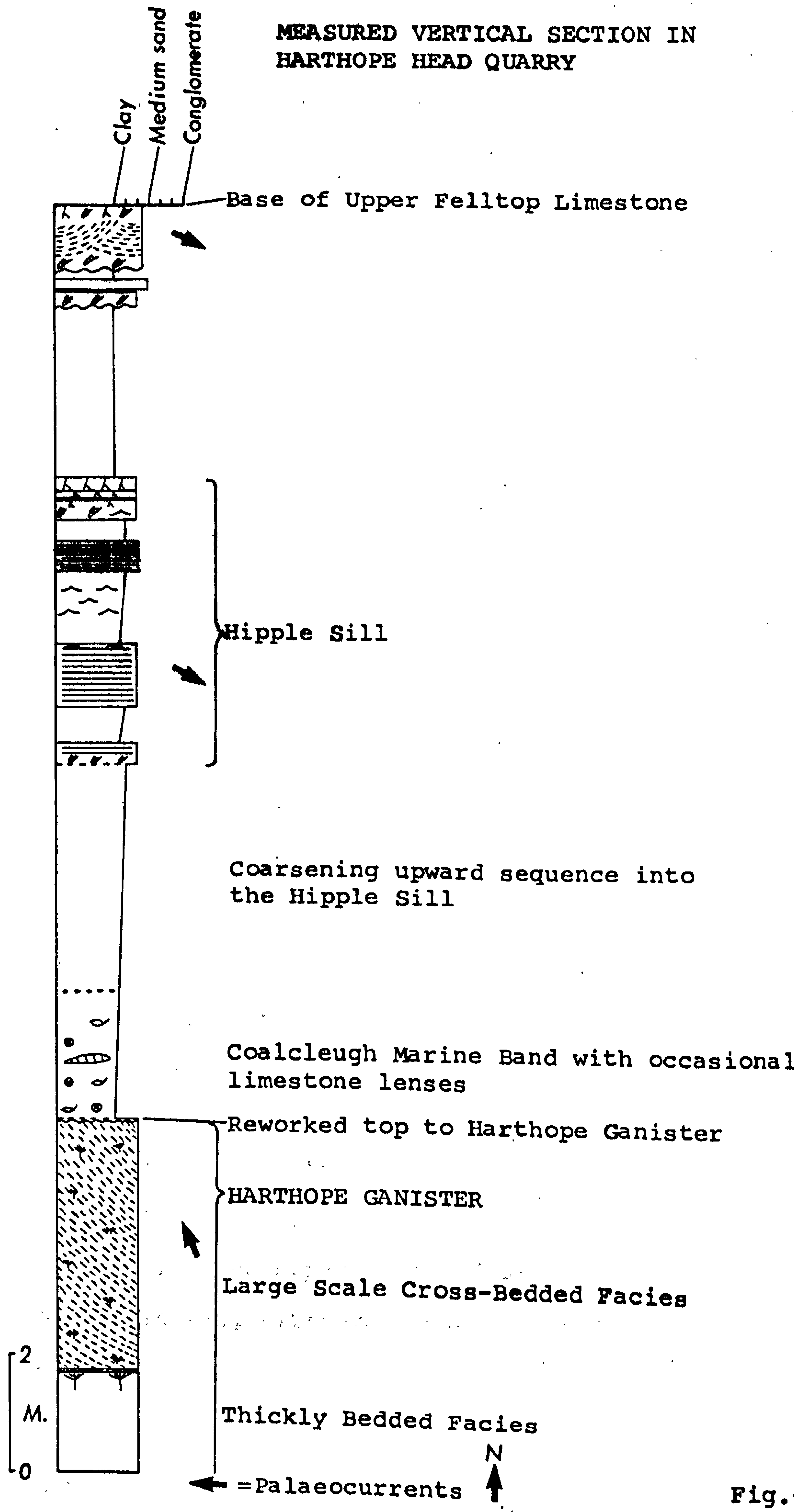


Fig.63

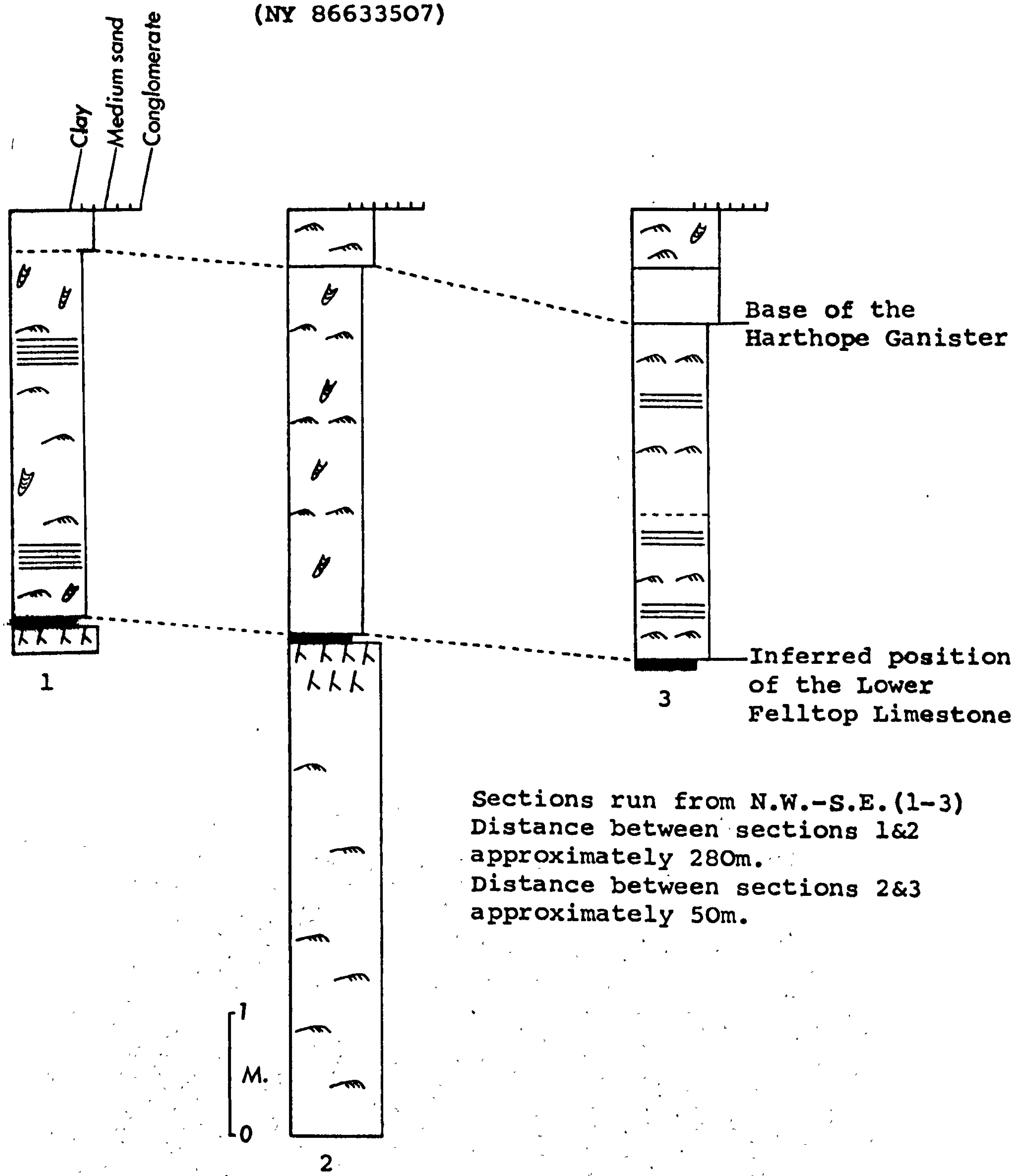
The Harthope Ganister consists of a fine grained quartz arenite containing very well to moderately well sorted, subrounded detrital quartz grains. In thin section the quartz arenite contains up to 99.5% quartz. Thin shale laminae are occasionally present, and these tend to increase towards the base of the sandstone body, resulting in a transitional contact with the underlying sandy shales. The latter are approximately 3 m. thick and lie on a thin coal and its associated seatearth which is thought to mark the approximate position of the Lower Felltop Limestone (Fig.64).

The Harthope Ganister thus forms the top of a 9-12 m. thick coarsening upward sequence. Slight variations in the thickness of the Harthope Ganister are due to an irregular top which occasionally displays a ridge and swale type topography. Variations in elevation are generally <1 m. with wavelengths of approximately 100 m. In the field the Harthope Ganister is divisible into 3 facies:-

(a) Thinly Bedded Facies

This is the most widespread of the 3 facies, extending over the entire known area of the sandstone body. It consists of laterally extensive beds of quartz arenite from a few cms. to a few 10's of cms. thick, interbedded with thin shale laminae (up to a few cms. thick) (Fig.65). Beds often display sharp bases with toolmarks, and internally parallel lamination associated with streaming lineation is common. Generally, the upper parts of beds are current ripple cross-laminated, although occasionally wave ripples may be present.

VERTICAL SECTIONS THROUGH THE BASE OF THE HARTHOPE GANISTER IN 3 CURROCKS QUARRY (NY 86633507)



Sections run from N.W.-S.E.(1-3)
Distance between sections 1&2 approximately 280m.
Distance between sections 2&3 approximately 50m.

Fig.64

Thin laterally persistent beds of quartz arenite separated by occasional thin shale laminae,Thinly Bedded Facies,Harthope Bank Quarry(NY 86503380). Hammer 33cms.long.

Fig.65

Low angle bedding plane showing an undulating surface, Thinly Bedded Facies,Three Currocks Quarry.

Fig.66

Exposed upper surfaces of sandstone beds are often undulatory (Fig.66). These undulations have wavelengths of up to 11 m. and heights of 50 cms. Sections through the crests display domed up laminae similar to the hummocky cross-stratification of Harms, *et al* (1975).

Bioturbation is common within this facies and includes star-shaped traces (described on p.275), *Arenicolites, Muensteria, Monocraterion, Cochlichnus,* and horizontal feeding traces. Within a sandstone bed bioturbation tends to decrease in intensity downwards. Body fossils are rare, the only one recorded being a single specimen of a small (approx. 2.5 cms. long) unidentified thin shelled bivalve.

Thinly bedded quartz arenites occur dominantly at the base of the sandstone body, but are present interbedded with the overlying Thickly Bedded Facies. Low angle depositional dips ($<10^{o}$) are common and generally trend northwards (Fig.61).

Petrographically the sandstones consist of fine grained quartz arenites containing up to 8% sericite, kaolinite and muscovite (Fig.67). Detrital quartz grains are subrounded, and moderately well to well sorted. Bedding planes often contain abundant clays and micas, resulting in the rock being too impure for refractory use. Gradually this facies passes down via parallel laminated and ripple drift cross-laminated fine grained muddy sandstones into the underlying sandy shales.

Palaeocurrents are restricted to measurements of trough cross-lamination from the tops of sandstone beds. These suggest currents flowing to the W. or W.N.W. (Fig.68). Rare wave ripples show crestal trends of 48^{o}-228^{o}.

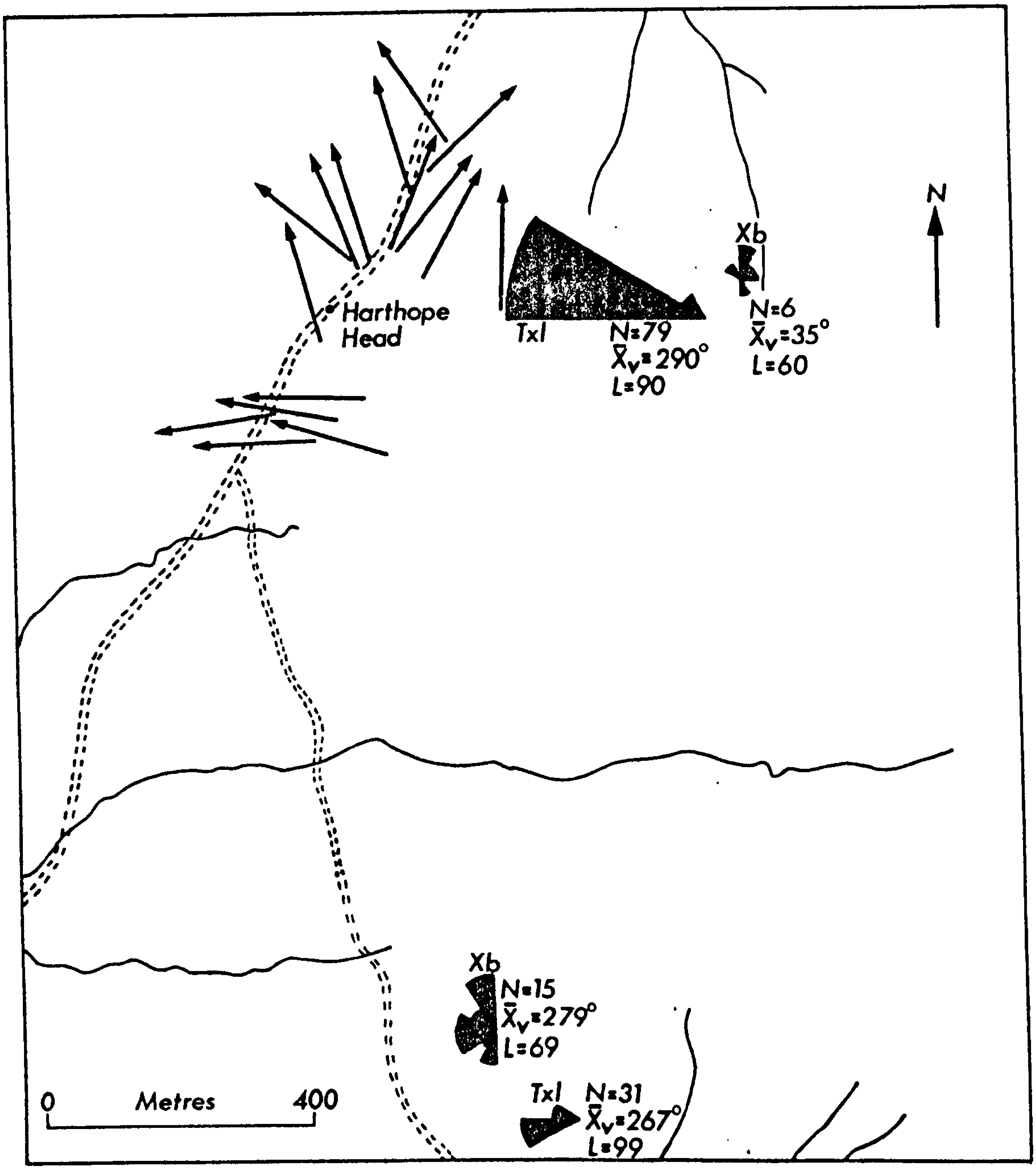
POINT COUNT ANALYSES OF SHALLOW-MARINE QUARTZ ARENITES AND ASSOCIATED STRATA

Horizon /Facies	Quartz %	Mixed Layer Clay/Sericite %	Kaolinite %	Feldspar %	Muscovite %	Carbonaceous Material %	Heavy Minerals %	Goethite %	Biotite %	Chlorite %	N
Harthope Ganister Thinly Bedded Facies	92	5.5	0.5		2						200 [1]
Harthope Ganister Thickly Bedded Facies	97.5	2							0.5		200 [1]
Harthope Ganister Large Scale Cross-Bedded Facies	99.5	0.5									200 [1]
Coalcleugh Transgression Beds, Sipton Cleugh (NY85425025)	85	9	1		0.5	0.5	0.5		2.5	1	200 [1]
Flinty Quarry Sandstone Parallel Laminated Facies	99	1									300 [1]
Flinty Quarry Sandstone Reworked Top	95.33	3.33	0.67		0.33			0.33			300 [1]
Basal Quartz Arenite, Lynnshield	98		1			1					200 [1]
3rd Quartz Arenite, Lynnshield	96	3.5		0.5							200 [1]
Park Quartz Arenite	98.5		0.5				0.5	0.5			200 [1]
Dun Fell Sandstone, Cross Fell	99	0.5				0.5					200 [1]

N=Total number of point count measurements(number in top right hand corner refers to the number of thin sections analysed)

Fig.67

HARTHOPE GANISTER PALAEOCURRENTS



⟵ =Foreset dip directions from the Large Scale Cross-Bedded Facies.Each arrow represents a single measurement.

Txl=Trough cross-lamination directions from the Thinly Bedded Facies.

Xb=Cross-bedding directions from the Thickly Bedded Facies

N=Number of palaeocurrent measurements

$\bar{X}_v$=Vector mean

L=Magnitude of vector in terms of per cent

Measurements taken from quarries shown in Fig. 61

Fig.68

(b) Thickly Bedded Facies

This generally overlies the Thinly Bedded Facies and consists of fairly laterally persistent thick beds (<2.5 m.) of sharply or erosively based quartz arenite. Low angle depositional dips to the N. are common and many beds when traced along quarry faces extend from the top to the bottom of the sandstone body (Fig.69). Occasionally, however, beds may be terminated by northerly dipping, low angle truncation planes. Truncation is evident mainly at the top of the sandstone body, and as these planes descend they become conformable with the low angle dipping surfaces.

Internally beds often display low angle or parallel lamination, and associated streaming lineation, together with wave or current rippled tops. Occasional planar and trough cross-bedding in sets up to 2.5 m. thick are present, particularly towards the top of the sandstone body. Some cross-bedding sets contain reactivation surfaces. Palaeocurrents from cross-beds are variable in direction, but show a dominant trend between W. and N.E. (Fig.68). Rarely beds exhibit domed up laminae similar to hummocky cross-stratification.

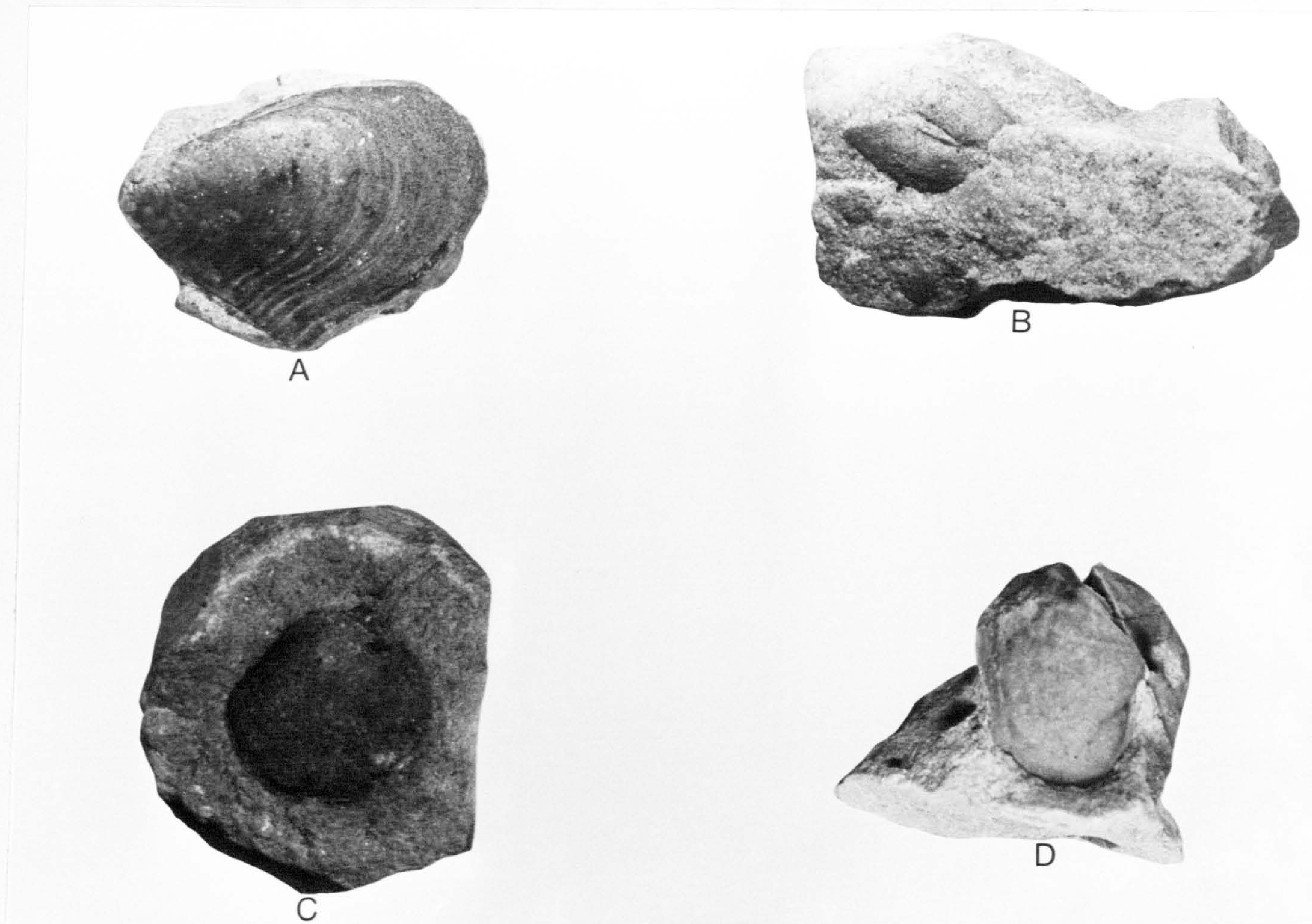
Occasional beds show loaded bases (Fig.70) and rarely highly convolute horizons are present. Scours at the base of beds often contain lags of intraformational shale clasts, driftwood, and broken and abraded shell debris. Fossils from these lags include *Myalina verneulii*, *Schizodus sp.*, *Aviculopecten sp.*, and a small (generally <2 cm.) unidentified thin shelled bivalve (Fig.71). Bioturbation is uncommon and tends to be restricted to star-shaped traces at the tops of beds. In Harthope Bank Quarry approximately

Thickly Bedded Facies exhibiting low angle depositional dips,Harthope Bank Quarry.Quarry face approximately 7m. high and orientated N.W.-S.E.(left to right). Fig.69

Loaded base to sandstone bed,Thickly Bedded Facies, Harthope Bank Quarry.Approximately 75cms.of tape exposed.

Fig.70

FOSSILS FROM THE HARTHOPE GANISTER



A=_Myalina verneulii_ x0.97   B=Unidentified thin shelled bivalve x1.3
C=_Aviculopecten sp._ x0.78   D=_Schizodus sp._ x0.95
All 4 specimens come from the Thickly Bedded Facies in Harthope Bank Quarry.

Fig.71

3 m. from the top of this facies, an upright *Calamites sp.* was found by a former quarry worker, Mr. J. Robson of Cowshill. The specimen was over 57 cms. in height, and in its apparent life position. Although the author did not witness this find, it is now in his possession. Compaction features on the specimen support the idea of burial in a vertical position.

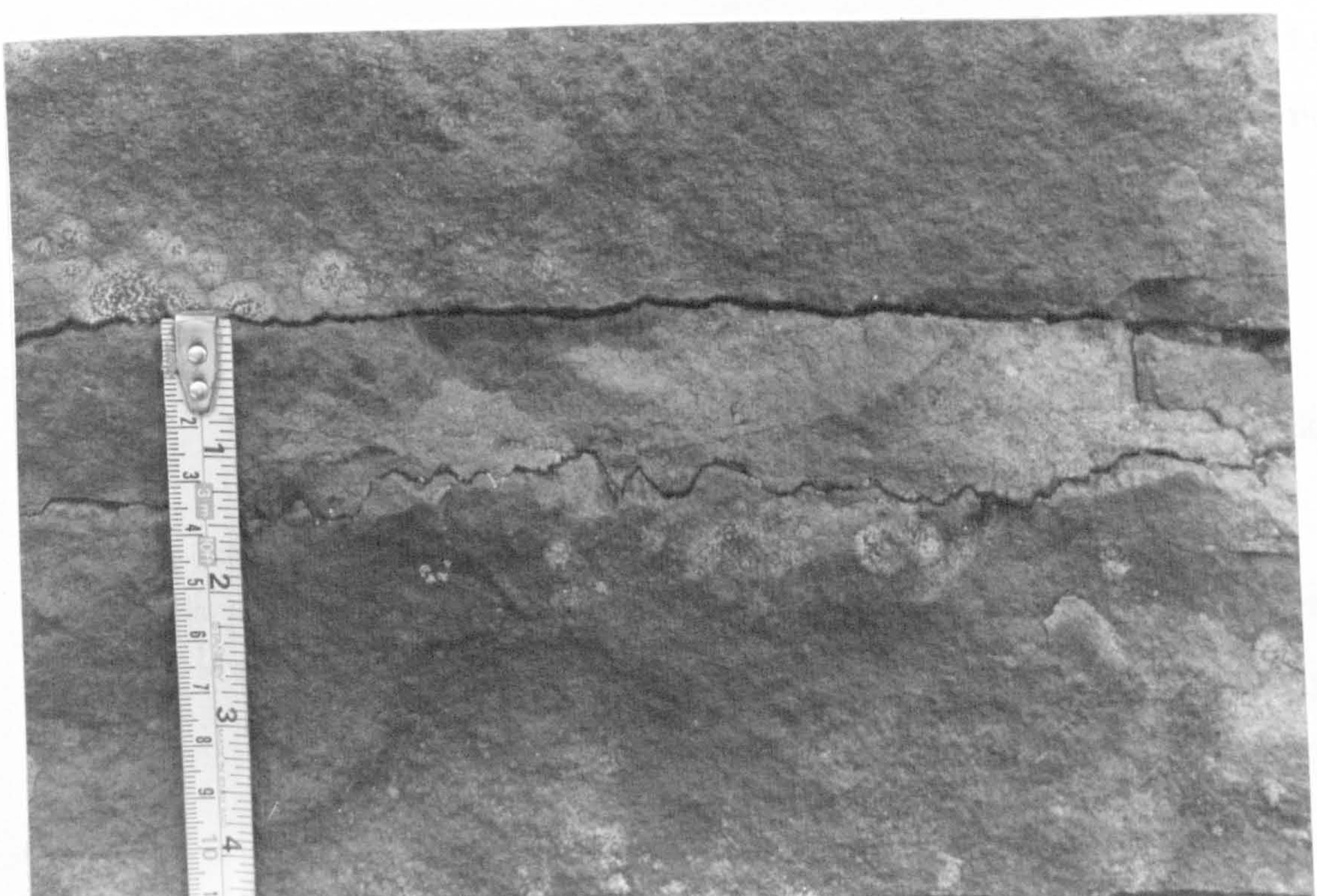
In thin section this facies consists of fine grained quartz arenites containing subrounded, moderately well sorted detrital quartz grains. The quartz arenites contain small amounts of clays and micas (Fig.67), and were the main horizons worked for refractory purposes.

(c) Large Scale Cross-Bedded Facies

This facies is restricted in occurrence to the N.W. portion of the sandstone body and consists of planar cross-bedded quartz arenite in sets up to 6 m. high (Fig.72). Foresets are inclined at angles up to 28^{o}, and generally increase in height down palaeocurrent until they form virtually the whole of the sandstone body. Beyond this point a decrease in foreset height often takes place, and as a result the whole sandstone body thins. Although many foresets appear massive (1 m. or more in thickness), most are made of relatively thin laminae only a few cms. thick. Down palaeocurrent from exposures of this facies the sandstone body dies away fairly rapidly, and probably terminates along a foreset.

Palaeocurrents from these cross-beds vary from W. to N.E. in a regular arc-like manner around the N.W. end of the deposit (Fig.68). Fossils are absent from this facies,

Large Scale Cross-Bedded Facies(X) showing 2 sets of cross-beds overlying the Thickly Bedded Facies(Y), Harthope Head Quarry.Hammer 33cms.long. Fig.72



Stylolite in quartz arenite indicating late diagenetic pressure solution of quartz,Thickly Bedded Facies,Harthope Bank Quarry.Left hand margin of rule is in cms.

Fig.73

and bioturbation is restricted to star-shaped traces. These occur along foresets, and their preservation indicates that erosion was uncommon, and most events were depositional.

Petrographically this facies consists of fine grained quartz arenites composed of subrounded, moderately well to well sorted quartz grains. The quartz content ranges up to 99.5% (Fig.67), and as a result this facies has been extensively worked for refractory purposes.

(d) Relationship between facies

The Large Scale Cross-Bedded Facies is laterally equivalent to the bulk of the other 2 facies, which form the major portion of the Harthope Ganister. In the region of Harthope Head this junction can be seen. Cross-beds formed on the low angle dipping surfaces of the Thickly and Thinly Bedded Facies gradually increase in height down palaeocurrent, until they form virtually the whole of the sandstone body.

In Harthope Head Quarry this draping relationship is well seen, and at least 2 earlier aborted attempts at producing the Large Scale Cross-Bedded Facies are visible. These consist of cross-bed sets up to 2.5m. high, which migrated out across the low angle dipping surfaces, but became abandoned due to deposition of an overlying thickly bedded unit (Fig.74).

The Thinly Bedded Facies generally occurs at the base of the sandstone body, commonly underlying the Thickly Bedded Facies, but does also extend out under the Large Scale Cross-Bedded Facies near the previously described transition zone. As the Thinly Bedded Facies has low angle depositional dips, one would expect beds to gradually pass up into the overlying

HORIZONTAL SECTION THROUGH PART OF THE HARTHOPE GANISTER IN HARTHOPE HEAD QUARRY

Fig.74

Thickly Bedded Facies when traced laterally. This does occur, and interbedded thick and thin quartz arenites are fairly common.

The thickly bedded quartz arenites should show a similar relationship when traced laterally down dip. Thick beds at the base of the sandstone body are, however, uncommon. It is likely that these beds gradually thin when traced down dip and may pass into the Thinly Bedded Facies at the base of the deposit. Alternatively these thick beds would have to terminate at the junction with the underlying Thinly Bedded Facies. As an abrupt contact is never seen, and no major angular discordance between the two exists, this seems very unlikely. All 3 facies therefore show transitional relationships between each other (Fig.75).

The Thickly and Thinly Bedded Facies thus occur in the central/thickest part of the sandstone body and pass in a N.W. direction into the Large Scale Cross-Bedded Facies. Towards the E. and S.E. the Thickly Bedded Facies dies away and in the headwaters of Swinhope Burn (NY 87903380) approximately 2 kms. E.S.E. of Harthope Head only a small development of the Thinly Bedded Facies is present.

At the top of the Harthope Ganister low angle dipping surfaces and cross-beds are truncated by a thin (generally <20 cm. thick) reworked horizon. This consists of a bioturbated, fossiliferous, moderately friable fine grained sandstone, which forms the base of the overlying Coalcleugh Marine Band (Fig.75).

SECTION THROUGH THE HARTHOPE GANISTER AND ASSOCIATED STRATA TO ILLUSTRATE THE STRATIGRAPHIC POSITION AND FACIES VARIATION OF THE GANISTER

A=Thinly Bedded Facies
B=Thickly Bedded Facies
C=Large Scale Cross-Bedded Facies

Fig.75

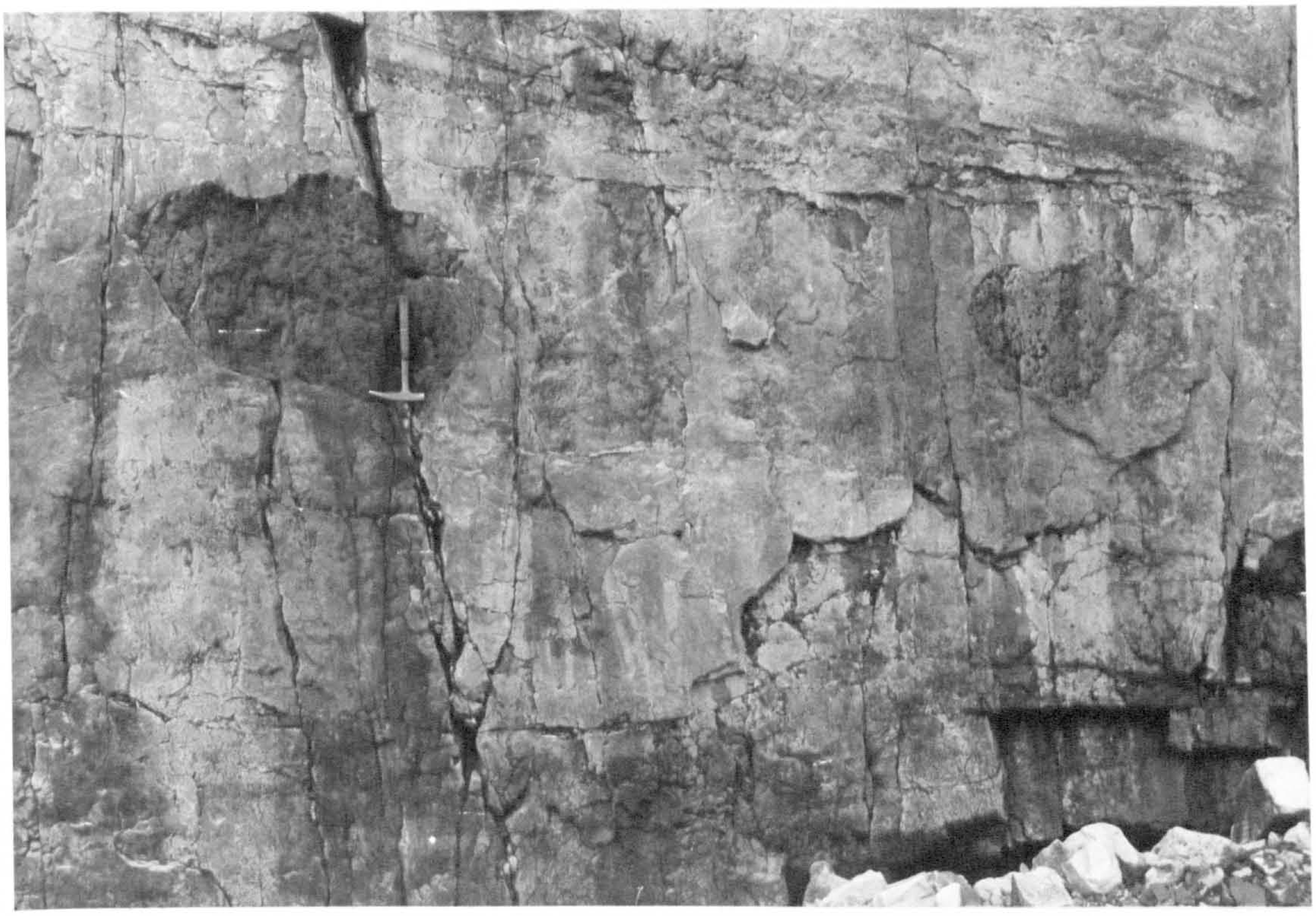
(ii) Diagenesis

Diagenesis of the Harthope Ganister has consisted mainly of compaction, and cementation by interlocking quartz overgrowths. This has resulted in a reduction in porosity to approximately 8%. Heavy minerals such as zircon and tourmaline have also developed overgrowths.

Stylolites are fairly common, particularly along bedding planes, and may exhibit interpenetrating columns up to 2 cms. high (Fig.73). These indicate moderately extensive late diagenetic pressure solution. Silica released along these surfaces may have formed a source of cement for adjoining low pressure areas of the rock.

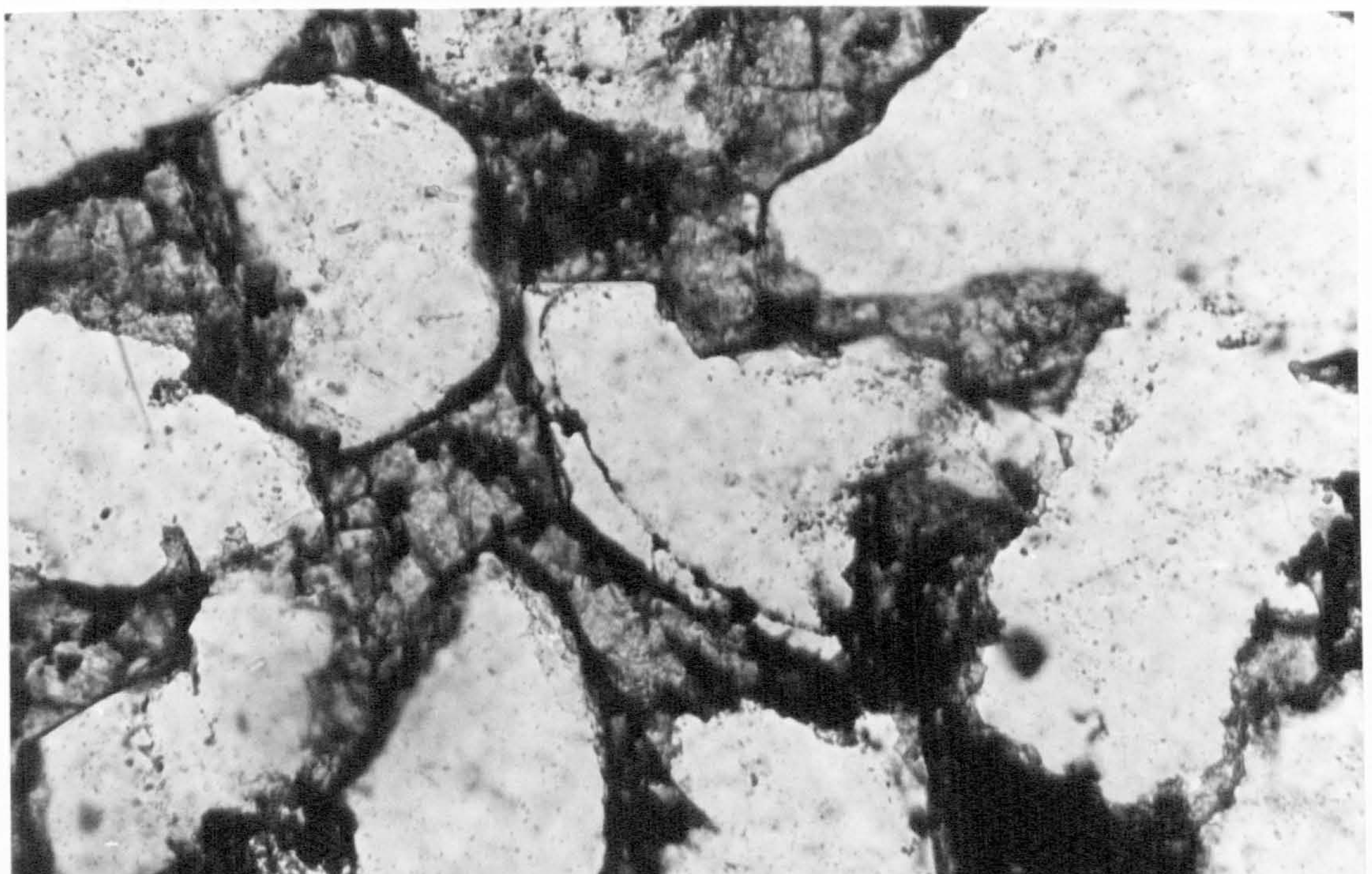
Occasionally large (1 m. or more in diameter) poorly cemented nodules exist within the Harthope Ganister (Fig.76). These consist of original pyrite?, siderite and calcite cemented zones, which have lost the majority of their cement due to recent weathering. Oxidation has resulted in the decomposition of pyrite? and development of goethite in its place. Commonly this coats grains and lines pores, and evidently the original pyrite? must have preceded deposition of the enclosing carbonate cement. Quartz grains and overgrowths in the nodules are extensively replaced by the cement, which is thus late diagenetic in origin (Fig.77).

The reworked sandstone at the top of the Harthope Ganister appears fairly similar diagenetically to these nodules. Quartz grains show extensive evidence of replacement by a cement which has been removed by recent weathering. The presence of abundant iron stained quartz grains in the sandstone, together with the mineralogy of the directly overlying calcareous mudstones and limestones suggests that the



Large, late diagenetic nodules originally cemented principally by siderite, transition zone between the Thickly Bedded Facies and the Large Scale Cross-Bedded Facies, Harthope Head Quarry. Hammer 33cms. long.

Fig.76



Photomicrograph of part of a late diagenetic nodule, showing siderite replacing both original detrital quartz grains and overgrowths. Length of photomicrograph 0.52mm.

Fig.77

cement consisted of siderite, calcite, ferroan calcite, ferroan dolomite, and pyrite. Although no direct evidence has been seen to indicate the timing of this replacement and cementation, the similarity with the nodules in the Harthope Ganister suggest a late diagenetic origin.

The source of the dominantly carbonate cement appears to be the overlying Coalcleugh Marine Band. The limestones and calcareous shales of this horizon contain abundant calcite, ferroan calcite, ferroan dolomite, siderite and pyrite (X-ray diffraction analysis). During diagenesis, solutions rich in these components supplied to the Harthope Ganister would soon result in formation of the observed features. Subsequent dissolution of the cement in the reworked zone has developed a secondary porosity of approximately 26%.

(iii) Interpretation

(a) Thinly Bedded Facies

The presence of sharp tool marked bases to sandstone beds, together with the passage upwards from parallel lamination to ripple cross-lamination, suggests rapid deposition from currents of waning flow strength. The abundance of bioturbation at the tops of beds, and the presence of interbedded thin shales indicate that these periods of high energy were interspersed with quieter water sedimentation.

These features together with the occurrence of hummocky cross-stratification suggest deposition took place in a storm-dominated environment. During major storms sand was emplaced into quiet water areas where physical reworking was limited.

This facies exhibits many similarities with the sub-littoral sheet sandstones of Goldring and Bridges (1973), which are thought to form by storm generated sandy density current flows.

(b) Thickly Bedded Facies

The washed in marine fauna from this facies contains articulated bivalve shells which have evidently not been transported far, suggesting deposition in a shallow-marine environment. The upward passage from parallel lamination to ripple cross-lamination within beds, occasional presence of hummocky cross-stratification, and the general occurrence above and lateral passage into the Thinly Bedded Facies suggests a storm-dominated origin. Convolute horizons support the idea of rapid sand emplacement, and suggest that deposition occasionally took place on top of poorly compacted water rich sand.

The thick erosively based nature of beds suggest sedimentation occurred under high energy conditions in a position proximal to the sand source. Deposition probably took place from bottom currents of storm-surge origin during the waning stages of storm activity. Gradually the velocity and transportational capacity of these currents decreased when traced into deeper water away from the sand source. This resulted in the down palaeocurrent transition from the Thickly to the Thinly Bedded Facies.

The paucity of bioturbation and occurrence of cross-bedding up to 2.5 m. high suggest that during fair weather periods energy levels were often fairly high. The presence of thin clay laminae indicate that occasionally very low energy conditions existed, allowing mud deposition. Bioturbation seems to have taken place during these periods.

The occurrence of an upright *Calamites sp.* in this facies may indicate a rare period of emergence and plant colonization. Plants can, however, float vertically under certain conditions (e.g. when debris is entangled in the root system), but deposition in a vertical position is less likely.[1] Reorientation of originally flat lying plant debris could perhaps have taken place by post depositional vertical deformation within the enclosing bed. Although there is no evidence to suggest that the upright *Calamites* is not *in situ* its sole occurrence without any supporting evidence of emergence is anomalous and should be treated with caution.

The low angle depositional surfaces extending from the top to the bottom of the sandstone accumulation, visible in both the Thinly and Thickly Bedded Facies, indicate that during deposition the sand body formed a bar up to 8.8 m. high. These low angle surfaces dip towards the N.-N.W. suggesting deposition from currents flowing from the S.-S.E. Scours from the base of beds indicate a similar trend, but current ripples commonly show W.-W.N.W. palaeoflow. This may reflect a slight change in current direction during a waning storm event, or result from subsequent reworking.

(c) Large Scale Cross-Bedded Facies

The draping nature of the foresets, and their moderate angle of dip suggest that deposition took place by migration

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1. Vertical deposition of plant debris is known to occur, but generally takes place in debris flows, e.g. Fritz (1980). Evidence of debris flow deposition is absent in the sandstones of the Thickly Bedded Facies, and such a mode of origin therefore seems unlikely.

of avalanche faced bedforms into deeper water alongside the bar form produced by the previous 2 facies. Initial generation of a bedform took place at the top of a low angle dipping surface. Gradually migration took place out across this surface, and the bedform increased in height. Occasionally during the early stages of formation of this facies, large storm events halted beform migration, and deposition of a thickly bedded unit took place. Migration at any one locality, occurred at right angles to the line of junction with the other 2 facies resulting in the observed palaeocurrents. Where 2 bedforms merged laterally, interfingering and lensing of foresets took place.

The presence of faunal colonization surfaces along foresets and very occasional thin muddy drapes indicate that sand deposition occurred intermittently. Rapid deposition was interspersed with longer periods of little or no sedimentation. The periodicity in energy levels must have been large enough to allow colonization of the foresets. Tidal cycles would be too short in this respect. Together with the lack of other criteria indicative of tidal activity, and the association with the previous 2 facies, this suggests a longer periodicity, storm generated origin for the foresets.

Bedforms with avalanche faces up to 6 m. high (sand waves) are uncommon in modern storm-dominated environments. However, the foresets result from draping of an original topographic high, and are thus not exactly comparable with those formed by sand waves. It is therefore suggested that deposition took place under the influence of wind-driven currents. The thickness of the foresets indicates that energy levels were much less than those required to form the previous facies.

(d) Overall depositional model

The presence of marine fossils, geometry of the sandstone body and its mode of deposition, suggest formation as a shallow-marine sand bar. Variations in thickness, and the distribution of facies allows approximate delineation of the limits of this sand bar in the field (Fig.78). Towards the N. the occurrence of the Coalcleugh Coal and its seat-earth suggest the presence of an E.-W. trending shoreline to the N. of the R. Wear (approximately 4 kms. N. of the sand body). The bar was therefore orientated at approximately 65° to this shoreline. During formation of the sand bar there appears to have been 2 major phases of migration and deposition:-

1. Bar formation and initial migration

Bar formation took place to the S.E. of the present location. The actual mode of initiation and aggradation is unknown. Gradually the bar migrated towards the N.W. over the surrounding muddy sea floor. Deposition of the Thinly and Thickly Bedded Facies took place by rapid sand emplacement down the landward (N./N.W.) bar flank (Fig.79). Sand was supplied by storm erosion of the seaward (S./S.E.) side of the bar. This erosion truncated the upper parts of previously deposited sands, resulting in a low angle S./S.E. dipping surface on the seaward side of the sand bar. At the S./S.E. end of the sand bar only the lowest parts of the sequence escaped erosion. Consequently the Thickly Bedded Facies dies away in this direction, and only part of the lowest Thinly Bedded Facies is preserved. In cross section from N.W.-S.E. the sand bar appears to be asymmetric in profile, with its steepest face (3-10°) towards the N.W. in the direction of migration.

PALAEOGEOGRAPHIC RECONSTRUCTION OF PART OF UPPER WEARDALE AT THE TIME OF ABANDONMENT OF THE HARTHOPE GANISTER SAND BAR

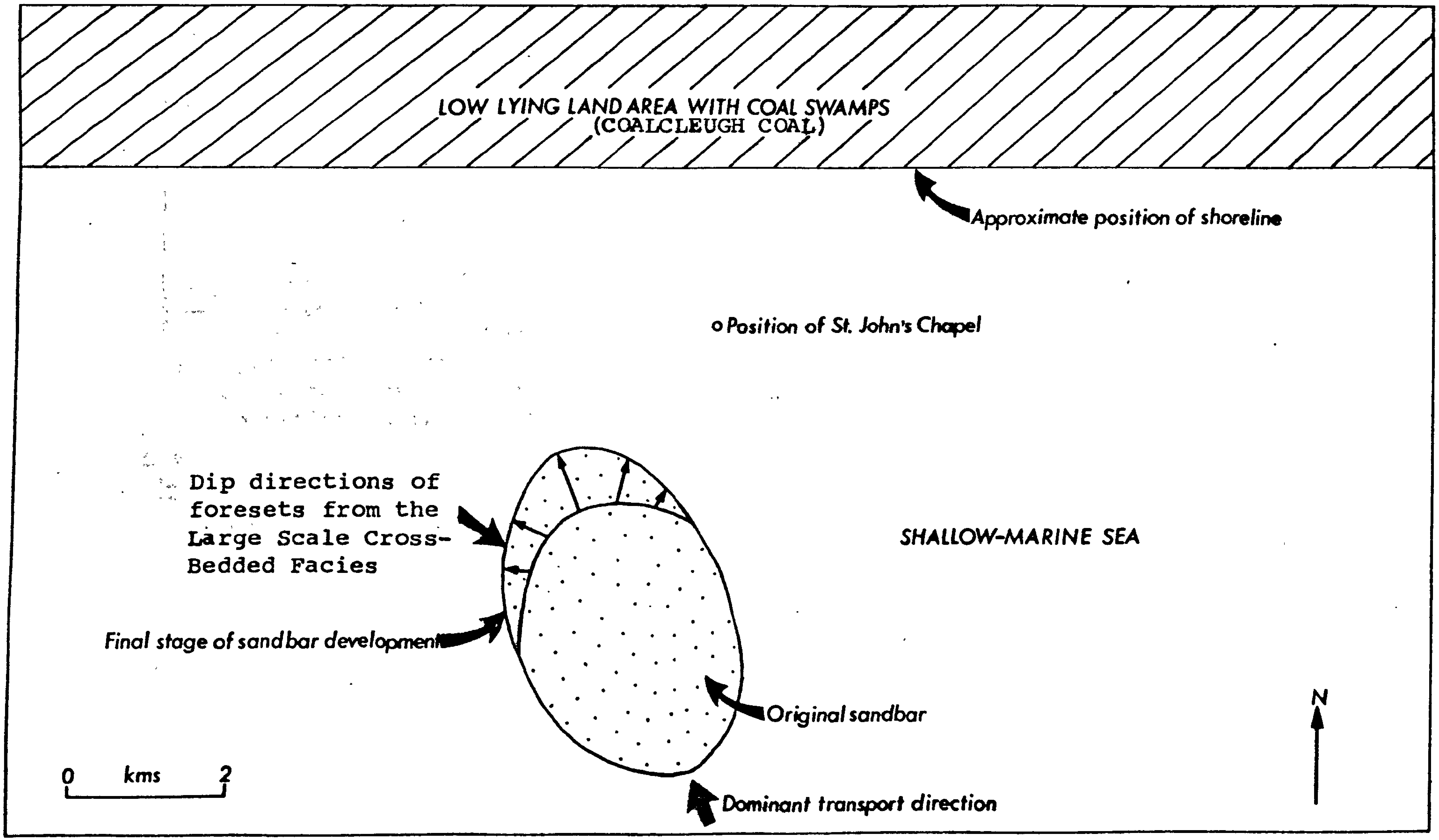
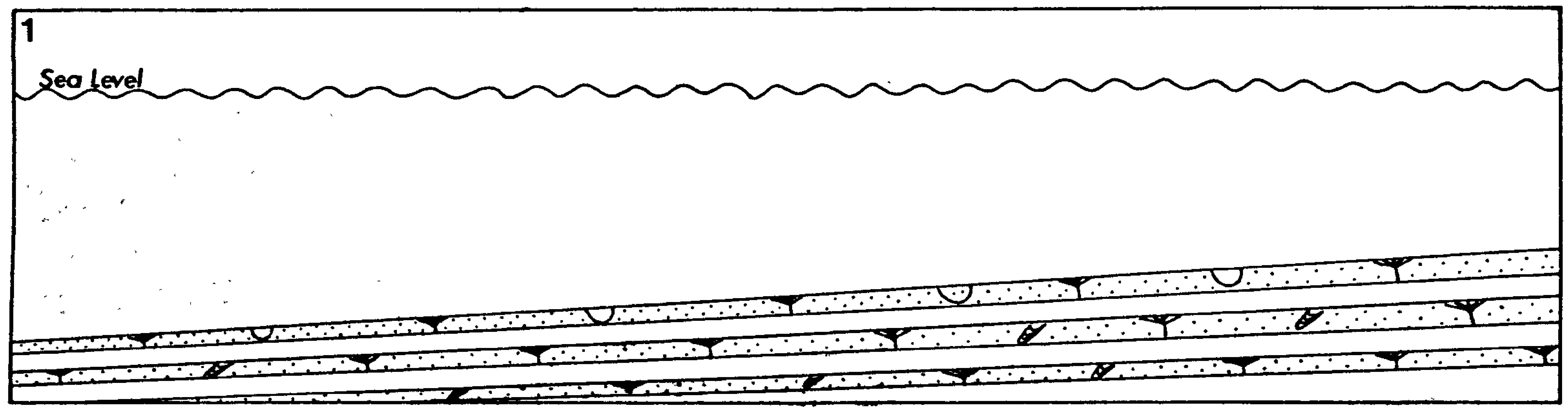
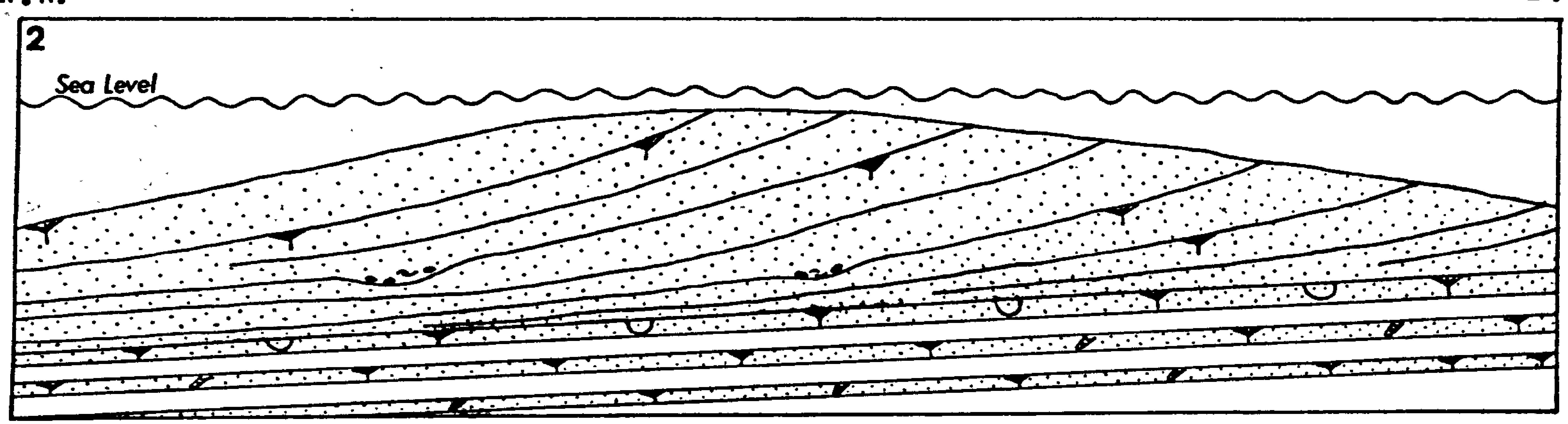


Fig.78

INTERPRETED MODE OF DEVELOPMENT OF THE HARTHOPE GANISTER SAND BAR, PARTS 1 & 2



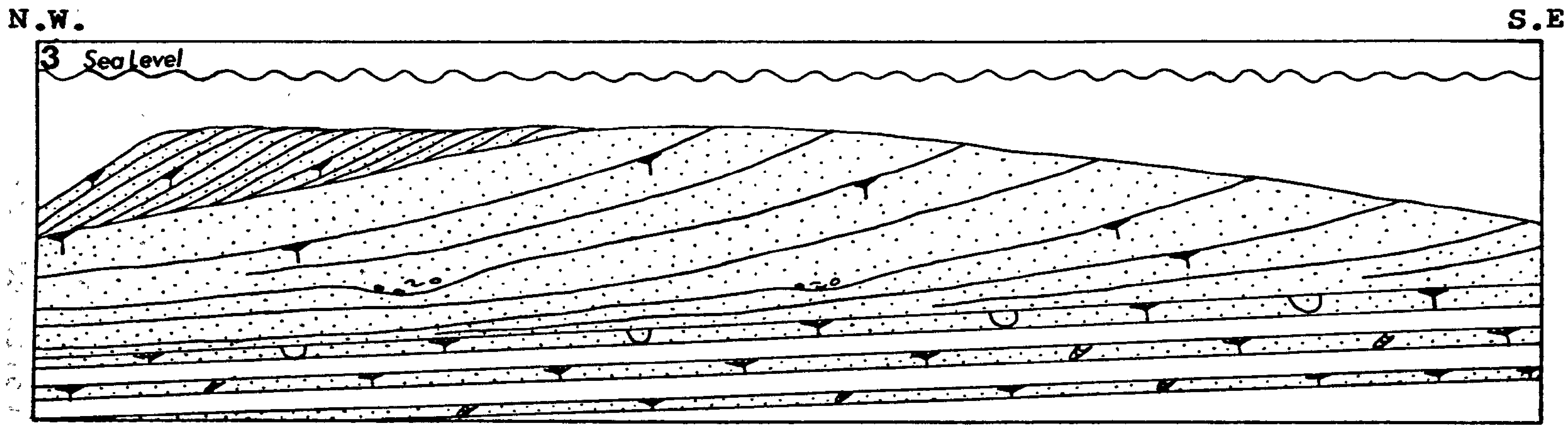
1) Rapid emplacement of thin quartz arenite sands along the northern margin of the bar during storm events. Reworking (physical and biogenic) and mud deposition during quieter water periods.



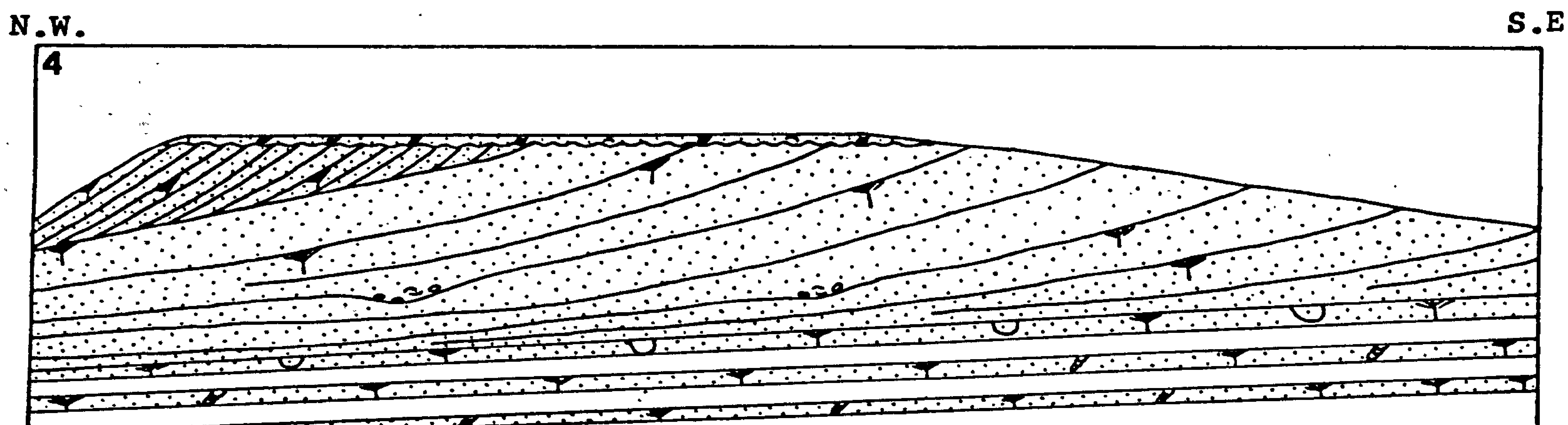
2) Migration of the main bar form into the Harthope area results in deposition of thicker, more proximal sands, during storm events.

Fig.79

INTERPRETED MODE OF DEVELOPMENT OF THE HARTHOPE GANISTER SAND BAR, PARTS 3 & 4



3) Storm deposition wanes (rise in sea level?) and bedforms migrate out across the N.W. bar flank under the influence of wind-driven currents.



4) A relative rise in sea level (above the top of the diagram) causes bar migration to cease. Reworking of the top takes place before the bar is carried below fairweather wave base.

Fig.79

During migration the bar crest would have continually moved towards the N.W. (Fig.79). The thickness of the deposit in the region of Harthope Bank Quarry (NY 86503380), and its central position in relation to the known extent of the sandstone body, indicate that the final position of the crest lay in this area. Cross-bedding is moderately common at the top of the deposit at this locality, and probably reflects dune and possibly sand wave migration in the high energy shallower water. Occasional reversals in cross-bedding direction may reflect some tidal action in this zone (de Raaf and Boersma, 1971).

The only possible evidence of plant colonization, also occurs at Harthope Bank Quarry, where the upright stem of a *Calamites sp.* was found within a thick quartz arenite, approximately 3 m. below the top of the sandstone body. This bed displays a low angle depositional dip, and as a result everywhere updip from the *Calamites* would have been emergent and liable to colonization, thus making the sand bar an island. The lack of any other evidence of emergence might be due to lack of preservation. Alternatively the *Calamites* is not *in situ*, or represents colonization during a rare relative drop in sea level. None of these ideas explains the facts satisfactorily, and the significance of the specimen remains in doubt.

Although the sand bar may not have become a shoal/island, damping of wave activity across the crest appears to have been sufficient to allow faunal colonization, and mud deposition and preservation on the landward side. Vertical sections through the central portion of the sand bar show coarsening and thickening upward sequences (generally <12 m.

thick) overlain by fossiliferous marine shales and limestones. These sequences together with the geometry of the sandstone body exhibit broad similarities with the sand bar deposits described by Brenner and Davies (1974), and de Raaf *et al* (1977).

2. Deposition of the Large Scale Cross-Bedded Facies

Initiation of this facies began along the broad curving surface of the N.W. end of the sand bar, formed during the previous phase of deposition. This surface was inclined at approximately 5^{o}. Progradation of bedforms cut across this surface to produce the Large Scale Cross-Bedded Facies further increased the N.W.-S.E. asymmetry of the bar (Fig.79).

Migration was intermittent, and appears to have taken place mainly under the influence of moderate energy wind-driven currents. This represents a decrease in maximum energy from the previous 2 facies. Eventually energy levels decreased even further foreset height diminished, and finally migration of the sand bar ceased altogether.

Bar abandonment may have occurred as a result of a relative rise in sea level, which led to deposition of the Coalcleugh Marine Band (Figs.79 and 80). The top of the sand body underwent low energy reworking, resulting in a thin bioturbated, fossiliferous sand. Eventually reworking ceased and deposition of the overlying fossiliferous shales and limestones took place.

The bar thus represents shallow-marine deposition during a transgressive event. The majority of the sea level rise occurred subsequent to bar formation and migration, and resulted in bar abandonment. However, the decrease in energy

SCHEMATIC SECTIONS SHOWING THE RELATIVE RISE IN SEA LEVEL WHICH MAY HAVE RESULTED IN ABANDONMENT OF THE HARTHOPE GANISTER SAND BAR

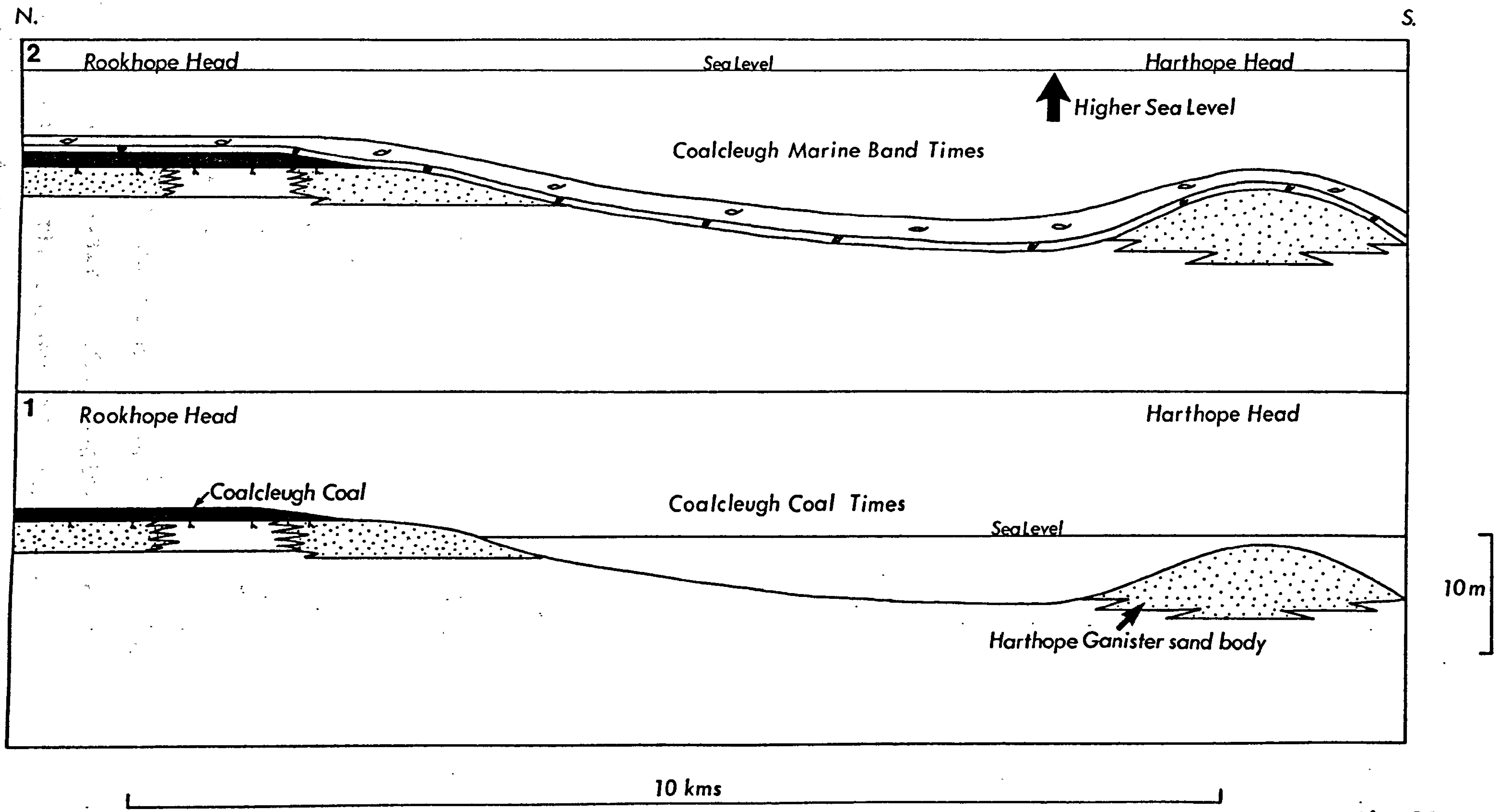


Fig.80

conditions leading to deposition of the Large Scale Cross-Bedded Facies may have been caused by an increase in water depth.

It is therefore suggested that bar growth and migration was at least in part concomitant with a relative rise in sea level. Eventually bar aggradation could not keep pace with sea level rise, and the bar became drowned *in situ*.

In some respects the Harthope sand bar deposits resemble barrier island sands; both the Thickly and Thinly Bedded Facies being similar to washover fan deposits (Andrews, 1970). One of the main arguments against a barrier island origin is the lack of any unambiguous signs of emergence. Often these occur at the top of the sand body, and as a result are commonly removed by subsequent erosion. This is particularly common during transgressions where shoreface erosion often results in removal of the upper parts of the barrier island sequence.

Erosion of the upper part of the sand body has occurred at Harthope. Original variations in topography on the top of the sand body are still evident to some degree, and together with the bioturbated, fossiliferous nature of the reworked sand suggest that erosion was limited and took place under fairly low energy conditions. Beach lamination which one might expect at the top of a transgressive barrier island sequence is also absent.

Formation of the Large Scale Cross-Bedded Facies occurred entirely subaqueously. The draping nature of the foresets over the edge of the topographic high produced by the other 2 facies, indicates that during formation of the Large Scale Cross-Bedded Facies, the entire sand body was probably submerged.

Spit platform sediments are the nearest equivalent facies in modern barrier islands, but foresets are only approximately 3 m. high and overlie previously deposited tidal inlet sequences (Kumar and Sanders, 1974). Both the size of the foresets and the nature of the underlying sequence make the Large Scale Cross-Bedded Facies incompatible with such an origin.

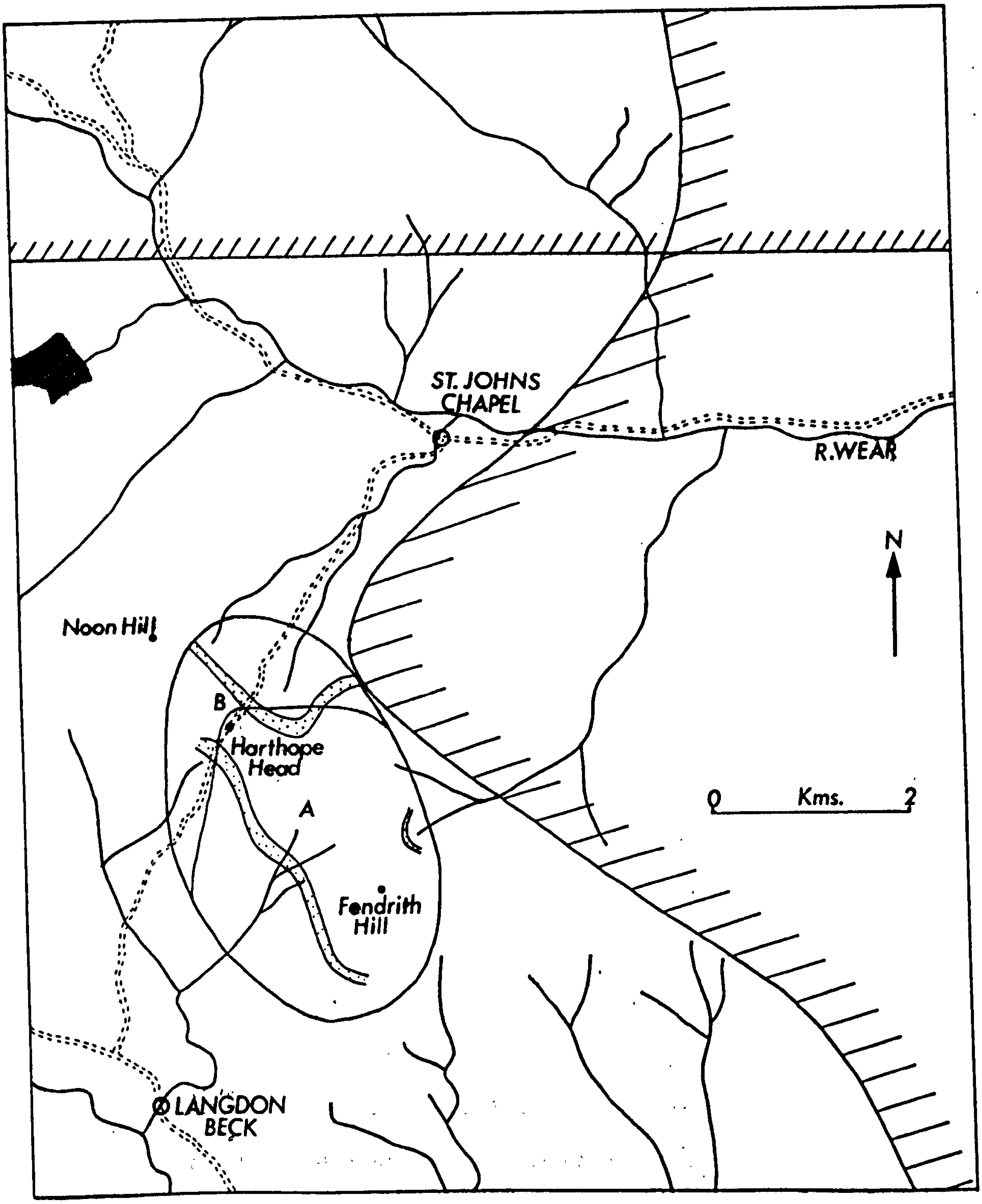
The geometry of the deposit, its relationship to the shoreline, and the sporadic presence of hummocky cross-stratification, together with the preceding evidence indicates that a barrier island origin is unlikely. Similarities between the Thickly and Thinly Bedded Facies, and modern barrier island washover deposits, results from a similar mode of deposition of the sands during storm events.

Although the mode of formation of the Harthope Ganister sand bar is unknown, the sand for its formation appears to have been winnowed from adjacent shelf areas as in many modern examples. Other contemporaneous sand bars may have existed, but in many instances have probably been lost due to subsequent erosion.

(e) Relationship between Harthope Ganister and the High Grit Sill

The High Grit Sill forms a 23 m. thick, erosively based, ribbon-like development of coarse-very coarse grained sandstone which is thought to be fluvial in origin (Pattinson 1964). The Harthope Ganister is laterally equivalent to, and occurs closely associated with this horizon (Fig.81). Evidently with such different modes of origin the two cannot be contemporaneous. Indeed deposition of the High Grit Sill is more likely to have been initiated during a regression rather than the transgression which is inferred to have taken

RELATIONSHIP OF THE HARTHOPE GANISTER TO LATERALLY EQUIVALENT STRATA



=Approximate southern limit of the Coalcleugh Coal

=Approximate western limit of the High Grit Sill(modified from Jones,1956 and Pattinson,1964)

=Approximate extent of the Harthope Ganister sand bar

A=Major area of occurrence of the Thickly and Thinly Bedded Facies

B=Area of occurrence of the Large Scale Cross-Bedded Facies

=Outcrop of Harthope Ganister

Fig.81

place during deposition of Harthope Ganister.

As a result it is suggested that High Grit Sill sedimentation began prior to deposition of the Harthope Ganister, which formed during the initial phases of the Coalcleugh Marine Band transgression into the Weardale-Teesdale area. The relative rise in sea level which caused the transgression may have aided aggradation of the High Grit Sill channel in more northerly (landward) areas.

(f) Relationship between Harthope Ganister and the overlying sequence

From the preceding discussion it is evident that formation and preservation of the Harthope Ganister sand body was intimately related with the transgression which led to deposition of the overlying sequence. At Harthope Head this overlying sequence consists of an approximately 10 m. thick coarsening upward sequence capped by the Hipple Sill and its associated seatearth (Fig.82). The Hipple Sill consists of an approximately 4 m. thick sequence of parallel laminated, cross-bedded, trough cross-laminated, bioturbated fine grained sandstones and interbedded silty and sandy shales. Palaeocurrents from the sandstones trend towards approximately 120°. Wavy, lenticular and flaser bedding is common in heterolithic units towards the base (Fig.83) and wave ripples in these units show crestal trends of approximately 64°-244°. The sandstones are completely transitional with the underlying shales. These are silty and kaolinite rich, and pass down gradationally into the fossiliferous limestones and illitic shales of the Coalcleugh Marine Band.

The coarsening upward nature of the sequence, its lithology and sedimentary structures, and the transition from marine to terrestrial conditions, suggests deposition in an interdistributary setting during progradation of a

INTERPRETIVE SECTION THROUGH THE HARTHOPE GANISTER AND ASSOCIATED STRATA

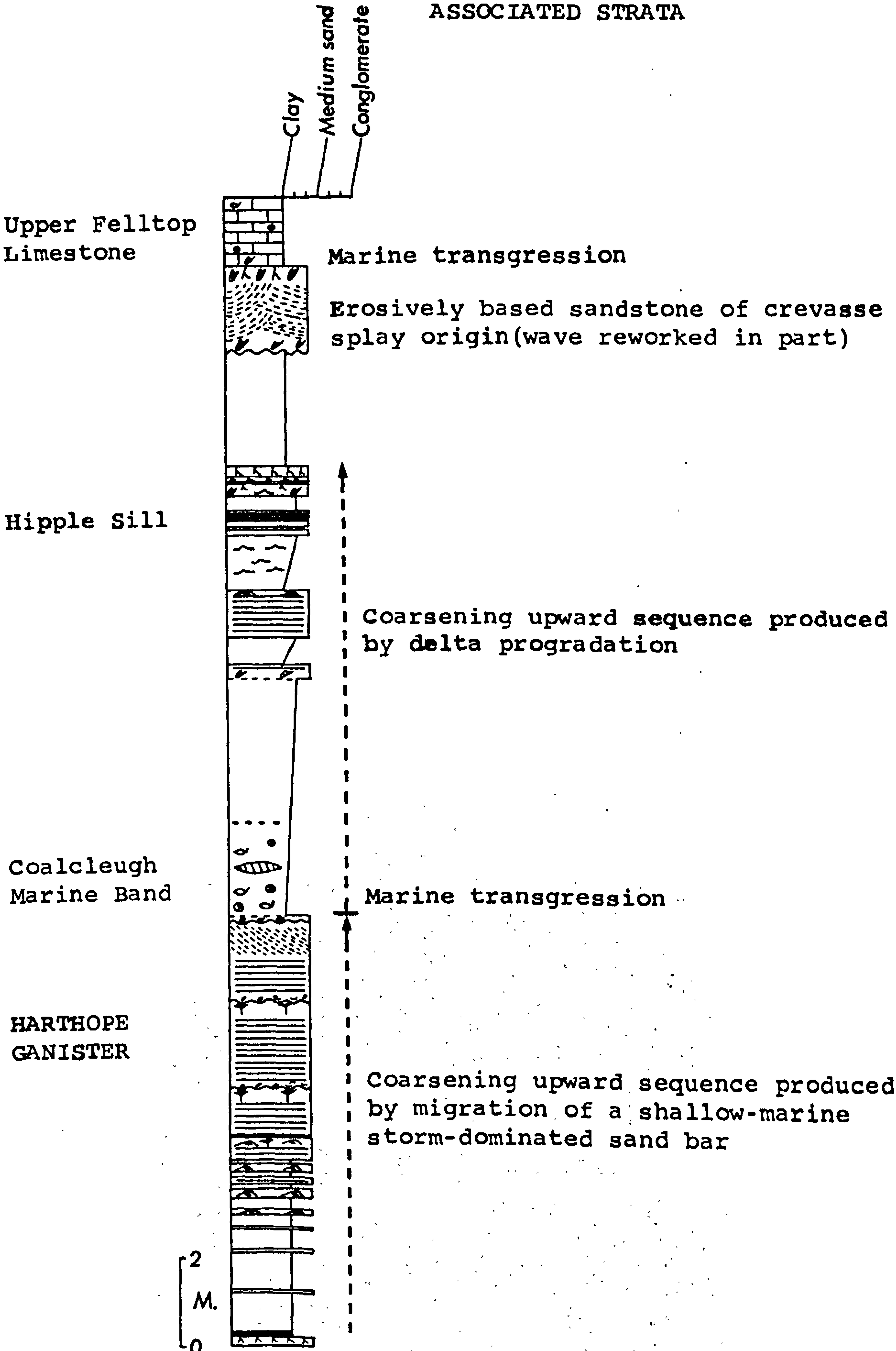
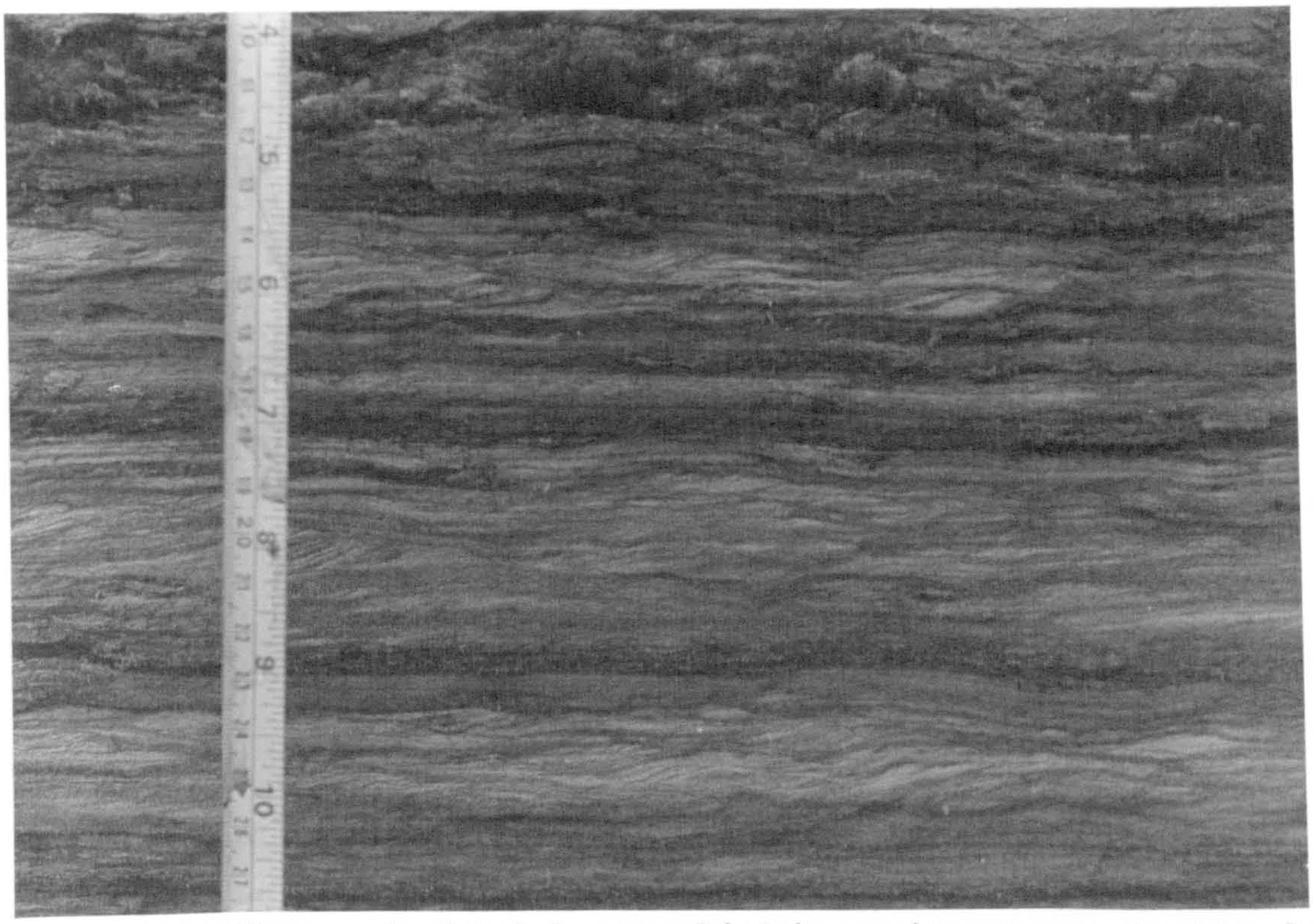
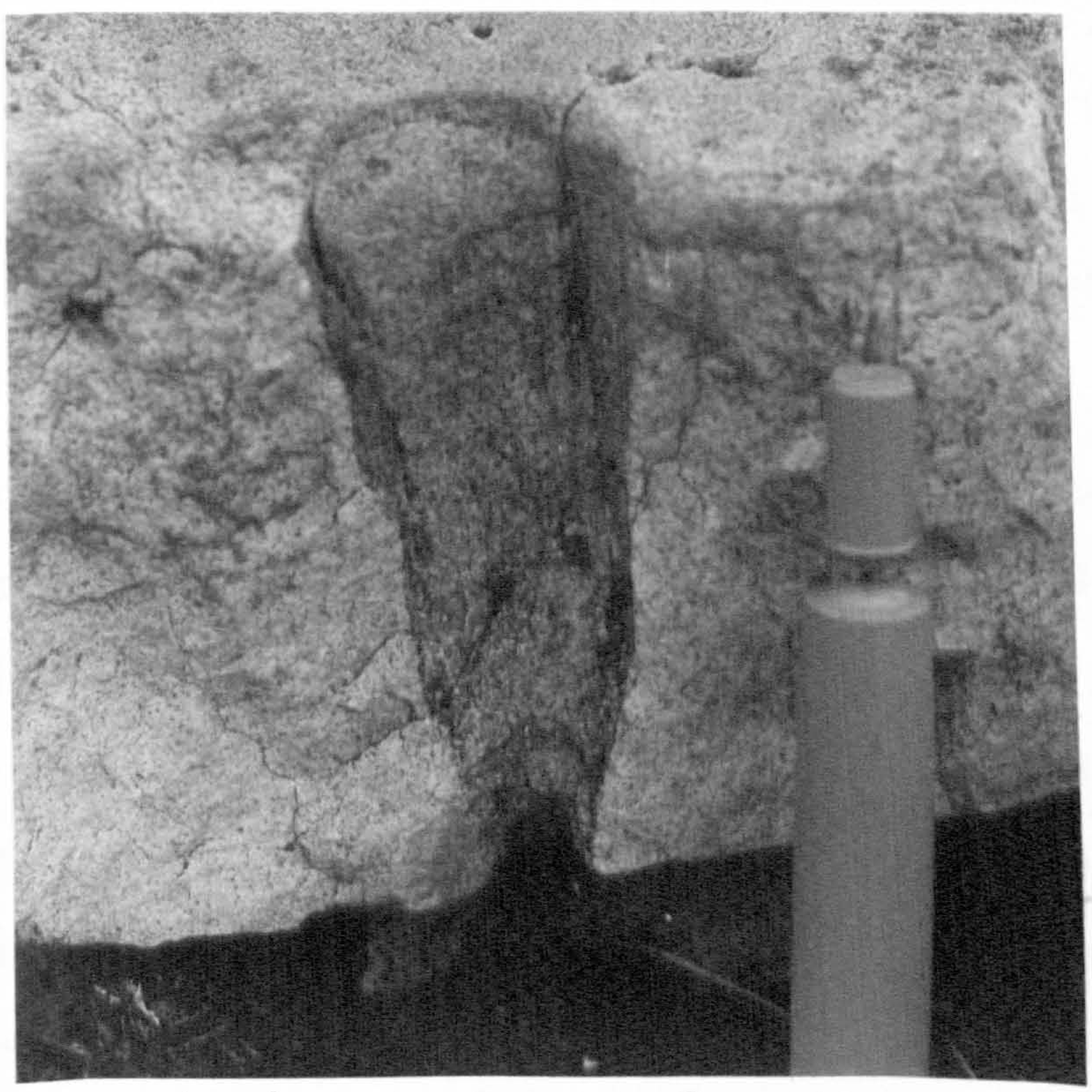


Fig.82



Wavy and flaser bedded heterolithic units towards the base of the Hipple Sill,Harthope Head Quarry.Left hand margin of rule is in cms.

Fig.83



Large _Monocraterion sp_. burrow from the reworked top of the Flinty Quarry sandstone.Exposed portion of pen 10.7cms. long.

Fig.84

river-dominated delta. The thickness of the coarsening upward sequence approximately indicates the depth of marine water into which the delta prograded (assuming most compaction occurred soon after deposition, etc.) (Klein, 1974).

This 10 m. depth of water was the result of 2 main contributary components:-

(1) Water depth over the Harthope Ganister sand bar during its formation (the amount of subsequent erosion from the top of the sand bar appears to be minor).

(2) The post sand bar, rapid relative sea level rise which caused bar abandonment, and deposition of the Coalcleugh Marine Band.

Although the actual amount contributed by either of these components cannot be calculated, it is evident that during formation of the Large Scale Cross-Bedded Facies at Harthope Head, the depth of water above the bar at this locality was <10 m. In fact as the subsequent rise in sea level caused abandonment of the bar, this is likely to have been much less. The crest of the bar appears to have been near Harthope Bank. In this region water depths may have been very shallow during deposition.

By the time the relative sea level rise had increased water depth over the sand bar at Harthope Head to 10 m., reworking of the top had ceased. In present day shallow-marine seas, fairweather wave base varies in depth, but is commonly of the order of 10-15 m. It is therefore suggested that the termination of reworking was a result of submergence below fairweather wave base. Delta progradation was subsequently fairly rapid, and resulted in preservation of the sand bar.

(iv) Conclusions

The Harthope Ganister formed as a storm-dominated shallow-marine sand bar during the initial phases of the Coalcleugh Marine Band transgression into the Weardale-Teesdale area. The sand bar was approximately 4.7 km. long, and 3 km. wide, and migrated into its present position from its place of origin further to the S.E. At maximum the bar reached a height of approximately 9 m. above the surrounding sea floor. Water depths across the bar crest appear to have been very shallow, probably only a few metres at maximum. This caused waves to shoal, and protected the landward side of the bar, except during major storm events.

Preservation of the sand bar was due to submergence below fairweather wave base caused by a rapid relative rise in sea level, followed by burial beneath a rapidly prograding delta.

C. Flinty Quarry sandstone

(i) Description

Flinty Quarry lies at an elevation of approximately 1950' (594 m.) on Flinty Fell, above Nenthead, and consists of an approximately 300 m. long working which exposes a 4-5 m. thick fine grained quartz arenite (Figs. 85 and 86). The exact stratigraphic position of this horizon is uncertain, lying somewhere between the Firestone Sill and Lower Felltop Limestone.

Borehole evidence from Nunnery Hill (NY 76854285) approximately 1.2 kms. to the N. indicates that only 2 major sand-

PALAEOCURRENTS AND LOW ANGLE DEPOSITIONAL DIPS FROM THE FLINTY QUARRY SANDSTONE

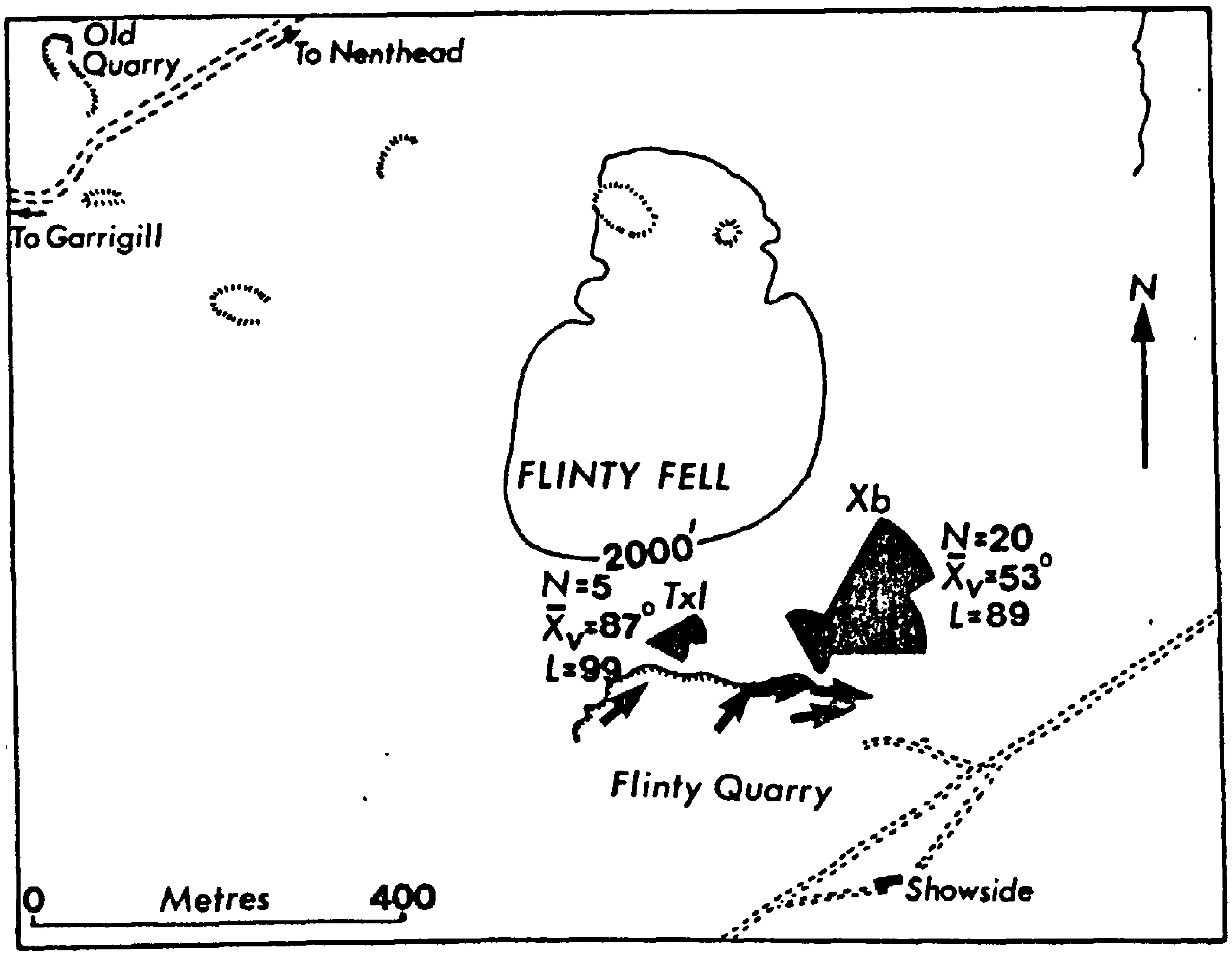


Fig.85

→ =Dip direction of low angle(<10°) bedding planes
Txl=Trough cross-lamination directions(parallel laminated facies)
Xb=Cross-bedding directions(small scale cross-bedded facies.
N=Number of palaeocurrent measurements, $\bar{X}_v$=Vector mean
L=Vector magnitude in terms of per cent

MEASURED VERTICAL SECTION THROUGH THE CENTRAL PART OF FLINTY QUARRY

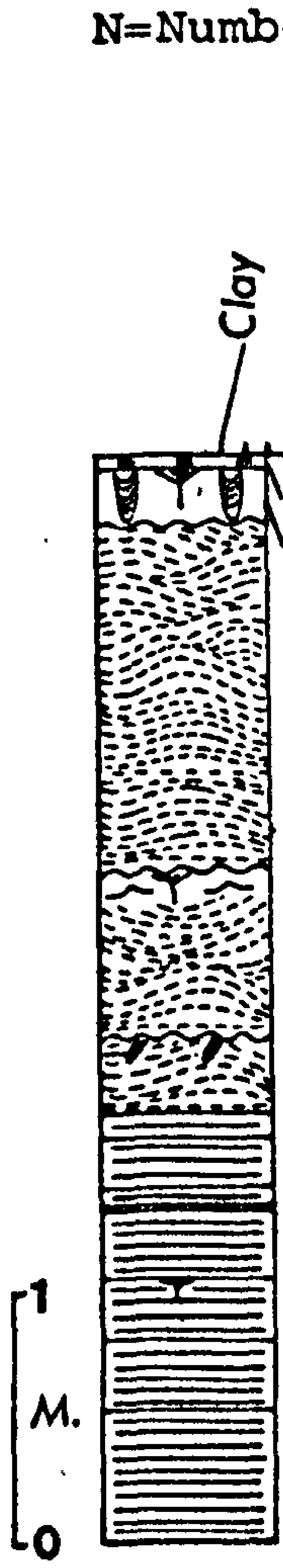


Fig.86

stones occur in this stratigraphic interval. The lowest directly overlies the Oakwood Coal, and is probably the local representative of the Fiddlers Sill. The second sandstone occurs approximately 28 m. above the Oakwood Coal suggesting a position in the Slate Sills Formation (Pattinson, 1964). This sandstone is approximately 18 m. thick but occasionally occurs as 2 discrete sandstones separated by interbedded sandstones, siltstones, and shales. The topmost of these 2 sandstones is exposed in Dowgang Hush (NY 77304290) where it is 2-3 m. thick, and overlain by a decalcified fossiliferous sandstone. According to Dunham (1948) this represents the High Slate Sill, and overlying Upper Rookhope Shell Beds. Consequently the lower sandstone leaf is thought to correlate with the Low Slate Sill.

Exposures in Flinty Quarry show a similar sequence to that in Dowgang Hush. This together with a similar position above the Oakwood Coal suggests that the Flinty Quarry sandstone is equivalent to the High Slate Sill of E_1, Pendleian age (Hull, 1968).

In Flinty Quarry the quartz arenite is divisible into 3 facies:-

(a) <u>Parallel Laminated Facies</u>

This facies is well exposed at the western end of the quarry, and consists of laterally persistent, sharply based, thin beds of quartz arenite from a few cms. to a few 10's cms. thick, interbedded with occasional thin muds (generally <1 cm. thick). Internally the quartz arenites contain abundant parallel lamination and associated streaming lineation, occasionally passing upward into low amplitude hummocky cross-stratification or current ripple cross-lamination. Palaeocurrents from current ripples trend towards the E. (Fig.85).

Faunal remains are confined to this facies, and consist of small (approx. 1.5 cm.) unidentified thin shelled bivalves, similar to those from the Harthope Ganister. Trace fossils are rare, and generally restricted to star-shaped traces at the tops of beds (whose characteristics are described in detail later in this chapter).

(b) Hummocky Cross-Stratified Facies

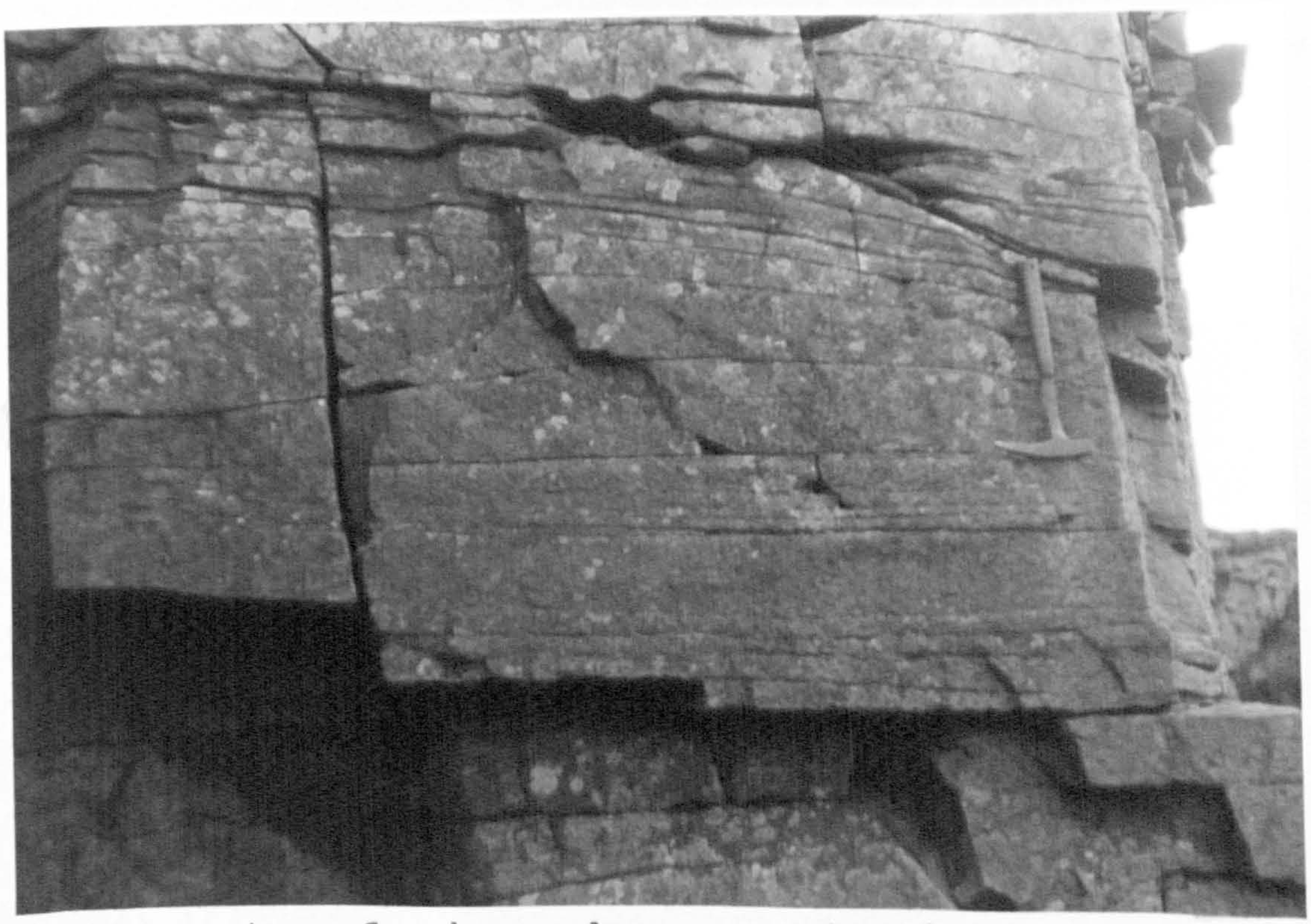
This consists of erosively based units of quartz arenite commonly <1 m. thick. Typical exposures occur in the central part of the quarry above the Parallel Laminated Facies (Fig.86). Internally beds often display parallel lamination with associated streaming lineation, passing up into hummocky cross-stratification (Figs.87 and 88). Wave ripples are occasionally present on the top surface of beds, and exhibit crestal trends of 70^{o}-250^{o}.

Individual hummocks consist of domed up laminae (Fig.88) and are elongated in an 80^{o}-260^{o} direction. In this orientation hummocks are up to 8 m. long and 22 cms. high (mean = 3.1 m. and 14 cms., n = 6). Trace fossils are rare within this facies, and the only fossil remains are occasional driftwood fragments.

(c) Small Scale Cross-Bedded Facies

This comprises a series of thinly bedded, small scale (generally <20 cms.) dominantly trough cross-bedded quartz arenites. Palaeocurrents from cross-beds trend towards 53^{o} (Fig.85). Bioturbation is moderately abundant, and includes shallow star-shaped traces up to 20.5 cms. in diameter.

Erosively based units up to lm. thick displaying parallel lamination and hummocky cross-stratification,Hummocky Cross-Stratified Facies,Flinty Quarry sandstone.Hammer 33cms. long. Fig.87



Close up view of a hummocky cross-stratified unit showing parallel lamination passing up into domed up laminae typical of hummocky cross-stratification,Hummocky Cross-Stratified Facies,Flinty Quarry sandstone. Fig.88

This facies occasionally overlies the Hummocky Cross-Stratified Facies, and occurs mainly in the eastern end of the quarry.

(d) Petrography

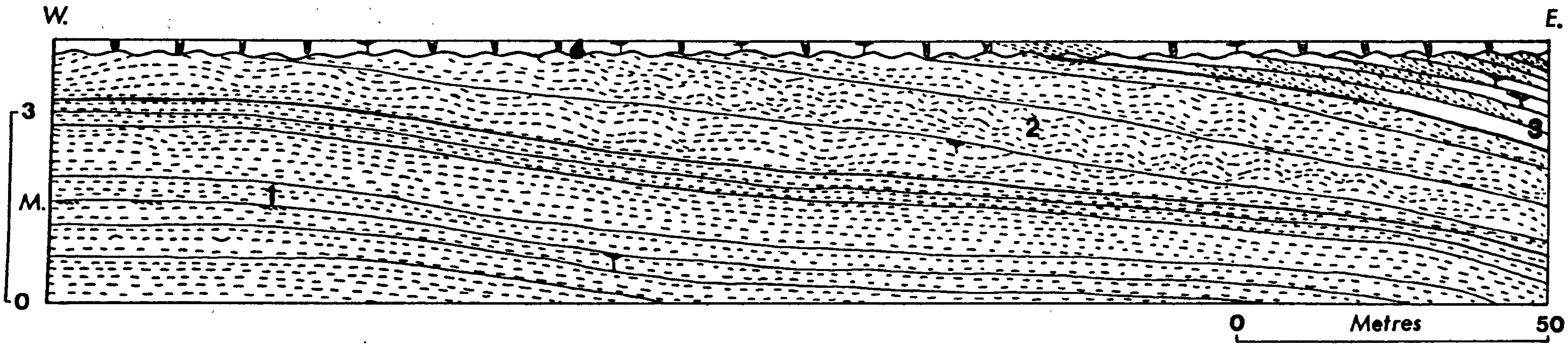
All 3 facies are similar petrographically and consist of fine grained quartz arenites containing subrounded to rounded, moderately well to well sorted quartz grains. Chert grains and rare multicycle quartz grains are present. Other minerals occur, and include sericite, kaolinite, tourmaline, zircon and rare altered orthoclase feldspar. These tend to be small in amount and the quartz content ranges up to 99% (Fig.67).

(e) Relationship between facies

All 3 facies display low angle depositional dips ($<10^{\circ}$) towards approximately 80° (Fig.85). The actual angle of dip is variable, and tends to be steepest at the E. end of the quarry. The result of these dips is that each facies dies away eastwards, and is replaced by the overlying facies (Fig.89). In an easterly direction there is thus the sequence; Parallel Laminated → Hummocky Cross-Stratified → Small Scale Cross-Bedded Facies. The Hummocky Cross-Stratified Facies is transitional to the Parallel Laminated Facies, but its junction with the Small Scale Cross-Bedded Facies is abrupt.

All 3 facies are overlain by a thin fine grained quartz arenite (approx. 20 cms. thick) (Fig.67) which truncates the low angle depositional surfaces and forms a capping to the deposit (Fig.89). This contains occasional easterly dipping cross-bedding, and an abundant trace fossil assemblage

DIAGRAMMATIC REPRESENTATION OF PART OF THE FLINTY QUARRY EXPOSURE SHOWING THE SPATIAL ARRANGEMENT OF FACIES



1=Parallel Laminated Facies
2=Hummocky Cross-Stratified Facies
3=Small Scale Cross-Bedded Facies
4=Reworked top containing large <u>Monocraterion sp.</u>

Fig.89

including *Aulichnites*, *Cochlichnus*, *Monocraterion*, and star-shaped traces. Of these *Monocraterion* is the most abundant, and consists of large spreiten filled, trumpet shaped burrows up to 20 cms. deep and several cms. wide which penetrate the whole thickness of the bed (Fig.84). Overlying this is a thin bed of decalcified sandstone containing abundant crinoid ossicles, thought to represent the Upper Rookhope Shell Beds.

(ii) Diagenesis

Diagenesis of the quartz arenites has consisted of compaction, and cementation by interlocking quartz overgrowths. Occasionally there has been a minor amount of late diagenetic growth of pyrite which has replaced both quartz grains and overgrowths.

(iii) Interpretation

(a) Parallel Laminated Facies

In many respects this facies is very similar to the Thinly Bedded Facies of the Harthope Ganister. Thin sharply based parallel laminated, hummocky cross-stratified, and current ripple cross-laminated sandstones have been described by Goldring and Bridges (1973), and Hamblin and Walker (1979), and are thought to form as a result of storm generated, sandy density currents (p.202). Deposition of the Parallel Laminated Facies is thus thought to have taken place under similar conditions. Density current flows appear to have been towards 80°. These introduced sand into quieter water areas where subsequent reworking was minimal. During fair-weather periods bioturbation, and deposition of thin mud laminae took place.

Initial density current velocities were high, and resulted in rapid deposition of parallel laminated sands. The occasional presence of low amplitude hummocky cross-stratification at the top of beds is thought to indicate the effect of storm waves on the sedimentary surface during the waning stages of density current flow. Current rippled tops to beds developed in areas unaffected by storm waves.

Deposition of this and the succeeding facies took place along low angle dipping surfaces. These extend from the reworked top of the quartz arenite to the base of the quarry and indicate that during deposition the sand body formed a topographic feature at least 4.8 m. high.

(b) Hummocky Cross-Stratified Facies

The main feature of this facies is the presence of hummocky cross-stratification, which is thought to indicate deposition under the influence of large scale storm waves (p.204). The elongation of the troughs and the orientation of wave ripples suggest that during deposition wave crests were orientated approximately 75°-255°. Deposition, however, appears to have taken place by currents flowing to 80°.

It is suggested that sand was introduced by density currents into an area where storm waves actively affected the sedimentary surface. Initial scouring appears to have taken place during maximum wave intensities, and was followed by deposition of hummocky cross-stratified sands during the waning stages of storm activity. Many hummocky cross-stratified units probably represent single storm events, although occasional amalgamated units are present.

(c) Small Scale Cross-Bedded Facies

This facies represents deposition from migrating mega-ripples under moderately low energy conditions. The presence of bioturbation, dominantly at the top of beds indicates that periods of sand deposition were interspersed with quieter water conditions. The association with the previous 2 facies, and the lack of evidence of tidal activity suggest that meteorological currents caused bedform migration. The absence of storm, or wave generated structures indicates that wind-driven currents were probably the most important in this respect.

Cross-bed palaeocurrents are, however, virtually parallel, rather than orthogonal with postulated wave crest trends from the underlying Hummocky Cross-Stratified Facies. This may reflect storm to fairweather changes in wind direction, the Ekman spiral, or the effect of bar topography on the direction of flow of bottom currents.

(d) Overall depositional environment

The presence of low angle bedding planes, and the mode of deposition of the quartz arenites, indicates formation as a shallow-marine storm-dominated sand bar. No diagnostic shallow-marine fossils or trace fossils are present, but the assemblage is very similar to the association from the marine Harthope Ganister.

Migration of the sand bar took place by sand emplacement down the E.-E.N.E. flank, often during storm events. Sand was eroded from the S.W.-W. side of the bar, and resulted in truncation of the upper parts of the sequence in this region.

The association of hummocky cross-stratified sandstones and thin sandy density current deposits is uncommon at exactly the same horizon. Most ancient examples of hummocky cross-stratified sandstones often pass into thin sandy density current deposits below storm wave base (Hamblin and Walker, 1979; Bourgeois, 1980). The occurrence of both in Flinty Quarry may therefore reflect deposition close to storm wave base. Generation of the Small Scale Cross-Bedded Facies is unlikely to have taken place at such a depth. The arrangement and occurrence of the 3 facies at the same horizon, may reflect a gradual decrease in relative sea level during bar formation.

Storm deposition seems to have been terminated fairly rapidly, and the Small Scale Cross-Bedded Facies appears to represent quieter water, fairweather deposits. Eventually bar migration ceased and reworking of the top took place. Abundant *Monocraterion* escape burrows in the reworked quartz arenite indicate rapid sand deposition. This was followed by bioturbation and deposition of the overlying shell bed.

The sequence, in the central part of the quarry exhibits broad similarities with sections through the centre of the Harthope Ganister sand bar which is considered to be of similar origin. Both show coarsening and thickening upward sequences of sandstone beds, overlain by a bioturbated reworked top, and marine band. Deposition of the Flinty Quarry sandstone, however, appears to have taken place in deeper water, possibly during a slight regressive phase.

(e) Relationship to the High Slate Sill in Dowgang Hush

Exposures in Dowgang Hush approximately 1 km. to the N./N.N.E. exhibit a thin (2-3 m. thick) sandstone at the same horizon (p.247). This consists of micaceous sandstones passing up into quartz arenites. These display parallel lamination, streaming lineation, and occasional small (5-6 cms. in diameter) star-shaped traces.

The thinning of the sandstone is in a general down palaeocurrent direction from Flinty Quarry. This together with the less mature nature of the sandstones in Dowgang Hush, and the lack of low angle bedding planes suggests deposition in deeper water forward of the bar front.

D. Park Burn quartz arenites

(i) Introduction

Park Burn is a right bank tributary of the River South Tyne, which flows through Park Village (NY 68656165). Two major developments of quartz arenites occur in the lower reaches of the stream at Lynnshield (NY 69556120) and Park village. Carruthers and Anderson (1943) suggest these are the same horizon; Trotter and Hollingworth (1932) indicate that they are 2 separate occurrences at different stratigraphic levels. This together with the diagreement between these authors in the naming of the limestone marker horizons present, means that the exact stratigraphic position of the 2 developments is in some doubt.

During the present study it became apparent that the 2 occurrences are different, and that the stratigraphy formulated by Trotter and Hollingworth (1932) was much better at explaining the observable facts. As a result it is used during the following analysis. Although the names they proposed for the limestones are unsatisfactory in the light of recent stratigraphical work e.g. Ramsbottom (1977b), as a full revision of the succession does not exist, the names are retained to avoid confusion.

(ii) Lynnshield quartz arenites

(a) Description

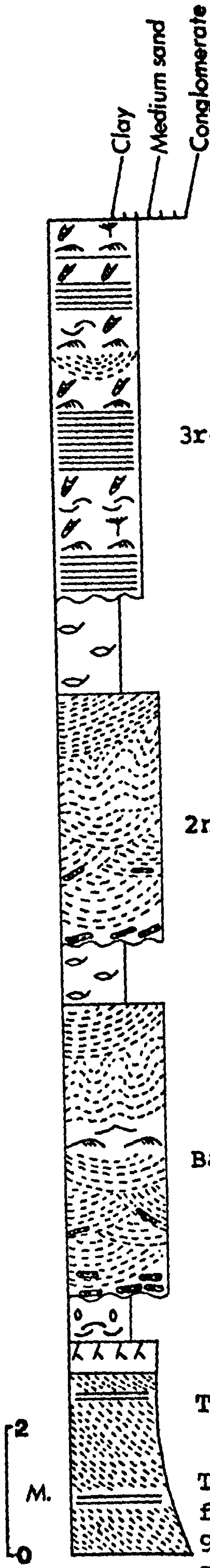
Exposures upstream from Lynnshield show a sequence containing 3 quartz arenites lying above the Thornborough Grit. These occur in the Thornborough Limestone cyclothem of Namurian, E_2, Arnsbergian age[1] (Ramsbottom, 1977b). The typical sequence seen in the stream is shown in Fig.90.

(1) Basal quartz arenite

This closely overlies the Thornborough Grit, and consists of an approximately 5 m. thick erosively based medium grained quartz arenite. This contains up to 98% quartz (Fig.67) dominantly as rounded, well sorted detrital grains. At the base the quartz arenite exhibits scours up to 1 m. or more in depth into the underlying strata. and contains abundant large driftwood fragments up to several metres long. The strata beneath the quartz arenite consist of a marine shale containing gastropods, bivalves, and ostracods overlying sandstones of the Thornborough Grit. Individual sandstone beds within the Basal quartz arenite are erosively based and lenticular in profile. Sedimentary structures are common and include trough cross-bedding, parallel lamination, convolute

1. The base of the Arnsbergian is normally taken at the base of the Lower Felltop Limestone, which according to Trotter and Hollingworth is the next limestone above the Thornborough. Recent correlations of the Thornborough Limestone with the higher limestones of the Alston Block suggest it is equivalent to the Lower or Upper Felltop, and thus of E_2 age (Ramsbottom, 1977b); Johnson, 1980). This means that the Lower and Upper Felltop Limestones of Trotter and Hollingworth (1932) are not equivalent to the 'type' Lower and Upper Felltop Limestones of the Alston Block (assuming that their identification of the Thornborough Limestone is correct).

MEASURED VERTICAL SECTION THROUGH STRATA OF THE THORNBOROUGH LIMESTONE CYCLOTHEM, LYNNSHIELD, PARK BURN



The Thornborough Limestone and overlying fossiliferous shales occur approximately 9m. below the base of this section in Park Burn.

Fig.90

lamination and wave, current and interference ripples. Occasional thin mud laminae and drapes to ripples are present, but are generally very lenticular due to erosion beneath the overlying sandstone. Plant debris and intraformational shale clasts are common throughout. Palaeocurrents from cross-beds are often difficult to measure due to distortion and production of convolute lamination but when undeformed show a S.S.W. trend.

(2) <u>2nd quartz arenite</u>

This forms a 4-5 m. thick horizon virtually identical with the underlying Basal quartz arenite. Commonly the 2 form a composite body up to 11 m. thick, but occasionally they are separated by a thin (approx. 1 m. thick) fossiliferous marine shale. The base of the quartz arenite is highly erosive and contains abundant large driftwood fragments (up to several metres long) and rare small vein quartz pebbles (Trotter and Hollingworth, 1932). Sedimentary structures, bed contacts, and palaeocurrents are identical with the Basal quartz arenite. Occasionally apparently massive beds up to 3 m. thick are present.

In the region of the waterfall in Park Burn (NY 70056108) this horizon dies away rapidly, being replaced laterally by a series of interbedded current ripple cross-laminated sandstones and shales containing occasional rootlet horizons. The actual junction is unexposed, but due to the close spatial association is likely to be abrupt rather than transitional (Fig.91).

(3) <u>3rd quartz arenite</u>

Overlying the 2nd quartz arenite and its laterally equivalent strata there is commonly a fossiliferous marine shale up to 1.5 m. thick. This is followed by the 3rd quartz arenite which consists of an approximately 6 m. thick erosively based sandstone. Petrographically this consists of a fine grained quartz arenite composed of subrounded, moderately well sorted quartz grains. Sericite and feldspar are present in appreciable amounts (Fig.67), and together with other features (grain size, bioturbation, fauna, etc.) distinguish this from the underlying horizons.

The quartz arenite consists of sharply or erosively based beds from a few cms. to a few 10's cms. thick with occasional interbedded shales. Individual sandstone beds display parallel lamination, trough cross-lamination, and trough cross-bedding with palaeocurrents towards the S.S.W. Bioturbation is common and includes *Muensteria*, *Pelecypodichnus* and star-shaped traces (described in detail later in this chapter) as well as a whole variety of other unidentifiable burrows. A fauna occurs, but appears to be restricted to bivalve shell fragments. These have undergone considerable post depositional dissolution and are impossible to identify. Plant debris is common throughout the sequence particularly at the base of sandstone beds.

(4) Relationship between quartz arenites

The lower 2 quartz arenites are as previously stated virtually identical, and often cannot be separated unless the intervening marine band is present. These occur in a series of undulating outcrops between Lynnshield and the waterfall.

South of the waterfall the 2nd quartz arenite is absent, and it is in this area that the 3rd quartz arenite reaches its maximum visible thickness. At NY 70106095 the marine band below the 3rd quartz arenite is absent due to erosion prior to deposition of the overlying sandstone. In this region interbedded sandstones and shales laterally equivalent to the 2nd quartz arenite display undulations and synsedimentary normal faults which are planed off beneath the 3rd quartz arenite (Figs.91 and 92). The main fault present strikes at 71°-251°, and has a downthrow of at least 2 m. to the N. Downstream from this point a similar relationship appears to hold with the 3rd quartz arenite forming a relatively flat horizon above the gently undulating lower strata (Fig.91).

(b) Diagenesis

This is similar for all 3 horizons and has consisted mainly of compaction, and cementation by interlocking quartz overgrowths. (Fig.93). Cementation of the 2 lower quartz arenites appears to have taken place fairly slowly due to their medium grain size, and consequent lower surface area/ volume ratio than comparable fine grained sands. Porosity in these horizons is still in the region of 14%. Stylolites are often present dominantly along bedding planes, and indicate late diagenetic dissolution of silica.

Other diagenetic features include the development of kaolinite pore fills, often in overgrowth lined pores, and the dissolution of shell material from the 3rd quartz arenite. Often moulds of shell material are preserved, indicating that dissolution of carbonate is post consolidation in origin.

(c) Interpretation

(1) Basal quartz arenite

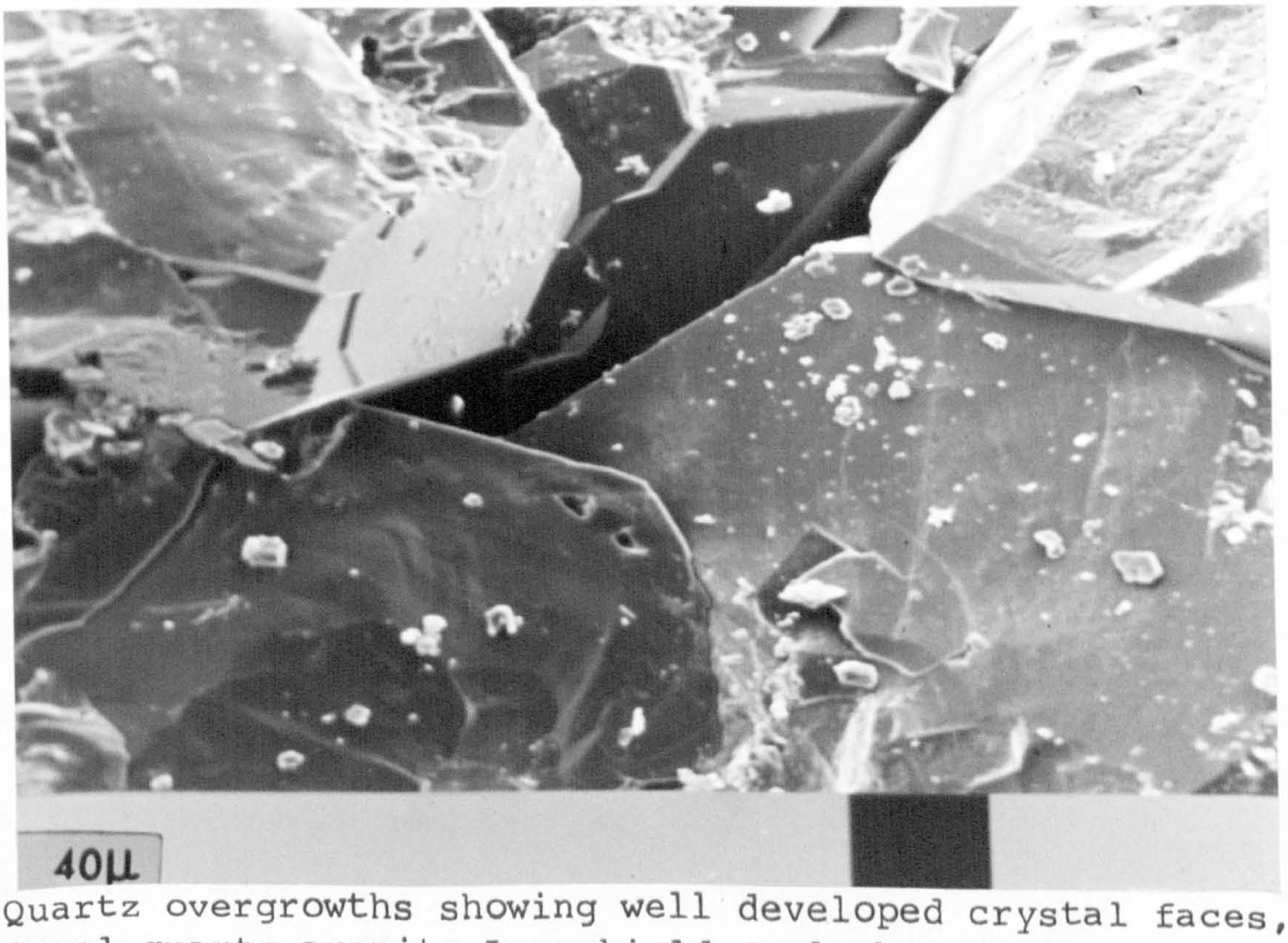
The mature, rounded, well sorted nature of the quartz arenite, its interbedded nature between 2 marine bands, and the lack of evidence of emergence suggests deposition in a

INTERPRETIVE SECTION THROUGH STRATA OF THE THORNBOROUGH LIMESTONE CYCLOTHEM, PARK BURN

Fig.91

Synsedimentary faults in Park Burn,truncated beneath the overlying 3rd quartz arenite(Q).Base of 3rd quartz arenite to stream level approximately 2.6m.

Fig.92



Quartz overgrowths showing well developed crystal faces, Basal quartz arenite,Lynnshield.Scale bar=40microns.

Fig.93

shallow-marine to nearshore environment. The lack of features indicating bar type topography (low angle bedding planes, draping foresets, etc.), together with the highly erosive base indicates deposition in a channel like topographic low.

The sequence preserved is broadly similar to tidal inlet fills along barrier coastlines (p.127). The deposit is ,however, thinner than most tidal inlet sands and lacks evidence of emergence at the top. These features do not appear to have arisen by erosion of the upper parts of an originally thicker sandstone sequence. This together with the lack of evidence of tidal activity suggests that a tidal inlet origin is not plausible.

The erosively based nature of beds, abundance of convolute lamination, and large driftwood fragments and the presence of interbedded shales indicate highly fluctuating energy levels, and rapid sand deposition. The periodicity of the fluctuations, and the powerful currents necessary, together with the foregoing evidence suggest a storm-dominated origin for the sandstone beds. Palaeocurrents are towards the S.S.W., which during deposition was in an offshore direction.

It is therefore suggested that sand deposition took place in a 'rip type' channel during major storm events. During fairweather periods this channel became abandoned and mud deposition occurred.

Modern rip channel systems are confined mainly to the nearshore zone. Seawards of the breaker zone rip currents are normally confined to the upper 3-5 m. of the water column. The deposits in the rip channels are erosively based sands

<3 m. thick, which display seaward dipping medium scale cross-bedding (Cooke, 1970; Davidson-Arnott and Greenwood, 1976; Hunter, Clifton and Phillips, 1979).

Deposition of the Basal quartz arenite appears to have taken place in deeper water than these nearshore rip channels, allowing mud deposition between storm events. Together with the larger current velocities necessary for its formation, and the thickness of the sandstone body, this suggests deposition in a larger scale, probably deeper water feature. Sand reworked in the nearshore zone was supplied to the channel during storm events. The scale of the channel required suggests that in a landward direction it may pass into a zone where water was funneled and stored during storm events, e.g. tidal inlet, coastal embayment.

Deposition is thus considered to have taken place in storm rip/surge channels broadly similar in origin to those envisaged by Brenner and Davies (1973) for coquinoid channel lag deposits. The lack of shell debris probably reflects a sand source originally low in this material, and post depositional leaching of carbonate.

(2) <u>2nd quartz arenite</u>

Due to its similarities with the Basal quartz arenite, a similar mode of origin is implied. The rapid termination of the quartz arenite in a down palaeocurrent direction suggests deposition at the end of a rip/surge channel. In the region of termination of the quartz arenite its top surface dips S. (Fig.91). This is partly due to compaction of the adjacent finer grained strata but also some topography on the sand body seems to have existed. This may reflect deposition in a terminal channel bar formed due to flow expansion.

The presence of an underlying marine shale, reflects a long period of quiet water sedimentation subsequent to deposition of the Basal quartz arenite. This may have been due to a decrease in storm activity or a small relative rise in sea level which brought the area outside the main zone affected by storm currents. Gradually these currents became reinstated and resulted in deposition of the 2nd quartz arenite.

Rootlet horizons in laterally equivalent strata do not appear to be contemporaneous deposits. Dips in these strata suggest that their present position is due to compaction and that originally they lay above the 2nd quartz arenite. Synsedimentary tectonics may have also aided in this respect.

(3) <u>3rd quartz arenite</u>

Prior to sedimentation of the 3rd quartz arenite and its underlying marine band, deposition of a series of interbedded shales and sandstones took place. Due to poor exposure, the exact depositional environment of these strata is unknown, but the presence of rootlet horizons suggest subaerial exposure.

Deposition of these strata was followed by a period of tectonic instability which produced gentle folds and small faults in the sediments. Visible synsedimentary faults trend and downthrow in exactly the same direction as the Stublick Fault approximately 2 kms. to the S. This is known to have been active during sedimentation (p. 59), and thus movements along this fault line are thought to have caused the synsedimentary tectonics visible in Park Burn. Topographic highs produced during this period appear to have been planed off by the transgression which preceded deposition of the overlying marine band. Locally this marine band was removed by subsequent erosion beneath the 3rd quartz arenite (Fig.91).

The fairly mature, moderately well sorted nature of the 3rd quartz arenite, together with the absence of features indicative of emergence, and the presence of abundant bioturbation and washed in shell debris suggests deposition in a shallow-marine environment. The presence of erosively based/sharply based sandstones and interbedded shales, and the lack of features indicative of tidal currents suggests a storm-dominated origin. The fairly laterally persistent nature of many sandstone beds, together with the offshore directed palaeocurrents indicate rapid deposition from unconfined storm-surge ebb-flows. During quiet water periods bioturbation and mud deposition took place.

Palaeocurrents are similar to the underlying quartz arenites suggesting that synsedimentary tectonics did not affect the regional palaeoslope for any appreciable length of time.

(iii) Park quartz arenite[1]

(a) Description

Exposures of the Park quartz arenite are limited to a small stream section in Park Burn (NY 68656175). At this locality it is very similar in appearance to the 2 lower quartz arenites of Lynnshield. This led Carruthers and Anderson (1943) to suggest they were all the same horizon. According to Trotter and Hollingworth (1932), the Park quartz arenite occurs in the Lower Felltop Limestone cyclothem of Namurian,

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1. Although this is not interpreted as a storm-dominated shallow-marine deposit, it is treated here owing to its similarities to the lower 2 Lynnshield quartz arenites, and to avoid repetition of the complex stratigraphy of this area (p.256).

E_2, Arnsbergian age (Hull, 1968), and is thus higher in the succession than the quartz arenites of Lynnshield.

In Park Burn the Park quartz arenite (Fig.67) consists of a 7.5 m. thick erosively based sandstone containing sub-rounded, moderately well sorted detrital quartz grains. This overlies shales and interbedded thin sandstones and consists of erosively based beds of trough cross-bedded sandstone up to 1 m. thick, interbedded with thin bioturbated muddy ripple cross-laminated sandstones. Driftwood fragments are common particularly at the base of beds. Convolute lamination is abundant, and comprises vertical displacements often affecting several beds. Distortion of cross-bedding and cross-lamination make palaeocurrent measurements impossible, but trough cross-beds often show a preferred N.-S. orientation. Clay content and bioturbation increases towards the top, and very occasionally rootlets are present in the uppermost few cms. Overlying the quartz arenite are a series of fine grained sandstones and shales beneath the Upper Felltop Limestone (Fig.94).

(b) Diagenesis

This is identical to the lower 2 quartz arenites from Lynnshield, except that cementation has often proceeded further, resulting in a greater porosity loss.

(c) Interpretation

The abundance and scale of the convolute lamination suggests widespread unstable conditions subsequent to sand deposition. Occasionally some horizons exhibit a brecciated appearance indicating that at least some lithification/cementation had occurred prior to sand movement. This together with the fact that several beds are often affected suggests that

MEASURED VERTICAL SECTION THROUGH THE PARK QUARTZ ARENITE AND ASSOCIATED STRATA, PARK BURN, PARK VILLAGE

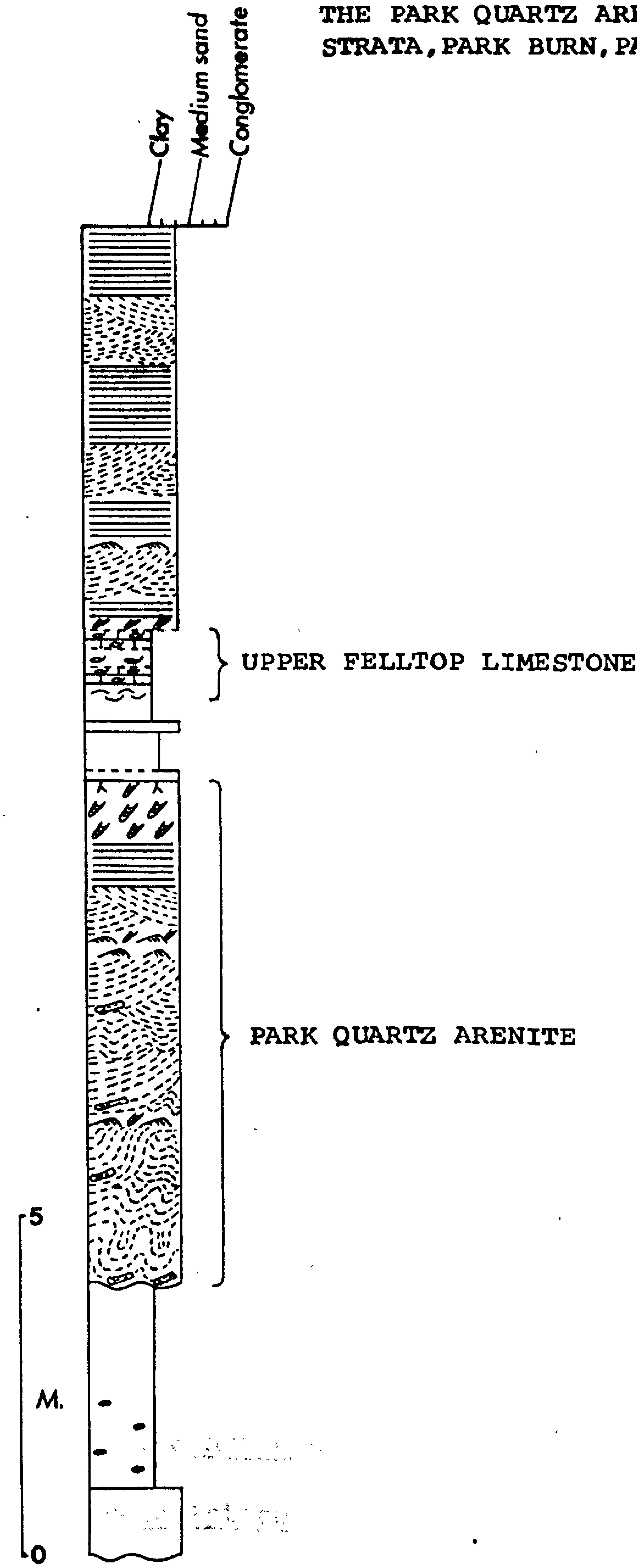


Fig.94

rapid sand deposition alone is not responsible. External tectonic movements, known to have been active in the area (p.266), were probably the main causative mechanism.

The occurrence of rootlets at the top of the quartz arenite is important as it indicates subaerial emergence. The lack of large scale synsedimentary tectonic structures e.g. faults at Park suggests that emergence was probably caused by sedimentation rather than tectonic uplift. The mature nature of the sandstone, its erosive base and the fining upward trend together with the presence of rootlets suggest deposition of the quartz arenite as a tidal inlet fill along a barrier island coastline (p.127). The highly erosive nature of beds and the presence of large driftwood dragments suggests that storm currents probably aided tidal currents in erosion and deposition.

Similarities between the Park quartz arenite and the 2 lower quartz arenites of Lynnshield suggest similar modes of origin. The dominant criteria for the 2 different interpretations is the presence or absence of rootlets. At Lynnshield their absence appears to be original rather than due to post depositional modification, thus indicating that the similarities between the quartz arenites are a result of similar depositional processes operating rather than identical depositional environments.

E. Dun Fell Sandstone

(i) Description

The Dun Fell Sandstone is confined to the Pennine scarp where it outcrops on the peaks of Cross Fell (893 m.), Great Dun Fell (847 m.) and Little Dun Fell (842 m.). Abundant loose sandstone blocks often mark the outcrop, but actual exposures are poor, and confined mainly to Cross Fell.

Stratigraphically the Dun Fell Sandstone lies approximately 28 m. above the Lower Felltop Limestone, and is of Namurian, E_2, Arnsbergian age. In Dun Fell Hush a coal approximately 9 m. below the base of the Dun Fell Sandstone has been correlated with the Coalcleugh Coal (Johnson, 1963; Burgess and Wadge, 1974). This suggests that the Dun Fell Sandstone lies in the Coalcleugh Marine Band cyclothem. The absence of the marine band above the coal, together with the fact that the true Coalcleugh Coal appears to die away S. of Weardale (p.240) casts some doubt on this correlation.

The Upper Felltop Limestone is not exposed on any of the above peaks but is thought to closely overlie the Dun Fell Sandstone (Johnson, 1963; Burgess and Wadge, 1974). This led Johnson (1963) to correlate the Dun Fell Sandstone with the Hipple Sill, which is a sandstone development in the Coalcleugh Marine Band cyclothem (p.209).

On Cross Fell, the Dun Fell Sandstone consists of an approximately 18 m. thick medium grained quartz arenite (Fig.67) containing rounded, moderately well sorted, quartz grains. Beds are sharply or erosively based, and range from a few 10's cms. up to approximately 2 m. thick. These display trough cross-bedding, parallel lamination and primary current lineation, with palaeocurrents directed northwards. Low angle depositional dips to the N. are commonly present, but in most cases appear to have been oversteepened by cambering downslope.

Bioturbation is common and includes abundant star-shaped traces at the top of beds (described in detail later in this chapter), and *Monocraterion* escape burrows. Fossils are rare, but include a complete and only slightly compressed internal mould of a regular echinoid, tentatively assigned to the Family Echinocystitidae (Figs. 95, 96 and 97).

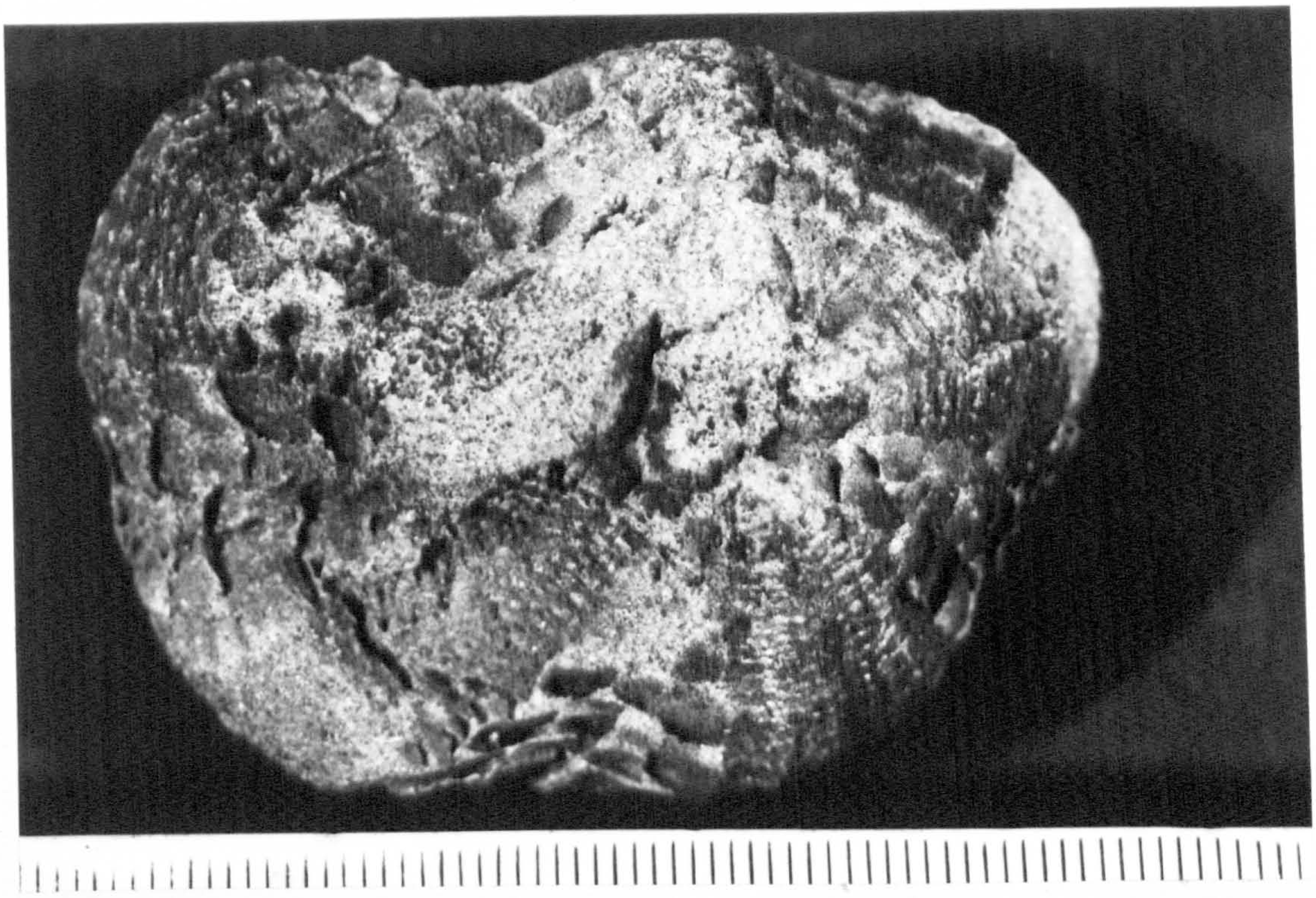
Occasionally large scale planar cross-bedding is present in sets up to several metres high. Foresets tend to drape over the edge of previously deposited sandstones, and increase in height down palaeocurrent (varying from N.W. to N.E.). The top of the sandstone body consists of a reworked iron stained zone up to a few 10's cms. thick. This is fairly friable due to dissolution of the original carbonate cement (probably siderite), and contains occasional crinoid ossicles.

(ii) Diagenesis

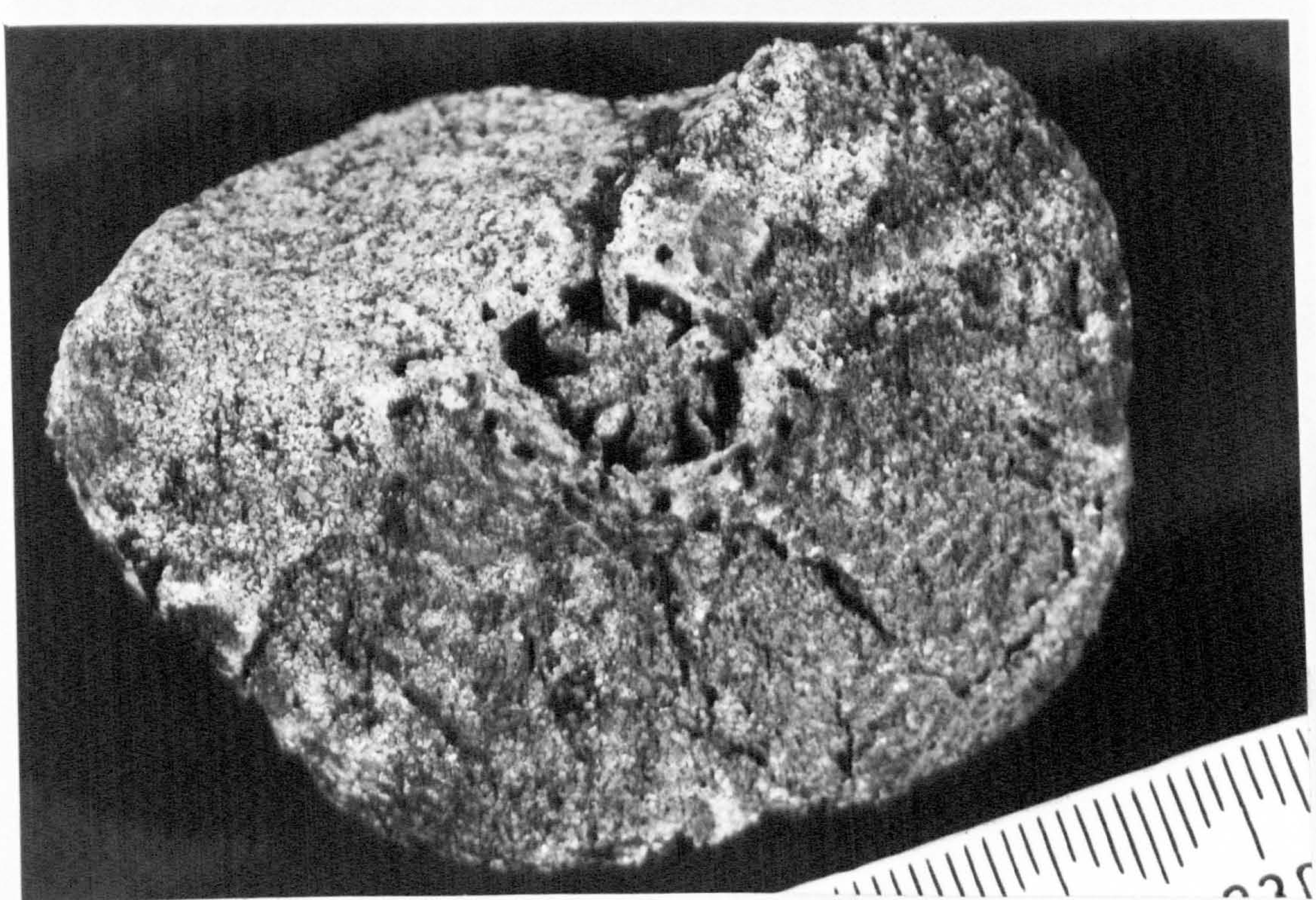
Like many of the previously described quartz arenites diagenesis has consisted mainly of compaction, and cementation by interlocking quartz overgrowths.

(iii) Interpretation

Due to the limited exposure a detailed interpretation of this horizon is impossible. It does, however, show many similarities with the previously described Harthope Ganister (p.205), both in bed contacts, bed thicknesses, sedimentary structures, trace fossils, and the presence of a reworked top. These features together with the unidirectional northerly palaeocurrents, the mature nature of the sandstone, and the presence of a very well preserved echinoid which undoubtedly has not been transported far, suggest deposition in a shallow-marine storm-dominated environment. The occurrence of draping

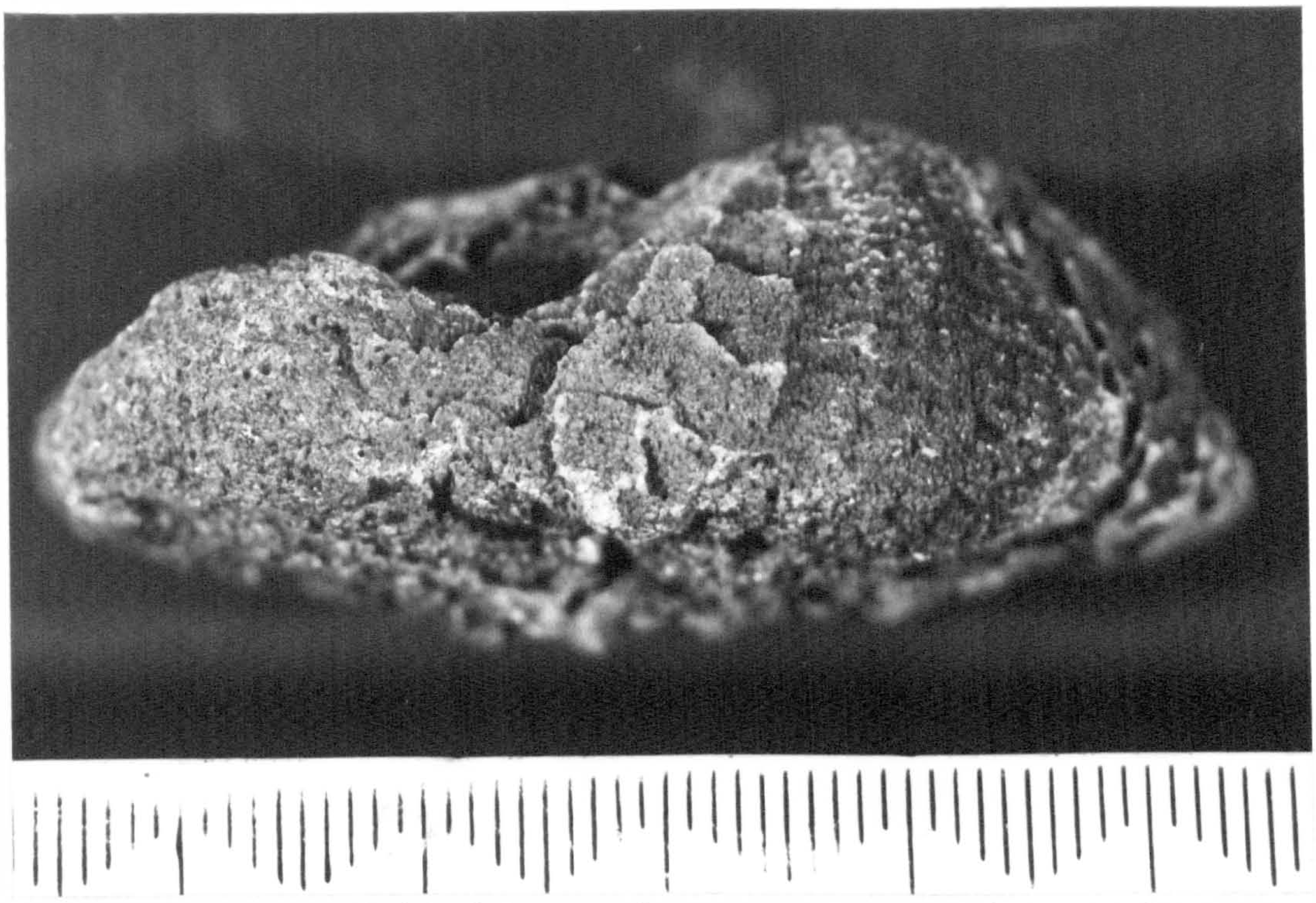


Slightly compressed internal mould of a regular echinoid tentatively assigned to the Family Echinocystitidae,Dun Fell Sandstone,Cross Fell.Aboral view showing the ambulacral and interambulacral areas.Scale divisions in mms. Fig.95



Oral view of above specimen showing the well preserved "Aristotle's lantern".Scale divisions in mms.

Fig.96



Side view of echinoid specimen.Scale divisions in mms.

Fig.97

Plan view of well developed star-shaped traces from a loose block of Harthope Ganister.Exposed portion of hammer 22cms. long.

Fig.98

foresets, indicates that during deposition the sand body formed a topographic high of at least several metres. Rapid deposition of the sharply based low angle sandstone beds appears to have taken place down the N./landward side of this feature during storm events.

The thickness of the Dun Fell Sandstone (approx. 18 m.) is much greater than the Harthope Ganister, and probably reflects deposition in an actively aggrading sand area rather than migration of a single bar form.

F. Star-shaped traces

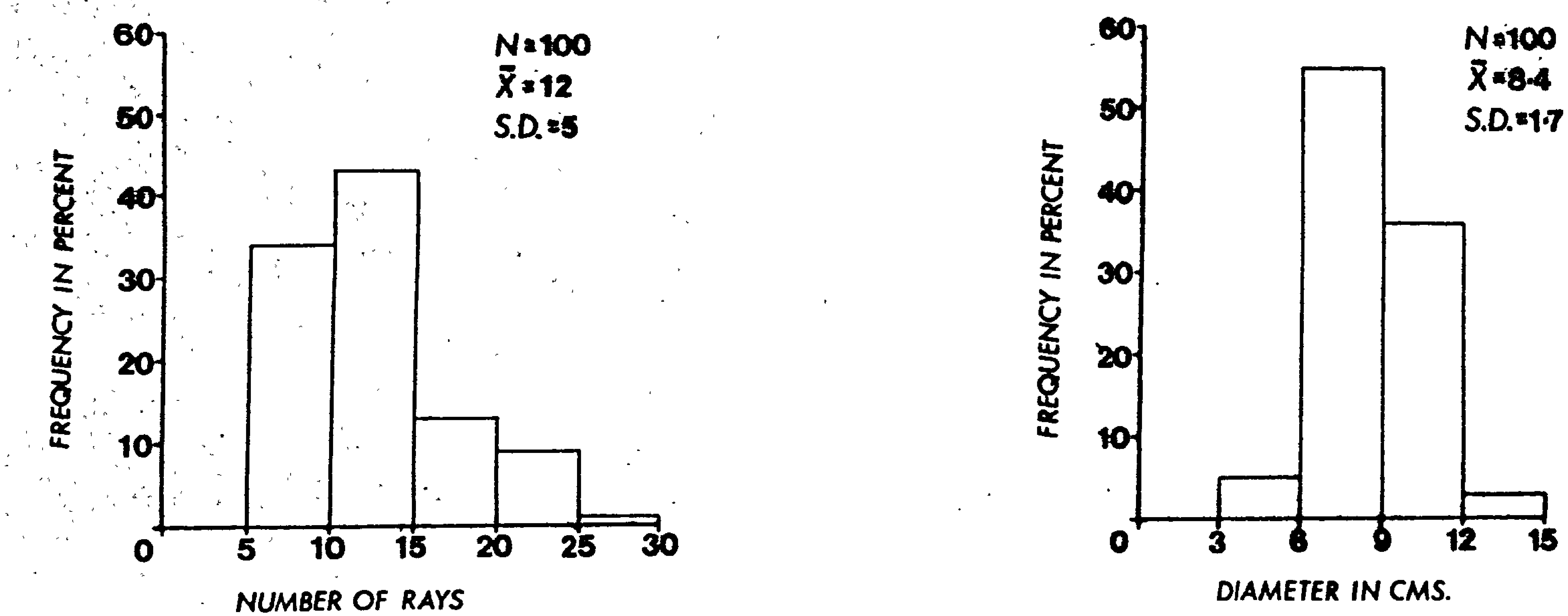
(i) Description

Star-shaped traces occur in all the previously described quartz arenites except the Park and lower 2 Lynnshield examples. They are also present in a fossiliferous quartz arenite from the Great Limestone cyclothem in High Flood Beck (NY 88303155), and from a fine grained sandstone overlying the Oakwood Coal in Dowgang Burn (NY 77604270). Both of these horizons are Namurian, E_1, Pendleian in age. Examples from all these localities are identical in appearance, but vary in abundance and size. Excellent specimens of this trace occur weathered out on bedding planes in the Harthope Ganister.

At Harthope the trace consists of concave epireliefs[1] up to 17 cms. in diameter (mean = 8.5 cms.) and 5.5cms. in depth (Figs. 98, 99 and 100). Internally individual epireliefs consists of a series of low angled inclined rays

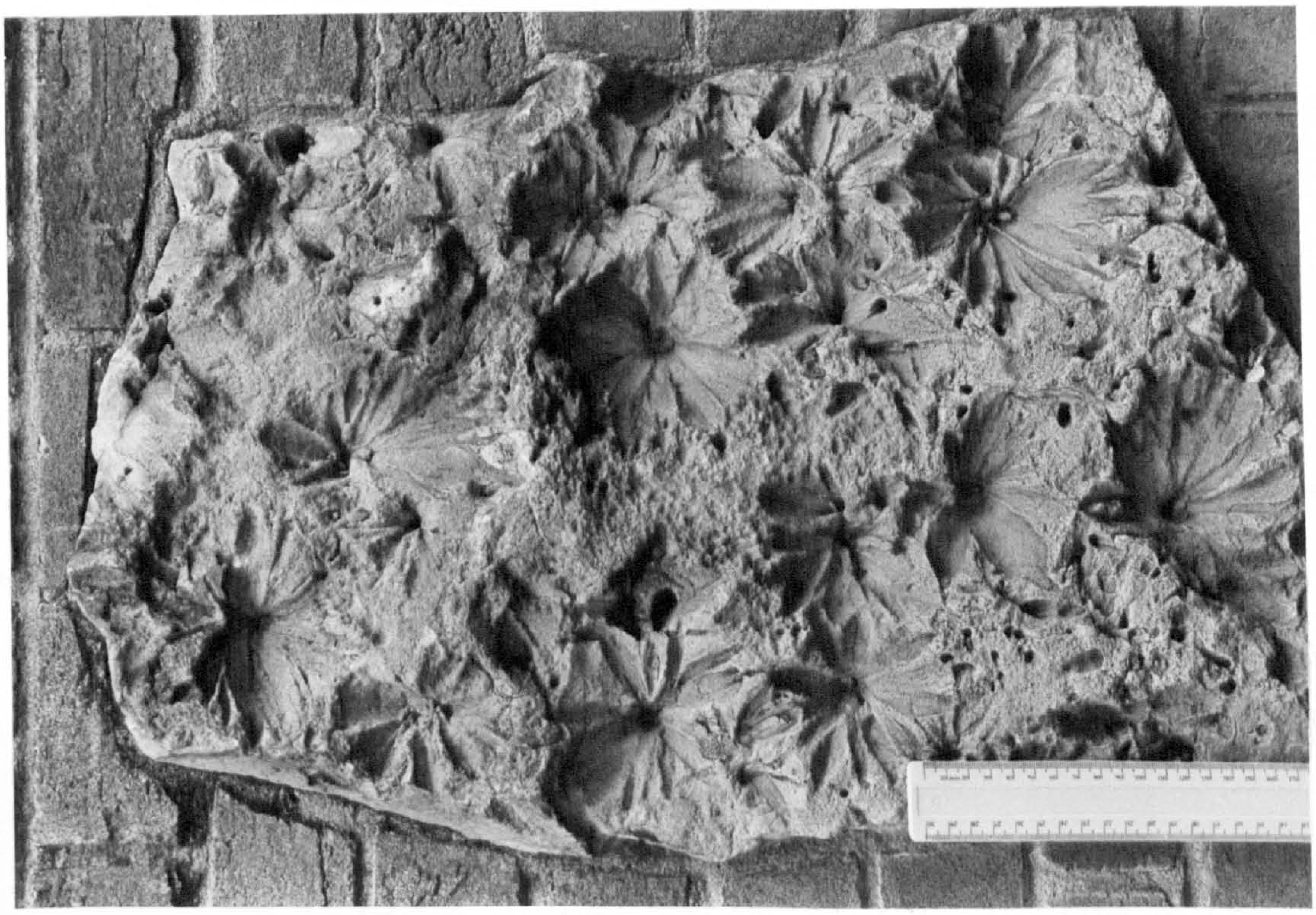
1. Occasionally the star-shaped traces occur as convex hyporeliefs. These represent infillings of concave epireliefs by an overlying sandstone bed.

STATISTICAL ANALYSIS OF 100 STAR-SHAPED TRACES FROM A SINGLE BEDDING PLANE IN THE THINLY BEDDED FACIES OF THE HARTHOPE GANISTER



S.D.=STANDARD DEVIATION

Fig.99



Block of Harthope Ganister showing well developed star-shaped traces consisting of a series of inclined rays arranged radially around a central depression.Exposed portion of block 56cms.long.

Fig.100

Vertical section through a star-shaped trace from the Thinly Bedded Facies of the Harthope Ganister,showing the underlying subvertical tube.Left hand margin of rule is in cms.

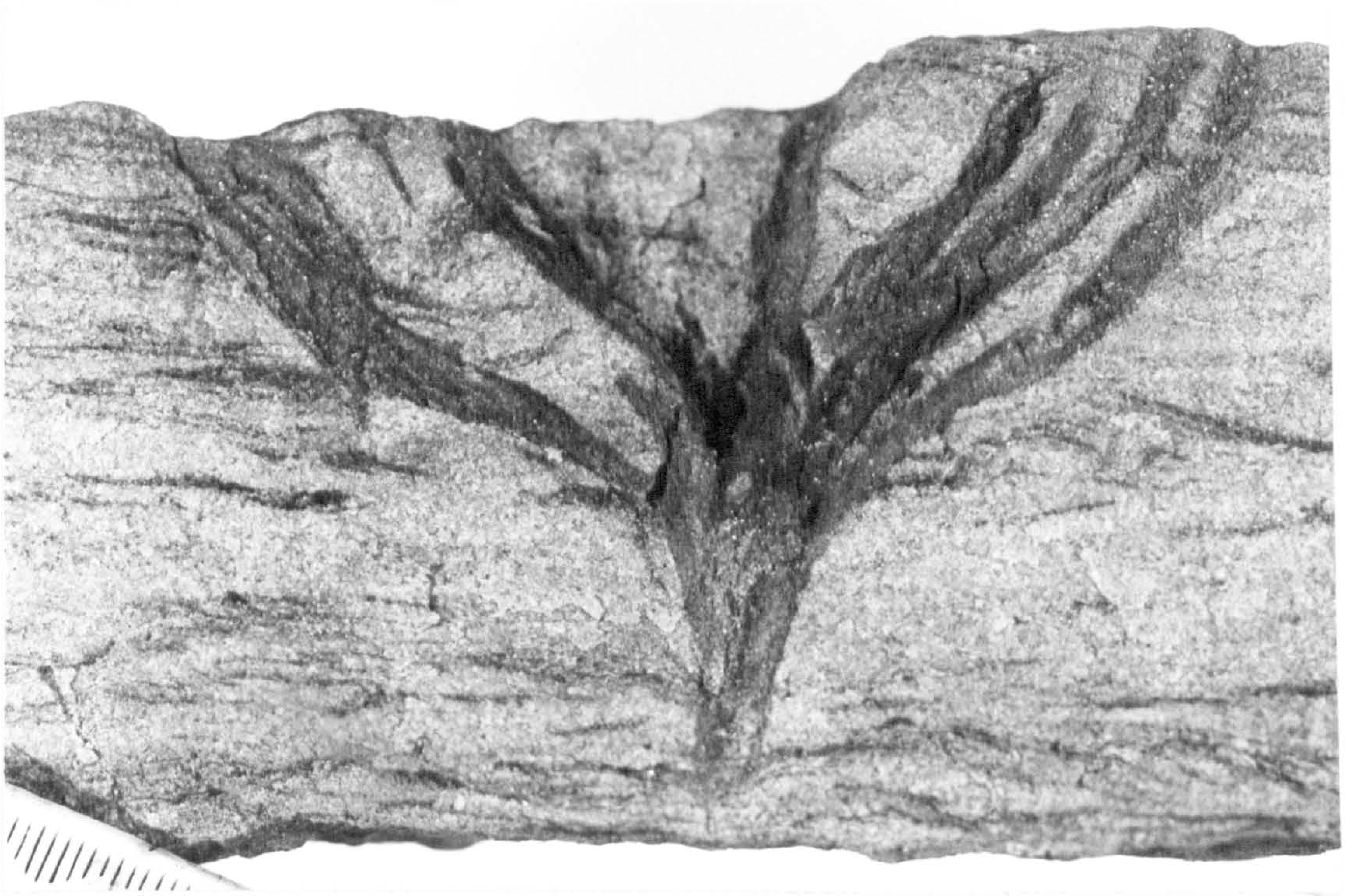
Fig.101

arranged radially (occasionally slightly curved around a central depression (generally < 2 cms. in diameter). The rays are parallel sided slightly ovate or lozenge shaped depressions several mms.-2 cms. wide, separated by small ridges. The number present varies, but may be up to 28. (Fig.99). At the centre of the epirelief these merge together in the central depression which passes down into a single vertical or J-shaped tube (Figs.101 and 102). This tube is a long slender structure approximately 2 mms. wide. Generally it is <20 cms. long but may rarely reach 35 cms. Where the star-shaped trace is absent this tube could easily be mistaken for *Skolithos*.

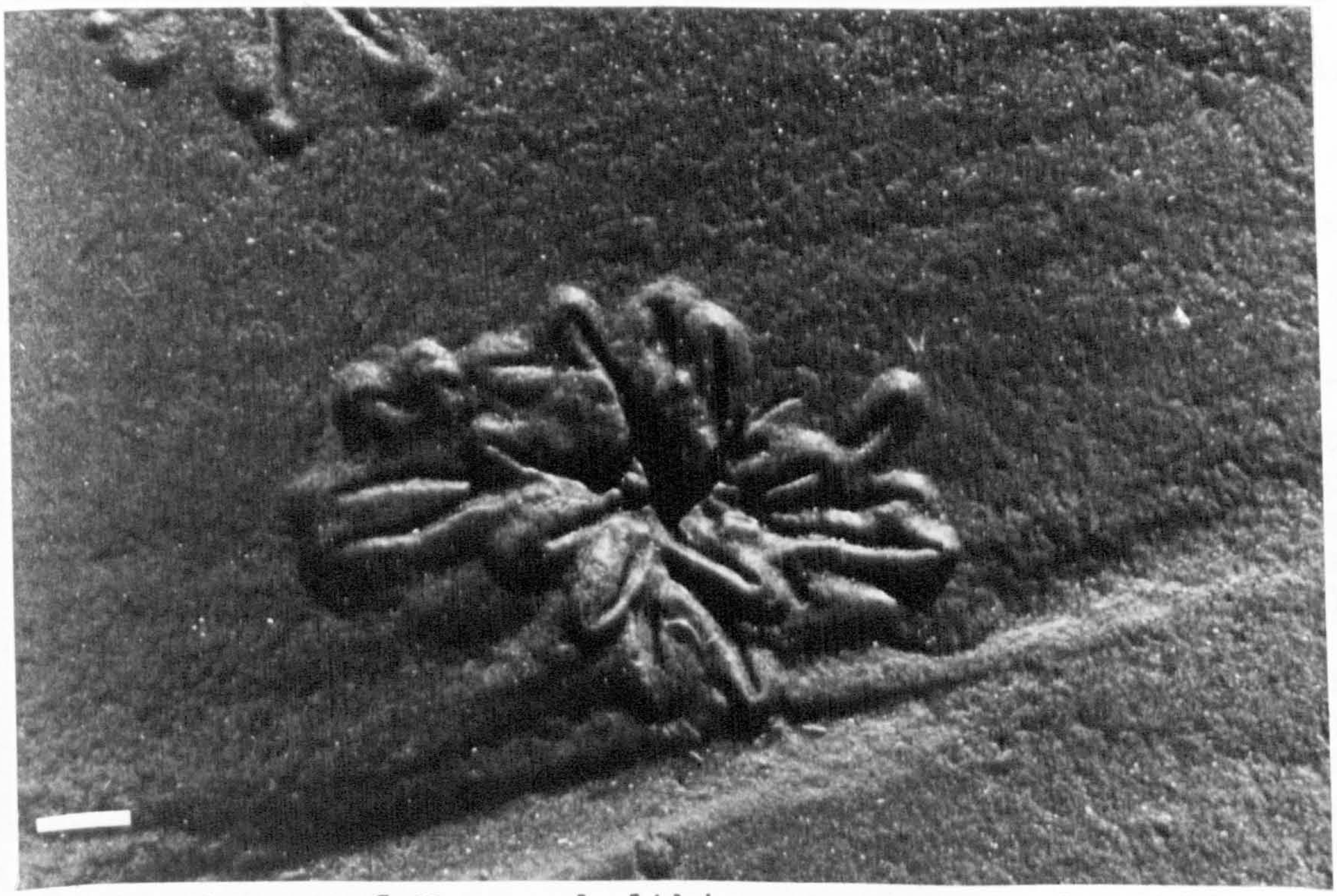
On bedding planes every variation from a few circularly arranged small holes up to well developed star-shaped traces are present. Often traces are preferentially developed on certain areas of the bedding planes where they may occur in concentrations of over 90 per $m.^2$

Sections through unweathered traces often show the rays to consist of inclined tubes of dark carbonaceous rich material (Fig.102). Occasionally these contain small concentric spreiten at their topmost ends and laminae parallel to their walls.

Star-shaped traces from Flinty Quarry, Dowgang Burn, and High Flood Beck tend to be larger than the Harthope specimens (up to 20.5 cms. in diameter) and more sparsely distributed. Associated trace fossils from all the localities include *Arenicolites*, *Aulichnites*, *Cochlichnus*, *Monocraterion*, *Muensteria*, and a variety of surface feeding traces. At several localities marine fossils occur associated with the star-shaped traces.



Vertical section through the top of an unweathered star-shaped trace from the base of the Harthope Ganister,showing the rays consisting of inclined tubes of dark carbonaceous rich material.Occasionally the rays exhibit laminae subparallel to their walls.Scale divisions in mms. Fig.102



Feeding trace of <u>Macoma balthica</u> exposed at low tide.Scale bar 1cm. After Risk and Moffat(1977).

Fig.103

(ii) Classification

A wide variety of star-shaped traces have been described in the literature (Grubić, 1970; Häntzschel, 1970). These have been classified by Häntzschel (1975) into various genera. The described specimens exhibit similarities with several of these genera, particularly *Asterosoma*, but differ in detail.[1] As a result at the present time these traces must remain unnamed.

(iii) Interpretation

Modern star-shaped traces are produced by a wide variety of organisms e.g. crabs, holothurians, medusae, molluscs, starfish. Large examples (several cms. plus in diameter) with a descending central tube are more restricted in their mode of origin, and appear to be formed by the feeding activity of either worms (particularly polychaetes) or bivalves. Modern star-shaped traces produced by the feeding activity of worms are often irregular, and consist of meandriform and or branching rays e.g. Okahada, Ohta and Niitsuma (1980); Shäfer (1972). Regular examples do occur, but are generally faint surficial features.

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1. *Asterosoma radiciforme* exhibits similarities with the described star-shaped traces, but commonly occurs preserved as convex hyporeliefs. Individual rays contain longitudinal wrinkles, and occasionally have smaller branches fanning from the end (Chamberlain, 1971, 1978; Hantzschel, 1975). Internally retrusive spreiten are common and indicate upward oblique or vertical migration (Chamberlain, 1971). The described star-shaped traces lack many of these features and appear to have formed associated with the sediment surface rather than as burrows within the sediment as with some examples of *A. radiciforme* (Chamberlain, 1971).

Star-shaped bivalve feeding traces are generally regular in outline with straight rays. These are formed principally by deep burrowing deposit feeding bivalves with long extensile siphons such as members of the Tellinacea. (Figs. 104 and 105). The star-shaped traces described show many similarities with the later type, and a similar mode of origin is thus invoked.

Modern star-shaped traces produced by the Tellinacea include those of *Macoma balthica* and *Scrobicularia plana* (Figs. 103, 106 and 107). The latter lives in muddy inter-tidal sediments around the British Isles (Tebble, 1976). During low tide the animal burrows to a depth of 15-20 cms., but as the tide comes in it moves up close to the surface, and begins to feed (Street, 1961) (Fig.105). The inhalent siphon is pushed out onto the sediment surface where it moves outwards sucking in sediment. Repetition of this event in a radial pattern results in a star-shaped trace around the central burrow (Fig.105). Modern examples on the intertidal flats of the Solway Firth are up to 15 cms. in diameter (average 6-10 cms.) and consist of up to 12 or more rays. The length of the bivalve producing the trace is generally <5 cms.

Due to the deep burrowing habit of the Tellinacea, protection is not required from the shell, and as a result this tends to be very thin. Fossil Tellinacea are known only as far back as the Upper Triassic (Moore, 1969). Feeding on deposited organic matter was a habit of the earliest bi-valves (Purchon, 1968). It is therefore quite conceivable that some may have developed a burrowing, and deposit feeding mode of life prior to the evolution of the Tellinacea s.s.

LIFE POSITION OF TELLINA SQUALIDA

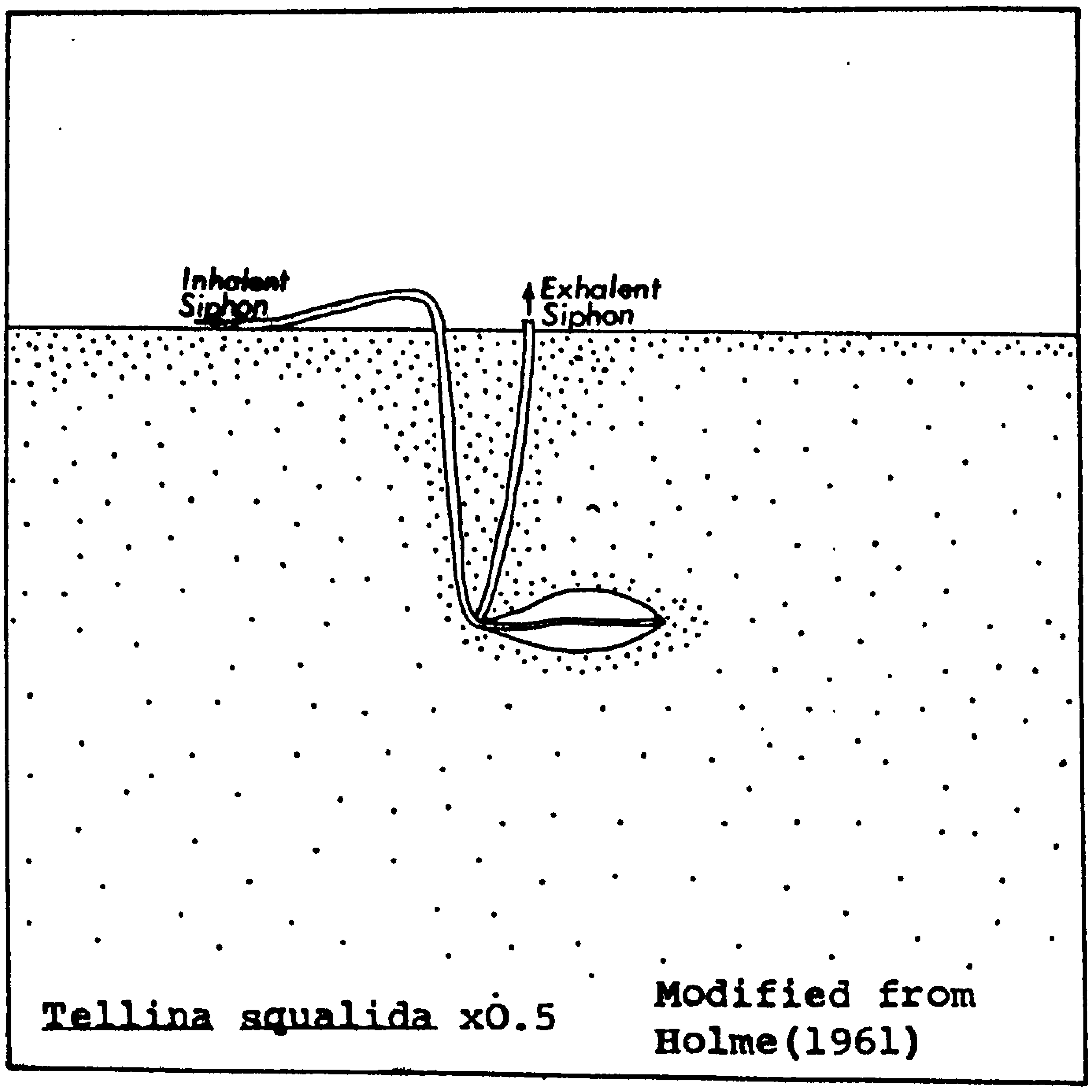


Fig.104

FEEDING POSITION OF SCROBICULARIA PLANA

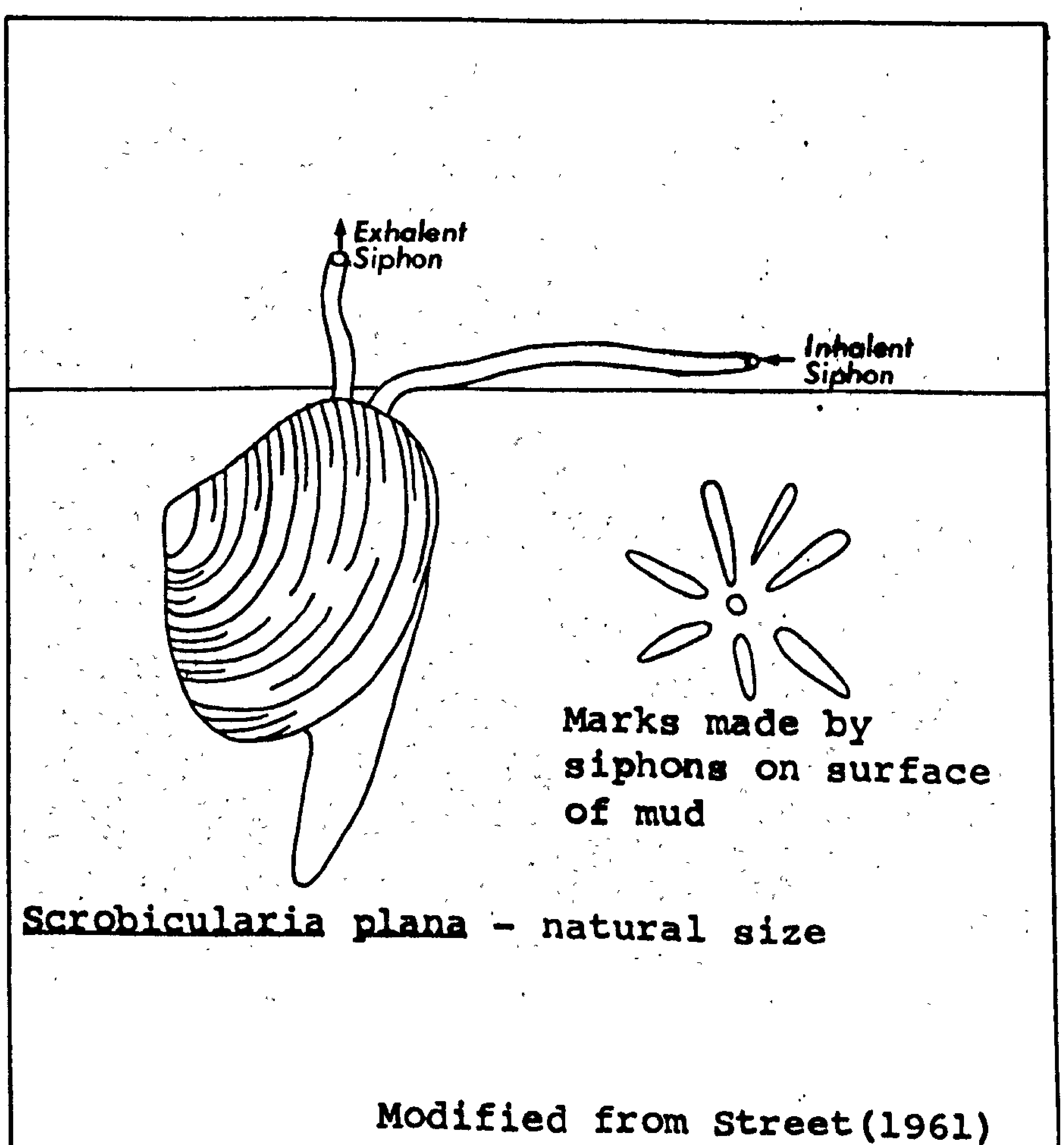
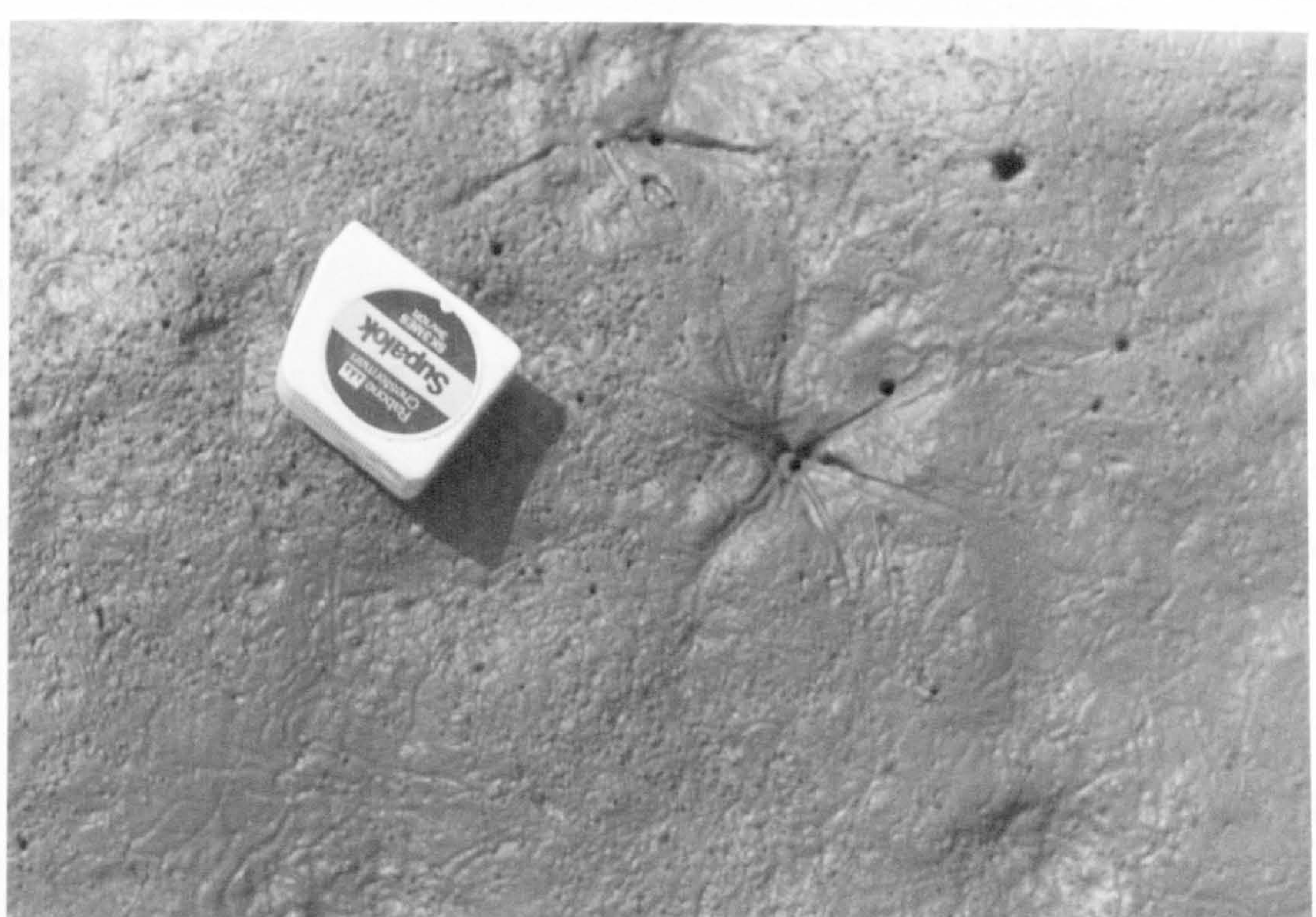


Fig.105

Feeding traces of Scrobicularia plana exposed at low tide in the Solway Firth. The sediment consists of a very fine grained muddy sand. Length of pen 14cms.

Fig.106



Close up view of a single Scrobicularia plana feeding trace showing the central hole into which the siphon has retracted. Top right hand edge of tape measure holder is 6.5cms.long.

Fig.107

Alternatively the absence of pre-Upper Triassic burrowing, and deposit feeding bivalves may be due to the lack of recognition of earlier members of the Tellinacea lineage. Poor preservation due to their thin shelled nature, may be of some importance in this respect.

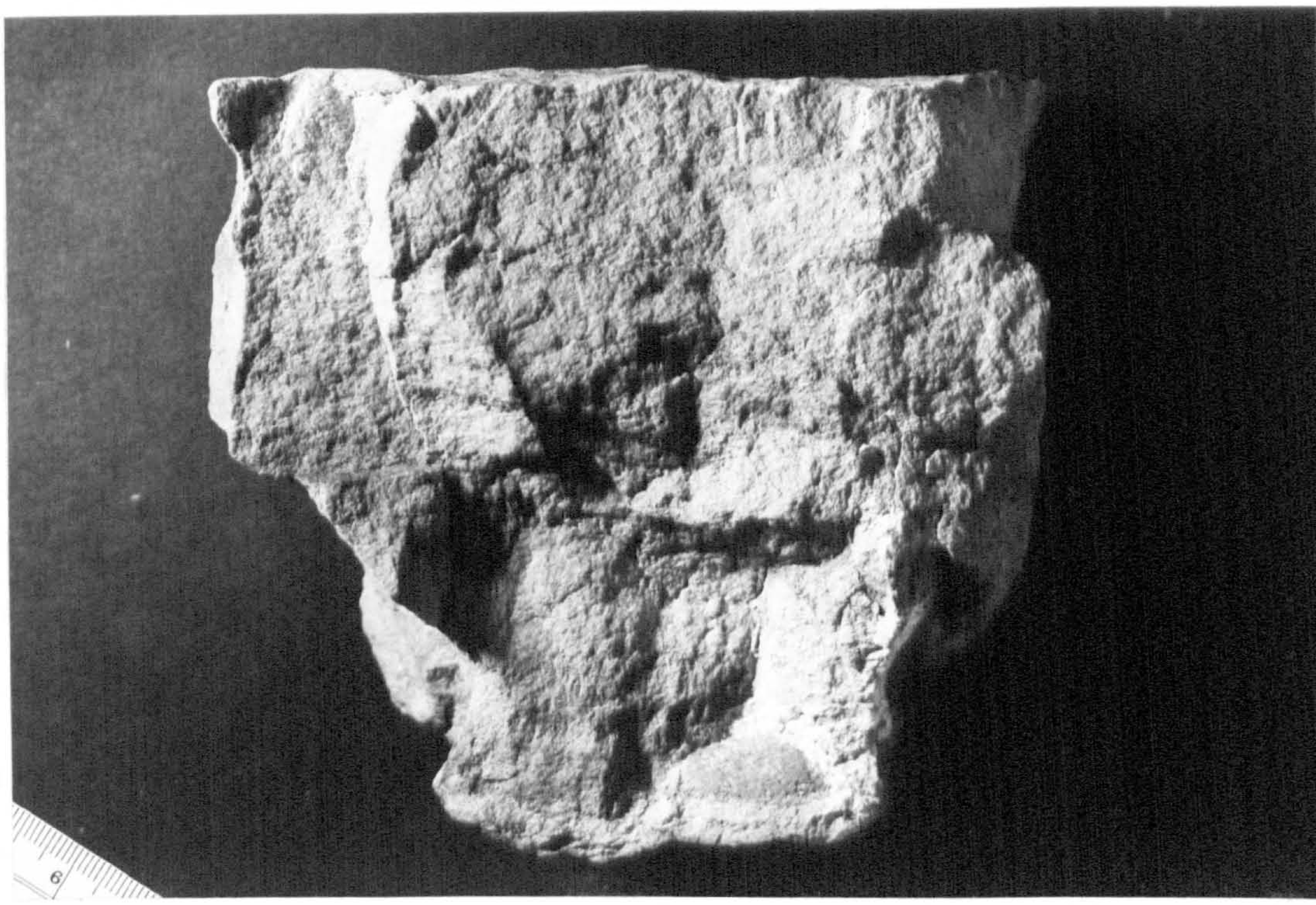
It is therefore suggested that the star-shaped traces were produced by deposit feeding, deep burrowing bivalves similar to modern members of the Tellinacea. These generally burrowed to depths of up to 20 cms., and maintained contact with the sediment surface through their long extensile inhalent siphons. The absence of fossil faeces associated with the traces may be due to their low preservation potential. Alternatively the exhalent siphon may have lain below the surface discharging into the surrounding porous sand (Yonge, 1949).

Unlike most modern examples, some of the traces formed just below the surface, and not as surficial markings. The presence of discrete tubular shaped rays to these traces suggests that the inhalent siphon was repeatedly pushed up onto the surface in a different position. Commonly this took place along a circular path above the bivalve to cover the maximum sediment surface area. Small spreiten at the ends of these rays, and laminations parallel to the walls indicate repeated longitudinal and sideways movement of the siphon.

Broad shallow traces such as those at Flinty Quarry probably formed as surficial traces by movement of the inhalent siphon across the surface. The presence of both trace types in the same deposit probably reflects changes in feeding habits due to changes in external conditions rather than formation by different organisms. Rare deep (up to 35 cms.) vertical tubes beneath the traces are too long to represent the length of the inhalent siphon. These may result from the siphon having been dragged down through the sand as the bivalve burrowed deeply for protection.

The excellent development of the traces relative to modern intertidal examples suggests they formed over a longer time period. In modern examples once the area covered by the inhalent siphon becomes depleted in organic matter the bivalve is forced to move sideways through the sand to a new position (Shâfer, 1972). In the above examples the absence of associated large horizontal burrows, together with the longer time period over which the trace appears to have formed suggests that sideways movement was relatively infrequent. The patchy distribution of the traces on some bedding planes may reflect the distribution of favourable sites for burrowing and deposit feeding, or insufficient time for complete colonization.

From 3 of the 6 horizons which contain star-shaped traces, small (<3 cms.) unidentified thin shelled bivalves have been collected, generally from washed in shell lags (Fig.71). These are evidently burrowing forms from their shape, and permanent posterior gape, and show broad similarities to the Tellinacea. Although a specimen has never been found connected with a star-shaped trace, in the Harthope Ganister an example was found at the base of a thin sandstone which contained abundant star-shaped traces in the top few cms. The specimen was lying in its apparent life position (Figs.108 and 109 (Holme, 1961). It is therefore suggested that this



Unidentified thin shelled bivalve in its apparent life position at the base of a sandstone bed from the Thinly Bedded Facies. In the field this sandstone bed contains abundant star-shaped traces in the top few cms. Scale divisions in mms.

Fig.108

Close up view of the unidentified thin shelled bivalve in Fig.108 . Scale divisions in mms.

Fig.109

bivalve is an example of the organisms which produced the star-shaped traces.

The occurrence of dominantly small individuals of this species in the washed in shell lags probably results from smaller juvenile forms being both more abundant in the population, and unable to burrow deeply. They are thus more numerous and more prone to erosion than larger deeply buried forms. Often the larger star-shaped traces are more widely spaced than smaller examples. This probably arises from fewer numbers of large individuals having been present, and that adult animals generally live at greater distances from each other (Reineck and Singh, 1973).

On the tidal flats of the Solway Firth, the ratio between the size of specimens of *Scrobicularia plana*, and the size of the star-shaped trace they produce is roughly 1:3. It is therefore possible that the largest fossil star-shaped trace seen in the Namurian quartz arenites was formed by a bivalve <7 cms. in length.

Lack of bivalves associated with the fossil traces is largely due to post-depositional solution of shell material. The thin-shelled nature of the bivalves, and the porous sandy nature of the host sediment could have resulted in this proceeding very rapidly.

(iv) Environmental significance

Most of the previously described examples of star-shaped traces in the Northern Pennines occur in Namurian (E_1 and E_2) quartz arenites interpreted to be of storm-dominated shallow-marine origin. Formation of these deposits consisted of episodes of rapid sand emplacement interspersed with periods of quiet water fine grained sedimentation. Colonization and bioturbation, particularly by deposit feeding organisms took place during these latter periods. Subsequent rapid sand emplacement often resulted in complete preservation of previously formed surface traces in low lying areas. The storm-dominated shallow-marine environment was thus ideal for the formation and preservation of star-shaped traces.

Other shallow-marine to shoreline environments evidently did not provide such conducive conditions for preservation. As a result, although star-shaped traces undoubtedly occur in Namurian shallow-marine to shoreline sandstones which were not deposited in a storm-dominated environment, such occurrences appear to be relatively uncommon.

G. Conclusions

Carboniferous storm-dominated shallow-marine deposition in the Northern Pennines appears to have reached its peak during E_1 and E_2 Namurian times. This resulted in deposition of a wide variety of dominantly thin quartz arenites often containing star-shaped traces.

Deposition of the Harthope Ganister and Flinty Quarry sandstone appears to have taken place from discrete migrating bars. These deposits often display coarsening and thickening upward sequences in their central portions and are overlain by a reworked top and associated marine band. The mode of formation of these bars is unknown, but it is quite possible that they were originally produced in an environment different to that in which their final migration took place.

Migration of these forms during storms occurred primarily by an overwash type process. This gave rise to the low angle bedding planes, each of which represents an old bar surface. When completely preserved the height difference between the top and the bottom of these bedding planes will give the approximate height of the original bar form. Often, however, these surfaces are truncated at their tops due to erosion of the 'upcurrent' bar flank, and/or erosion concomitant with bar abandonment. Recycling of sand due to bar migration, together with reworking predominantly on the 'upcurrent' bar flank resulted in the mature, quartzose nature of the deposits. The Dun Fell Sandstone appears to have been deposited under broadly similar conditions, but probably in an actively aggrading sand area. This resulted in a thicker and more complicated sequence.

The 2 lower Lynnshield quartz arenites form thin erosively based units interbedded with marine shales. These appear to have been deposited by offshore directed storm rip/surge currents. The mature nature of the sandstones is probably a product of continual reworking in the nearshore/shoreline zone. The Park quartz arenite is interpreted as a shoreline sand and probably reflects the type of sediment available for movement offshore.

The 3rd Lynnshield quartz arenite was similarly derived by storm erosion of the nearshore/shoreline zone. The less mature nature of this deposit may reflect erosion from a less mature source, but is at least in part due to bioturbation having incorporated finer grained sediment into the sandstones.

CHAPTER SEVEN

QUARTZ ARENITES AND 'GANISTERS' OF DOUBTFUL ORIGIN

A. Introduction

This chapter concerns a variety of horizons, all of which have been termed ganister, or worked for ganister. Most are poorly exposed, and determination of their mode of origin is often impossible, though they are believed to be of diverse origins. Each horizon is described, and a broad environmental interpretation is attempted.

Stratigraphically they range in age from Brigantian to Westphalian A, and include several horizons which were once major sources of refractory materials in N.E. England. Due to their diverse origins, these horizons are treated in stratigraphical order beginning with the oldest.

B. Topmost sandstone of the Peghorn Limestone cyclothem, East Cowgreen

(i) Description

A sandstone lying beneath the Smiddy Limestone of Brigantian age, was worked for refractory material on a limited scale at East Cowgreen (NY 81753095), (Dunham, 1948). At the present time approximately 3 m. of sandstone overlain directly by the Smiddy Limestone is exposed at this locality. This sandstone consists of a medium grained quartz arenite (Fig.110) containing rounded, moderately well sorted detrital grains. Sandstone beds display trough cross-bedding and parallel lamination and occur interbedded with occasional

POINT COUNT ANALYSES OF QUARTZ ARENITES AND 'GANISTERS' OF DOUBTFUL ORIGIN

HORIZON	QUARTZ %	MIXED LAYER CLAY/SERICITE %	KAOLINITE %	FELDSPAR %	MUSCOVITE %	CARBONACEOUS MATERIAL %	HEAVY MINERALS %	GOETHITE %	CHLORITE %	N
TOPMOST SANDSTONE OF THE PEGHORN LIMESTONE CYCLOTHEM	91.5	7		0.5	0.5			0.5		200 [1]
SMIDDY GANISTER, SWINDALE BECK	95.5	3	0.5		0.5	0.5				200 [1]
MIRK FELL GANISTER, SIDE GILL	97.5	0.5	0.5			1.5				200 [1]
KETTLEPOT GANISTER, SIDE GILL	86.5	11.5	1	0.5					0.5	200 [1]
CROSS GANISTER, EDMUNDBYERS CROSS	95.5	1.5			0.5			2.5		200 [1]
WEST BUTSFIELD GANISTER	97.25	0.5	1.75				0.5			400 [2]
LOWER KNITSLEY FELL GANISTER	95.5		1.5			2.5	0.5			200 [1]
TOW LAW GANISTER, BLACK BURN	99					0.5		0.5		200 [1]
UPPER KNITSLEY FELL GANISTER, IRON RICH ZONE	70.5	1						28.5		200 [1]
UPPER KNITSLEY FELL GANISTER	95	1					1	3		300 [1]

N=Total number of point count measurements(number in top right hand corner refers to the number of thin sections analysed)

Fig.110

thin (< 5 cms. thick) shale laminae. Palaeocurrents from trough cross-bedding are fairly unidirectional (vector magnitude = 92%) and indicate palaeoflow towards 33°. Large *Stigmaria sp.* and associated rootlets are commonly present at the top of the sandstone. Occasionally these are absent, probably due to reworking prior to deposition of the overlying Smiddy Limestone.

At Cow Green (NY 81053070) a similar sequence is seen, with approximately 2.5 m. of quartz arenite overlain by 28 cms. of sandy shale beneath the Smiddy Limestone.

(ii) Diagenesis

Cementation has been effected by the development of interlocking quartz overgrowths. Often pore filling sericite is present in appreciable amounts (Fig.110). Pores are occasionally too large to be intergranular features, and probably formed by the breakdown of feldspar which might have also liberated the required sericite.

(iii) Interpretation

The mature nature of the sandstone, together with the presence of sedimentary structures and roots suggests deposition in a high energy shallow water/emergent environment. In many respects the sandstone is similar to the top of the erosively based quartz arenites of the Low and High Brig Hazles which are interpreted as tidal inlet fills along a barrier island coastline(pp.150,172).This in association with palaeocurrents towards the N.E./N.N.E. in a direction opposed to the regional palaeoslope suggests that the exposed sandstone represents a flood-dominated intertidal sand body. Whether this formed as part of a barrier island complex remains unknown.

C. Smiddy Ganister[1]

(i) Description

The term Smiddy Ganister was introduced by Johnson (1963) for a thick (up to approximately 15 m.) sandstone at the top of the Smiddy Limestone cyclothem exposed along the Pennine Scarp. In Swindale Beck (NY 70752875) the Smiddy Ganister consists of a 13.6 m. thick fine grained quartz arenite (Fig.110) containing subrounded, moderately well sorted quartz grains. This erosively overlies shales, and often the basal few cms. to few 10's cms. of the sandstone body are slightly coarser grained. Individual beds are erosively based, up to 2m. thick, and commonly display planar and trough cross-bedding with palaeocurrents towards the E. (vector mean = 98°). Plant debris and intraformational shale clasts are common, and occasional thin interbedded shales are present. Bioturbation is uncommon, and consists mainly of obscure horizontal burrows.

In the top few 10's cms. the scale of sets of cross-stratification decreases rapidly, trough cross-lamination becomes abundant, and occasional rootlets are present. Overlying the Smiddy Ganister are a series of silty shales, followed by a sandstone beneath the Lower Little Limestone. These shales are thought to be equivalent to the Grain Beck Limestone (Burgess and Holliday, 1979).

Towards the E. the Smiddy Ganister thins, being only 7.5 m. thick in the Tees Valley (Johnson, 1963). Further to the E. at Rotten Row (NY 82153370) this horizon is represented by approximately 2.5 m. of fine grained sandstones overlying

1. This is entirely sedimentary in origin and thus not a true ganister (p. 5). The term simply refers to the quartz arenitic nature of the sandstone at the type locality along the Pennine Scarp.

fossiliferous shales. These sandstones contain trough cross-bedding, reactivation surfaces and wave ripples, and are penetrated by rootlets at the top.

(ii) Diagenesis

Compaction and cementation by interlocking quartz overgrowths have been the main diagenetic events. Stylolites are occasionally present and suggest late diagenetic pressure solution of quartz.

(iii) Interpretation

The erosive base, fining upward trend, decrease upward in the scale of cross-stratification, unidirectional palaeocurrents, and rootlet penetrated top suggest deposition took place in a migrating channel of fluvial or tidal origin. The lack of features indicative of tidal activity, e.g. herringbone cross-bedding (de Raaf and Boersma, 1971; Klein, 1977) tends to favour a fluvial origin. The mature nature of the sandstone would thus probably reflect erosion of a quartz rich source area. This seems unlikely as most Carboniferous fluvial sandstones in the Northern Pennines are texturally and mineralogically immature and reflect erosion of source areas containing a variety of rock types. This together with the easterly directed palaeocurrents which are orientated along the regional palaeoslope suggest deposition in a tidal environment, possibly as a tidal inlet fill.

D. Mirk Fell Ganister[1]

(i) Description

The Mirk Fell Ganister lies below the Mirk Fell Ironstones, and is thus of uppermost E_1, Pendleian age (Hull, 1968). A widespread erosion surface occurs below the Mirk Fell Ganister and becomes more pronounced towards the S. beneath the laterally equivalent Grassington Grit, where it attains the significance of an unconformity (Rowell and Scanlon, 1957; Ramsbottom, 1974).

At the type locality in Mirk Fell Gill (NY 90800680) 3 separate exposures of the Mirk Fell Ganister are present. The best exposure is at a small waterfall where the Mirk Fell Ganister consists of 102-115 cms. of fine grained sandstone erosively overlying grey shales. At the base the sandstone is bioturbated, and contains parallel lamination, and ripple cross-lamination. Thin shale laminae are present, but these die away upwards as the sandstone passes into a quartz arenite containing subrounded, moderately well sorted quartz grains. This contains rootlets at the top, and is overlain by plant rich shales.

In Side Gill (a small right bank tributary of Mirk Fell Gill, NY 90800670) the Mirk Fell Ganister is represented by an 86 cm. thick erosively based quartz arenite containing up to 97.5% quartz (Fig.110). This lies on a thin coal, and is overlain by softer, parallel laminated fine grained sandstones.

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1. At most localities this is not a true ganister. The name is often used in a stratigraphical sense for any fine grained sandstone developed beneath the Mirk Fell Ironstones.

The last of the 3 exposures occurs in the core of a small anticline in Mirk Fell Gill. The top surface of the Mirk Fell Ganister is exposed and contains horizontal branching rootlet systems (Fig.111). This is overlain by a mudstone and sandstone containing abundant vertical rootlets.

The only exposure of the Mirk Fell Ganister visited outside of Mirk Fell Gill lies approximately 10 kms. to the N. in Mawman Sike (NY 92601705). Here this horizon is represented by an erosively based lenticular sandstone up to 3 m. thick overlying a carbonaceous rich shale. At the top the sandstone becomes quartz rich, and contains abundant rootlets, and is overlain by shales at the base of the Mirk Fell Ironstone Series.

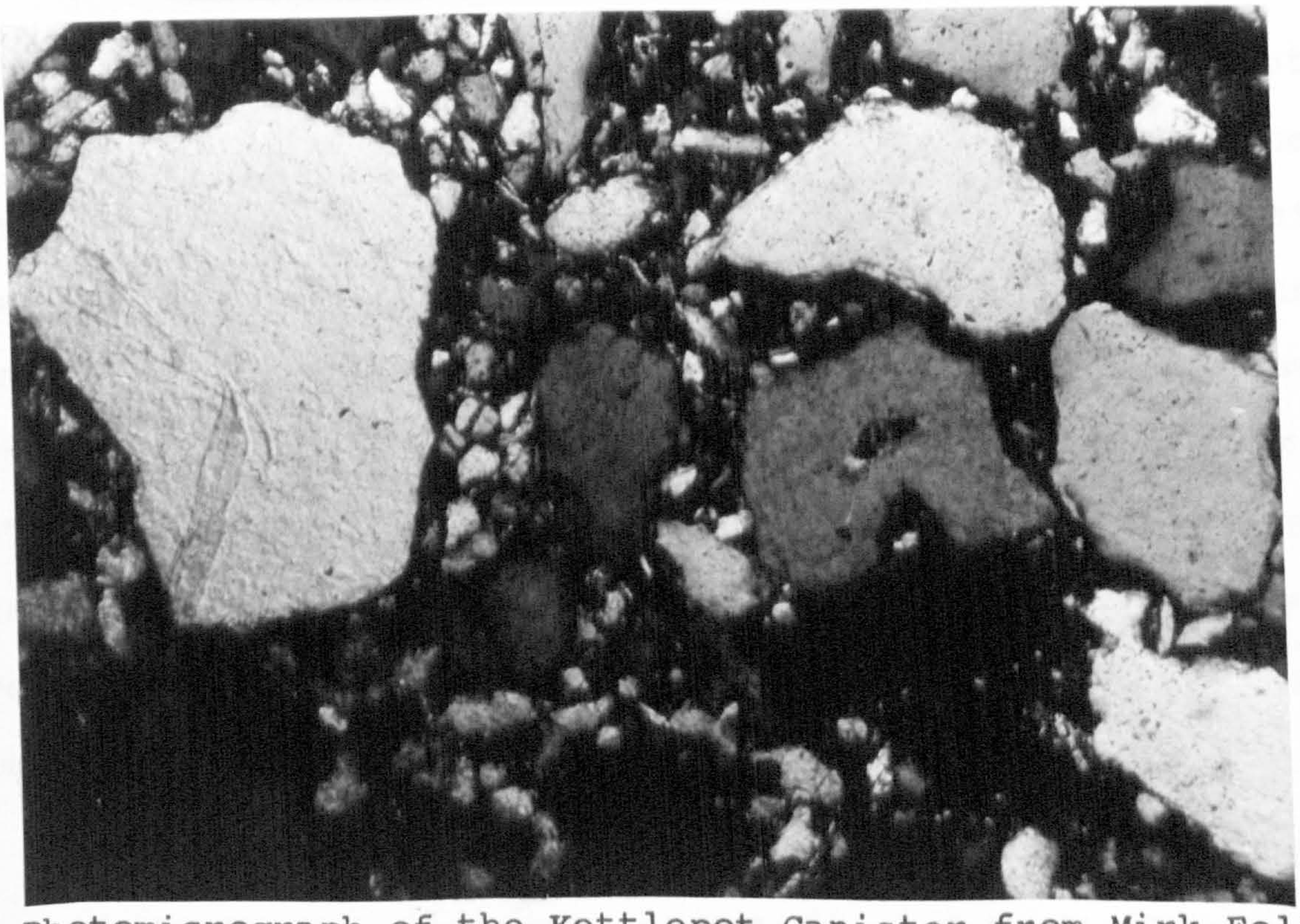
(ii) Diagenesis

At most localities cementation has occurred by the formation of interlocking quartz overgrowths. Occasionally late diagenetic iron minerals (principally goethite at present) have developed and replaced quartz grains. Specimens from the waterfall in Mirk Fell Gill often exhibit ferroan dolomite as both veins and poikilotopic cement. This replaces quartz grains and overgrowths, and is evidently late diagenetic in origin. The source of the carbonate was probably the overlying Mirk Fell Ironstone Series.

(iii) Interpretation

The term Mirk Fell Ganister encompasses a variety of sandstones occurring at the same stratigraphic level which are unlikely to be of similar origin. The Mirk Fell Ganister from Mirk Fell Gill contains few rootlets, and lacks any other features indicative of pedogenesis. This together

Plan view of branching rootlet system, top of Mirk Fell Ganister, Mirk Fell Gill. Length of pen 13.5cms. Fig.111



Photomicrograph of the Kettlepot Ganister from Mirk Fell Gill, showing distinct bimodal grain size distribution, and solution cavities in the large quartz grains. Length of photomicrograph 1.3mm. Fig.112

with the presence of sedimentary structures suggests a sedimentary origin for the quartz arenite at this locality. The mature mineralogy and the presence of rootlets indicates a high energy shallow water/emergent environment.

Conversely the quartz arenite in Mawman Sike contains abundant rootlets, and passes down gradationally into less mature sandstone. This suggests slight quartz enrichment of the topmost portion of sandstone due to pedogenesis. The short time period over which leaching probably took place, and the grain size and moderately mature mineralogy of the parent material resulted in the lack of development of soil horizons.

E. Kettlepot Ganister

(i) Description

The Kettlepot Ganister occurs below the Kettlepot or Tan Hill Coal of E_2, Arnsbergian age. In Side Gill the Kettlepot Ganister is approximately 2.4 m. thick, and consists predominantly of a poorly sorted sandstone. This contains subangular fine-coarse quartz grains, granules, and rare small vein quartz pebbles 'floating' in a muddy silt size quartz matrix, which gives rise to a distinctly bimodal grain size distribution (Fig.112). Feldspar grains are occasionally present (Fig.110) in a highly altered condition, and quartz grains often exhibit solution cavities.

At the base this sandstone passes into a very fine-fine grained muddy micaceous sandstone. This displays parallel lamination and overlies ripple cross-laminated silty and sandy shales which contain a thin wave rippled sandstone bed. The top of the Kettlepot Ganister contains abundant rootlets, and large *Stigmaria sp.* but these tend to die away with depth. Overlying the Kettlepot Ganister is the Kettlepot Coal which is approximately 1 m. thick (Hudson, 1941).

In Mirk Fell Gill (NY 91150750) the Kettlepot Ganister is similar in lithology containing subangular pebbles up to 1.2 cms. long set in a silt size quartz matrix containing sericite and fine grained clays.

(ii) Diagenesis

Cementation of the Kettlepot Ganister has been inhibited to a large degree due to the presence of fine grained clays. Quartz grains (dominantly silt size) occasionally appear to have developed overgrowths, but these tend to be small in amount, and consequently the rock is moderately friable. Solution cavities in quartz grains do not appear to be diagenetic in origin, and evidently formed prior to deposition.

(iii) Interpretation

The grain size, and mineralogy of the Kettlepot Ganister at the above localities excludes it from being a true ganister, regardless of its mode of origin. Poorly sorted 'matrix' supported sandstones can form in several ways:-

(1) By rapid deposition, resulting in dumping of material of various grain sizes, e.g. debris flow deposits (Middleton and Hampton, 1976), glacial tills, some types of storm deposited beach sediments (Hayes, 1967b).

(2) Diagenetically due to the chemical and mechanical breakdown of unstable mineral grains or rock fragments.

(3) By admixing of finer and coarser grained layers due to bioturbation.

(4) By intense chemical weathering e.g. some types of silcrete.

The predominance of silt size quartz grains in the matrix of the Kettlepot Ganister suggests that the breakdown of unstable grains has not been of prime importance, as this process would tend to produce clay minerals. Intense chemical weathering would destroy clay minerals and feldspars, both of which are present in the Kettlepot Ganister. Thus although the texture of the Kettlepot Ganister is similar to some types of silcrete, its mineralogy excludes it from being of similar origin.

This therefore indicates an origin either by rapid deposition, or bioturbation. Rootlets penetrating the Kettlepot Ganister could have resulted in the observed features provided the 'parent material' contained the necessary grain sizes. This would require interbedded silts, and coarse grained pebbly sands. This seems unlikely, and it is therefore suggested that the grain size distribution reflects original rapid sedimentation. This may have taken place by storm deposition in a beach environment or debris flow sedimentation. Subsequent to deposition of the Kettlepot Ganister colonization by a swamp type vegetation and coal formation took place.

F. Cross ganister

(i) Description

The Cross ganister occurs at the top of the Second Grit in the region of Edmundbyers Cross (NZ 00254470). It is of G_1, Yeadonian age, and is closely overlain by the

Quarterburn Marine Band which marks the base of the Westphalian. Exposures of this horizon are confined to a small quarry at Edmundbyers Cross (now partly obscured), where 35 cms. of grey fine grained quartz arenite (Fig.110) containing sub-rounded moderately well sorted quartz grains outcrops. This contains rootlets and is overlain by approximately 8 m. of silty shales, thought to include the Quarterburn Marine Band, followed by the Third Grit. The quartz arenite was formerly worked for refractory purposes in adjoining quarries, but at this locality is mineralized and of no economic importance. According to Strahan (1920) the quartz arenite is approximately 1.5 m. thick and lies on a thin coal and associated fireclay.

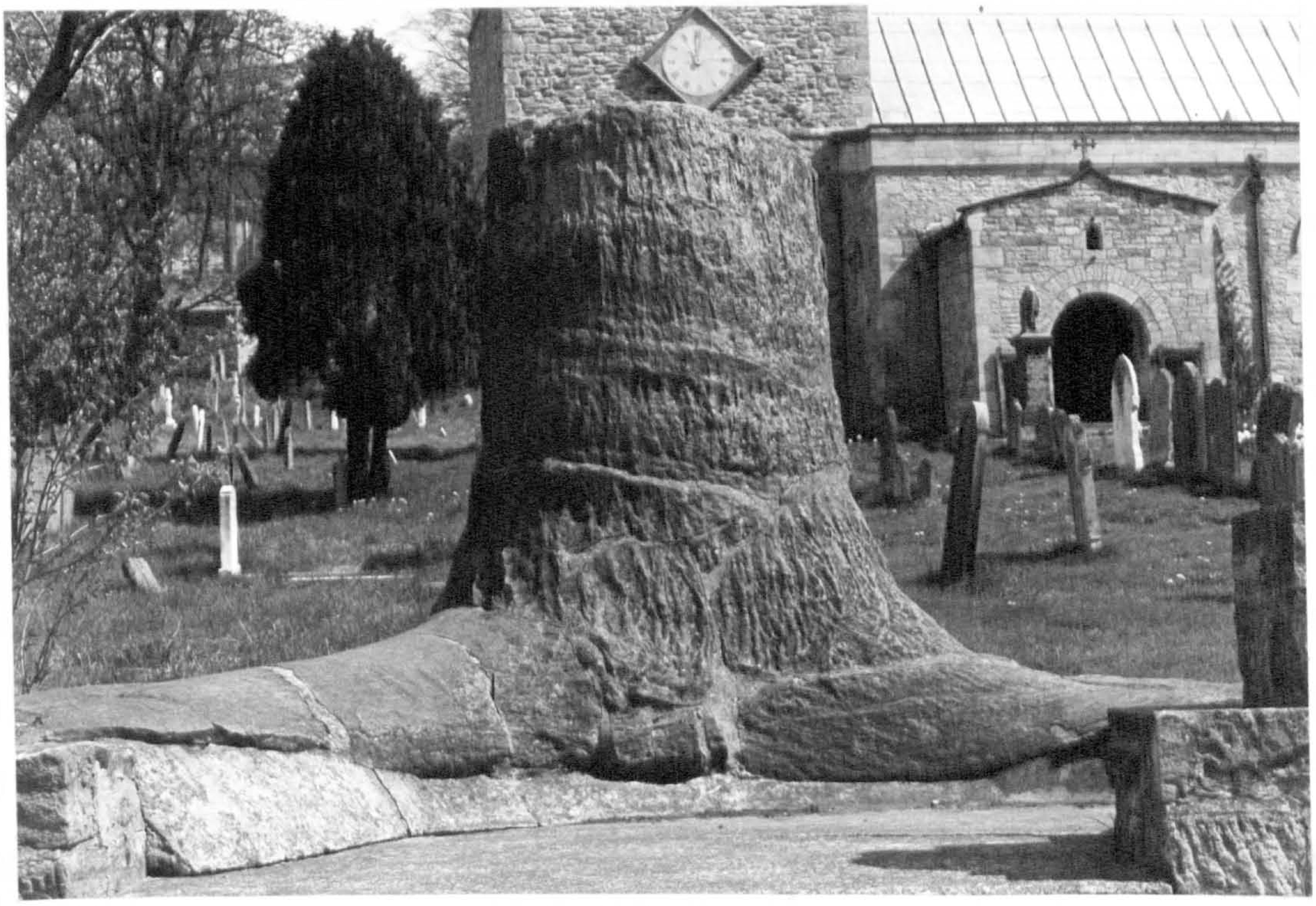
The most distinctive feature of this horizon is the presence of abundant large vertical boles of trees (*Sigillaria sp.*) which run through the whole thickness of the quartz arenite. These include a particularly well preserved specimen which can be seen in Stanhope churchyard (Fig.113).

(ii) Diagenesis

This has consisted principally of compaction and cementation by interlocking overgrowths. Authigenic brookite has developed, and occurs in minute, well formed crystals (Thomas *et al.* 1918; Strahan, 1920).

(iii) Interpretation

The occurrence of rootlets, large tree boles, and an underlying *in situ* thin coal suggests rapid sand deposition took place in a subaerial environment. The preservation of the tree boles suggests that pedogenesis concomitant with colonization of the top of the sand body was fairly minimal. This together with the lack of other features indicative of



Well preserved tree bole(Sigillaria sp.) on display in Stanhope churchyard.Specimen originally came from the Cross ganister at Edmundbyers Cross. Fig.113

Reworked top surface of sandstone bed,showing well developed Zoophycos,base of Kays Lea Marine Band,West Butsfield ganister Quarry.

Fig.114

pedogenesis suggests that the mature nature of the sandstone resulted from reworking in a high energy environment. Consequently the rock is not a true ganister.

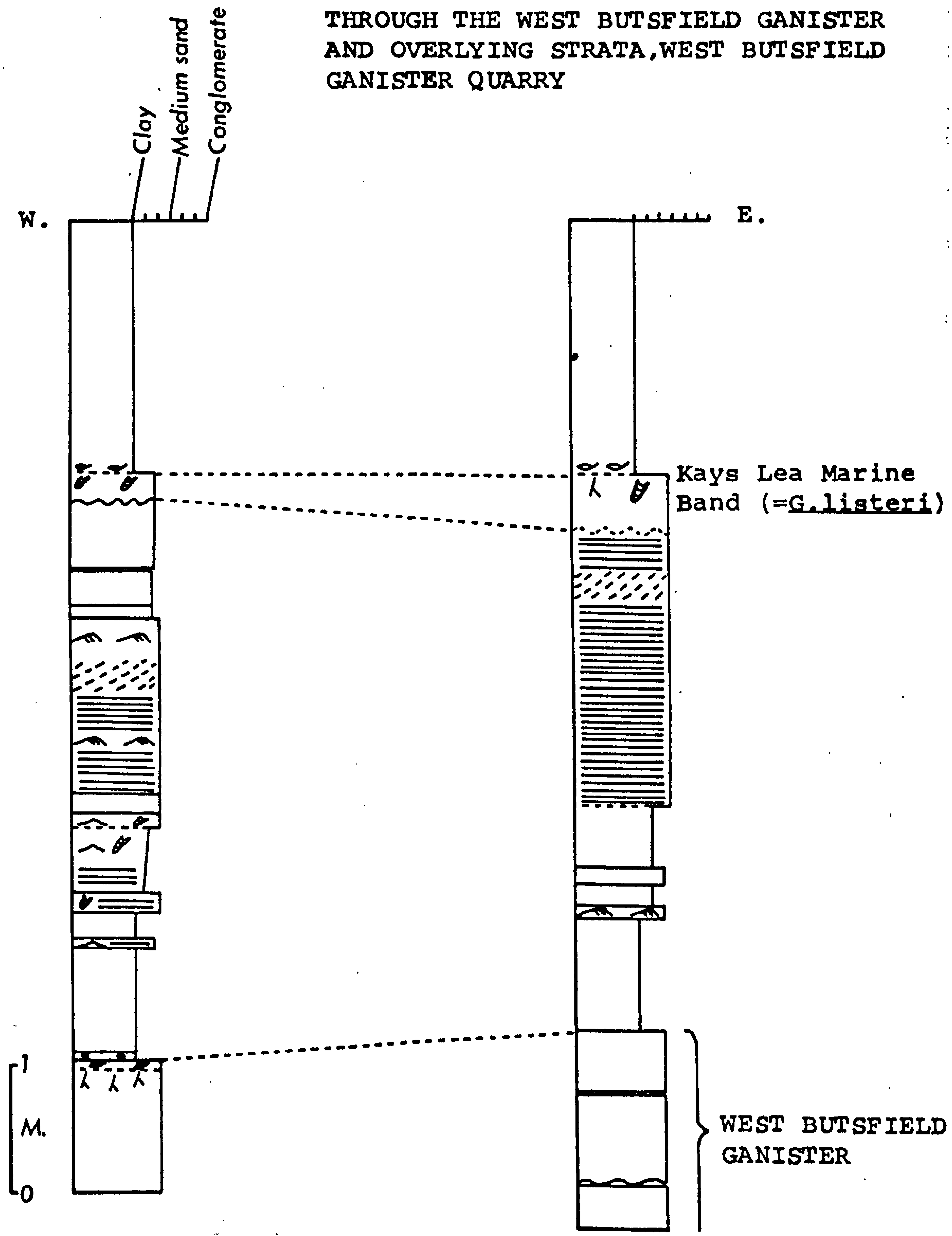
Deposition of the Cross ganister appears to have taken place on the landward side of a beach ridge or barrier island by washover of beach/shoreface sands during a storm event. Mature quartz sand was introduced into a swamp environment, and resulted in the preservation of the basal portions of large trees growing in this zone. The occurrence of washover deposits overlying a major fluvial/deltaic sandstone (p. 69) suggests formation during a delta destructive episode. Whether this was associated with the transgression which resulted in deposition of the Quarterburn Marine Band remains unknown.

G. West Butsfield ganister

(i) Description

This is a fairly lenticular horizon being restricted in occurrence to a small inlier in Butsfield Burn (NZ 09604465). Stratigraphically it is of Westphalian A age, occurring approximately 4.5 m. below the Kays Lea (*G. listeri*) Marine Band (Fig.114). The West Butsfield ganister was formerly worked extensively along its outcrop, particularly in a large quarry adjoining the A68 (NZ 09504425). In this quarry it reaches its maximum thickness of 3.2 m., from which it thins fairly rapidly both westwards and eastwards. The sequence in the quarry is shown in Fig.115. The Kays Lea Marine Band is well exposed and contains abundant brachiopods and *Zoophycos* (Fig.114).

COMPARATIVE MEASURED VERTICAL SECTIONS THROUGH THE WEST BUTSFIELD GANISTER AND OVERLYING STRATA, WEST BUTSFIELD GANISTER QUARRY



Borehole evidence shows that the West Butsfield ganister is approximately 3.2m. thick, and often sharply overlies shales and silty sandstones, although locally the contact may be transitional. Distance between sections approximately 150m.

Fig.115

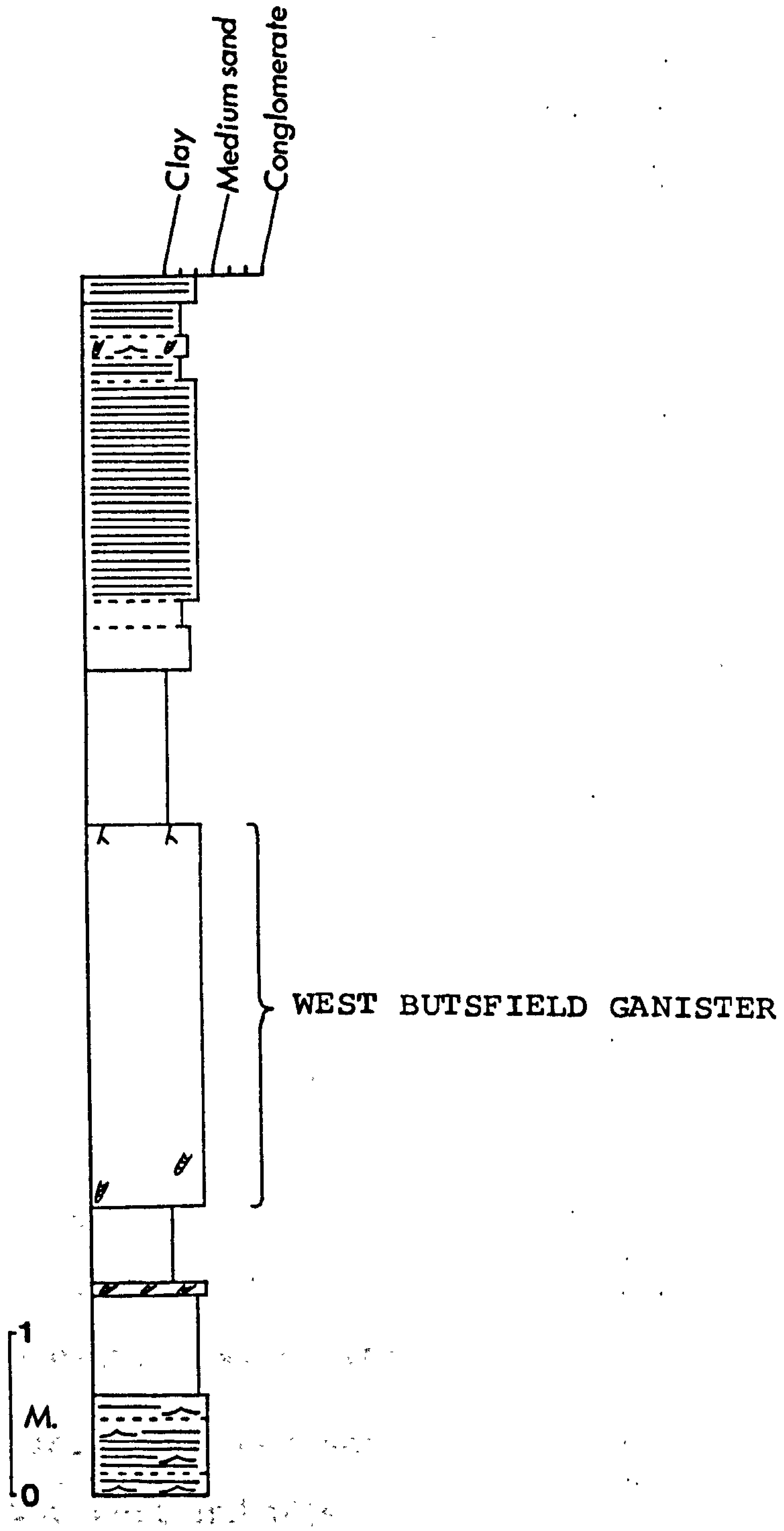
The West Butsfield ganister consists of an approximately 2.4 m. thick (visible thickness only) fine grained quartz arenite containing subrounded, moderately well sorted quartz grains. This occurs in erosively based beds generally several 10's cms. thick, interbedded with occasional thin shale laminae (up to a few cms. thick). Sedimentary structures are restricted to a solitary set of N.N.E. dipping current ripple cross-laminae. The base of the quartz arenite is not exposed in the quarry, but formerly visible sections (Strahan, 1920), together with borehole evidence suggests that the contact with the underlying silty sandstones and shales is commonly sharp, but may locally be transitional. Commonly the quartz arenite decreases in quartz content towards the base, and becomes silty and moderately clay rich. At Sawmill Bridge (NZ 09604463) the quartz arenite is sharply based, and overlies bioturbated, parallel laminated and wave ripple cross-laminated fine grained sandstones and shales (Fig.116). In the basal few 10's cms. the quartz arenite is bioturbated and contains a moderate proportion of clay.

The top of the West Butsfield ganister occasionally contains large *Stigmaria sp.* and associated rootlets. This is commonly overlain by a thin (approx. 7.5 cm.) bioturbated fine grained sandstone.

(ii) Diagenesis

Cementation of the quartz arenite has taken place by the formation of interlocking quartz overgrowths. Pore filling kaolinite has occasionally developed (Fig.110), and locally there has been a late diagenetic introduction of iron compounds (now principally goethite) which have replaced quartz grains and overgrowths.

MEASURED VERTICAL SECTION THROUGH THE WEST BUTSFIELD GANISTER AND ASSOCIATED STRATA, SAWMILL BRIDGE, BUTSFIELD BURN (NZ 09604463)



This section is located approximately 350m. N. of the sections in Fig.115.

Fig.116

The thin bioturbated sandstone lying on the quartz arenite contains patchy developments of quartz overgrowths, and fine grained (approx. 0.032 mm.) siderite cement. The latter replaces both quartz grains and overgrowths and is evidently late diagenetic in origin. Dissolution of quartz in this zone may have provided some silica for quartz overgrowth formation in the underlying quartz arenites.

(iii) Interpretation

The thickness, presence of sedimentary structures, shale laminae, and erosively based beds, together with the paucity of rootlets indicate that the West Butsfield ganister is not pedogenic in origin, and thus not a true ganister.

The presence of rootlets, and the mature nature of the sandstone suggests deposition in a high energy shoreline environment. The transitional basal contact with the underlying finer grained deposits which is occasionally present results in a coarsening upward sequence broadly similar to many prograding wave-dominated clastic shoreline deposits (Bernard *et al* 1962; Davies *et al*, 1971; Harms *et al*, 1975). Generally, however, such sequences tend to be laterally extensive and thicker (approx. 15 m.). This together with the sharp base to the quartz arenite at most localities suggests that the West Butsfield ganister did not develop in such a prograding shoreline environment.

Similar sequences and lateral relationships to those exhibited by the West Butsfield ganister occur in modern cheniers. These are isolate sand or shell-debris ridges (300-1,000 m. wide) up to 3 m. high set in marsh/mudflat sediments (Elliott, 1978b). Individual ridges are formed during periods of reduced sediment supply along an otherwise prograding muddy shoreline (Russell and Howe, 1935; Hoyt, 1969; Elliott, 1978b). Boreholes through modern cheniers exhibit either a small scale coarsening upward sequence capped by a soil horizon and marsh facies, or a sharply based sand body commonly due to storm washover deposition over marsh sediments (Gould and McFarlan, 1959; Hoyt, 1969; Elliott, 1978b; Otvos and Price, 1979).

It is therefore suggested that the West Butsfield ganister formed by reworking in the shoreline zone, possibly as a chenier ridge during a period of restricted sediment supply. The presence of thin shale laminae indicates occasional low energy conditions. Such conditions are unlikely to be preserved on the beach face, and together with the lack of swash lamination and the sharp base of many localities suggest that deposition took place principally by washover of beach/shoreface sands during storm events. The absence of any fauna probably results from post depositional leaching of shell material prior to consolidation.

H. Lower Knitsley Fell ganister

(i) Description

Stratigraphically this horizon is of Westphalian A age, apparently occurring several metres below the horizon of the Ganister Clay Coal. Exposures are restricted to 2 small disused quarries on Knitsley Fell (NZ 09503465). These display up to 4.1 m. of fine grained quartz arenite containing subrounded, moderately well sorted quartz grains, but none of the enclosing strata. The best exposure occurs in the S.E. quarry (NZ 09773467) where the top surface of the quartz arenite is seen to contain large scale undulations (Fig.117). These exhibit up to 1.5 m. of relief, and have wavelengths of the order of 60 m. No preferred orientation of the troughs and crests is visible in this small exposure.

The quartz arenite occurs in beds from a few cms. to a few 10's cms. thick, occasionally separated by thin mud laminae. These beds appear to dip radially in all directions. Commonly these dips are parallel to the undulating top surface, but occasionally a discordant relationship exists.

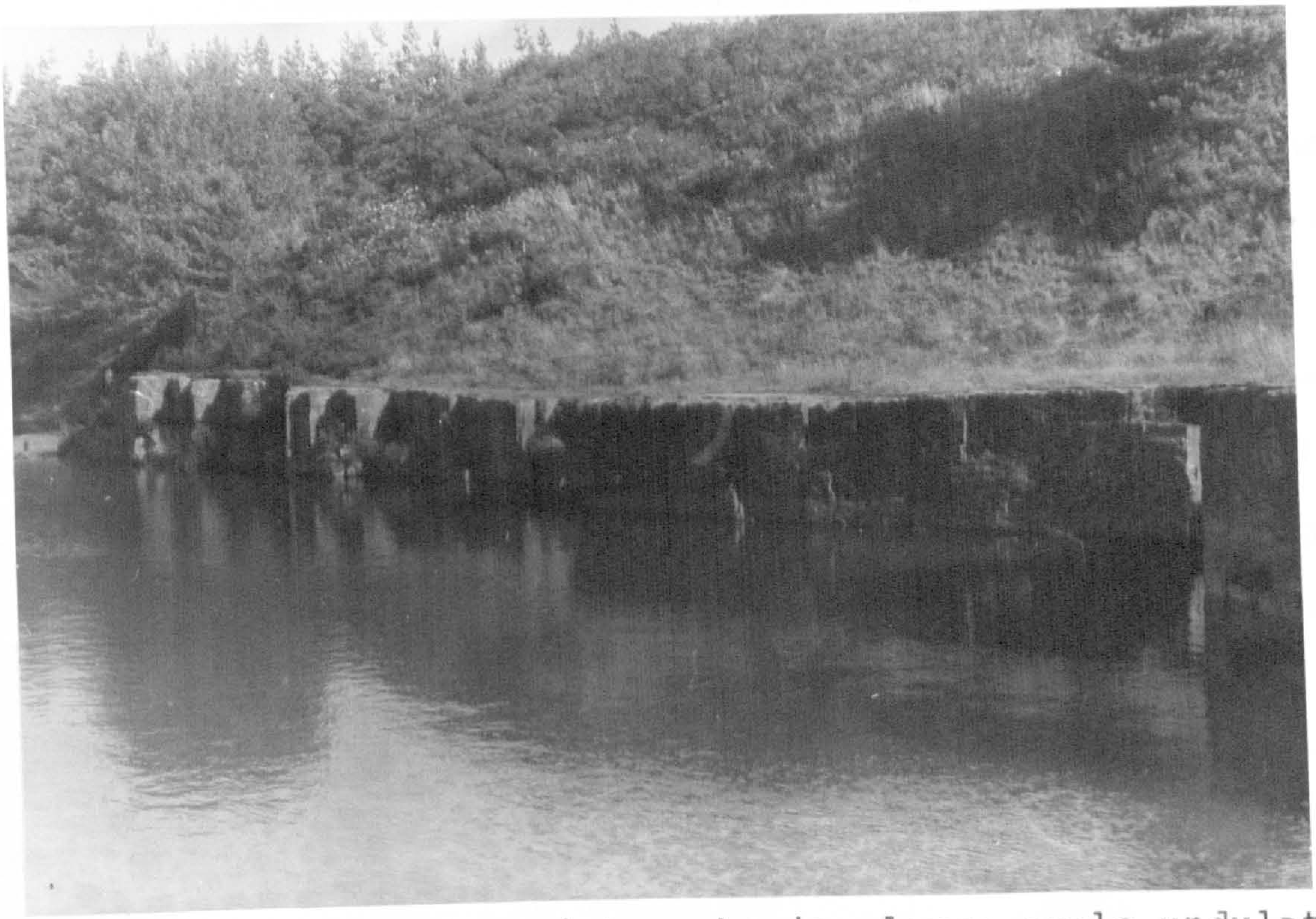
Rootlets are abundant in the top 20 cms. of the sandstone body, both in troughs and on crests. This rootlet penetrated zone differs quite markedly from the underlying quartz arenites (Fig.110) in containing an appreciable amount of clay.

(ii) Diagenesis

As in previous examples cementation by quartz overgrowths, development of pore filling kaolinite and a late diagenetic influx of iron have been the main post-depositional events.

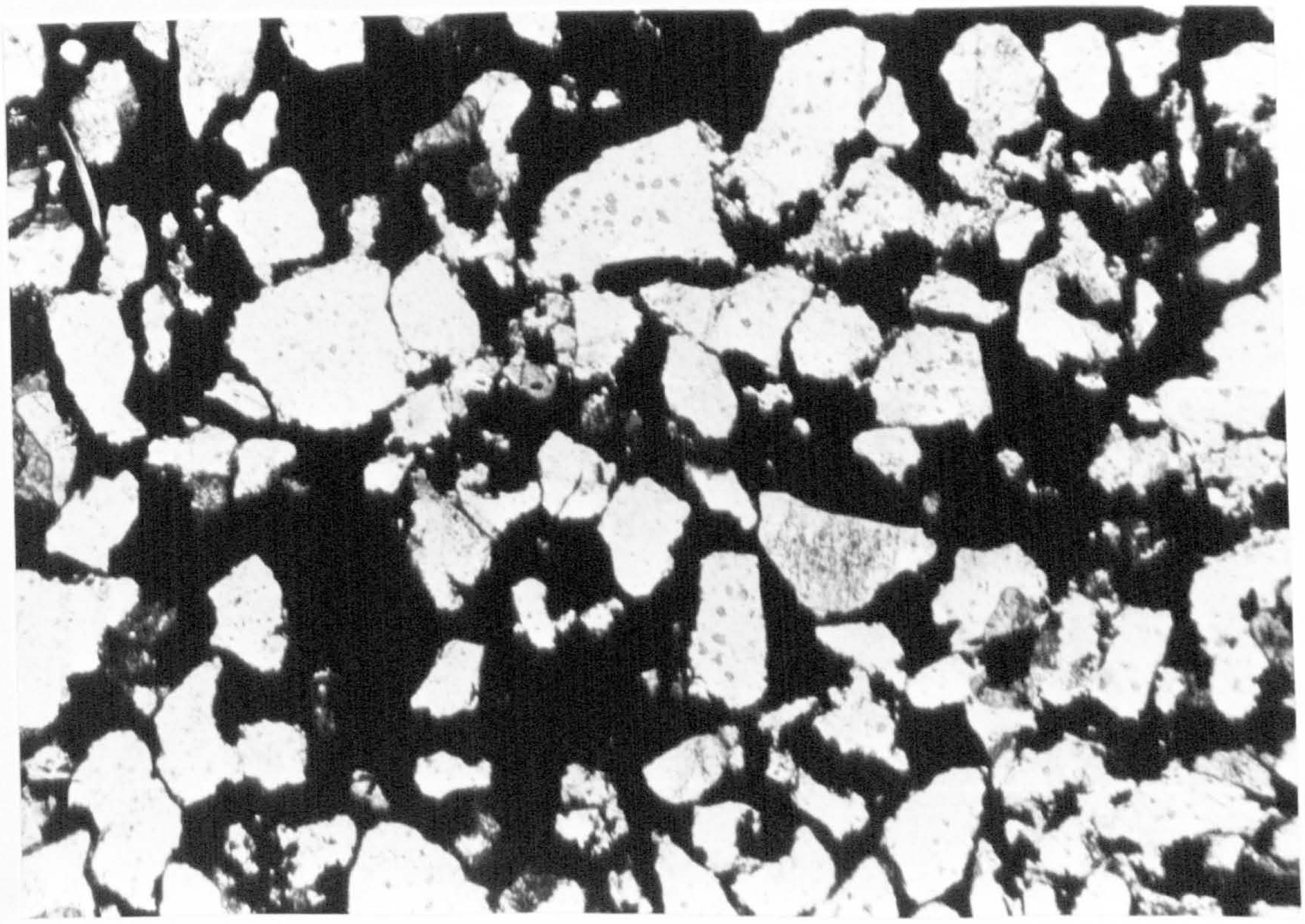
(iii) Interpretation

Similar arguments to those used for the West Butsfield ganister can be applied to this horizon. These suggest that the quartz arenite is not a true ganister, and results from high energy reworking in a shoreline environment. Pedogenesis does appear to have affected the top of the sand body resulting in the presence of moderately abundant admixed



Lower Knitsley Fell ganister showing large scale undulations of upper surface.The wavelength of these features is approximately 60m.

Fig.117



Top of Upper Knitsley Fell ganister showing extensive replacement of quartz by goethite.Length of photomicrograph 1.4mm.

Fig.118

clay, but no leaching and quartz enrichment seems to have taken place beneath this zone.

The presence of an apparently hummocky ridge and swale topography is the most striking feature of the quartz arenite, and may result from oblique sections through elongated bar/ridge forms. The occurrence of rootlets in the troughs indicates that the entire visible top of the sand body became emergent subsequent to deposition. This suggests that the quartz arenite developed as a series of accretionary beach ridges similar to those described by Curray and Moore (1964), Psuty (1965), Curray *et al*(1969), and Morgan (1970). Variable low angle dips are due to beach/shoreface accretion, and beach ridge washover processes (Psuty, 1965).

Available data suggest that the deposit is lenticular, and thus unlike the sheet sands produced by modern prograding strandplains/wave-dominated deltas. Wave reworking appears therefore to have been a fairly rare event; consequently it is quite possible that the deposit represents a series of small coalesced chenier ridges. A distinction between a beach ridge or chenier ridge origin in this example is impossible to make without additional data.

I. Tow Law ganister

(i) Description

The Tow Law ganister occurs directly beneath the Ganister Clay Coal of Westphalian A age. It was formerly the most sought after horizon in the Northern Pennines for refractory purposes, and was extensively quarried and mined in the Black Burn (NZ 08504565) to Doctors Gate region (NZ 07053280). Outside of this area the ganister appears to be absent.[1]

Although a large number of workings in this horizon exist, most are obscured, and present day exposures are confined to a small section alongside Black Burn. At this locality the ganister consists of approximately 57 cms. of fine grained quartz arenite (Fig.110) containing sub-rounded, moderately well sorted quartz grains. This contains an irregular 'knobbly' base with undulations up to 17 cms. deep. Large *Stigmaria sp.* and associated rootlets are common, particularly towards the top. At the top the quartz arenite is overlain by a 3.5 cm. bed of bioturbated fine grained sandstone. Burrows present within this horizon include *Teichichnus*.

The Ganister Clay Coal is absent from this section, and a medium to coarse grained trough cross-bedded sandstone apparently directly overlies the bioturbated sandstone and ganister. This contains fresh feldspars, moderately abundant micas and clay minerals, and occasional multicycle quartz grains.

The sequence below the ganister is not exposed, but former sections near Tow Law exhibited an impure fireclay at this horizon (Strahan, 1920; Collins, 1925). In these sections the ganister varied quite markedly in thickness up to a maximum of 1.8 m. This was apparently due to a highly irregular base (Collins, 1925).

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1. A ganister very similar in lithology and at approximately the same horizon was formerly worked on Burntshieldhaugh Fell (NY 94255240) 3 kms. N.W. of Blanchland.

(ii) Diagenesis

Cementation has taken place dominantly by the formation of quartz overgrowths. Occasionally some micro-quartz cement has developed, but this is small in amount and restricted to carbonaceous rootlet outlines. As in most previous examples there has often been a late diagenetic influx of iron (now principally goethite) which has replaced quartz grains.

(iii) Interpretation

Though poorly exposed the Tow Law ganister exhibits many similarities with the previously described true ganisters (p. 80) the most important of which are the presence of rootlets, and rapid thickness variations due to an irregular basal contact. It is therefore interpreted as pedogenic in origin due to leaching in a podzolic soil profile. The bioturbated top to the ganister is unlikely to have originated in a well drained soil profile, and probably formed subsequent to ganister development.

J. Upper Knitsley Fell ganister

(i) Description

This is Westphalian A in age, and apparently occurs just above the horizon of the Ganister Clay Coal. Strahan (1920) correlated this horizon with the Lower Knitsley Fell ganister. There is no evidence to support this correlation, and the 2 occurrences although similar in lithology appear to be at different stratigraphic horizons.

Exposures of the Upper Knitsley Fell ganister are restricted to 2 small quarries on Knitsley Fell. The best exposure occurs in the southern quarry (NZ 09603425) where up to 98 cms. of fine grained quartz arenite composed of sub-rounded, moderately well sorted quartz grains outcrops beneath a series of interbedded sandstones and shales (Fig.119). The quartz arenite contains rootlets in the top 10-20 cms. but these die away rapidly with depth. Petrographically the quartz arenite contains muscovite, biotite, and clay minerals making it slightly less mature than some previous examples (Fig.110).

The base of the quartz arenite is not exposed, but it appears to lie on a further thin (approx. 20 cm.) quartz arenite which sharply overlies a rooted fine grained muddy sandstone. The geometry of the deposit is unknown, but appears to be fairly lenticular as previously 2.1 m. of quartz arenite was worked at this locality (Strahan, 1920).

(ii) <u>Diagenesis</u>

Diagenesis was virtually identical with the Lower Knitsley Fell ganister. At the top, however, the effect of the late stage introduction of iron is much more pronounced. and the rock contains up to 28.5% of iron minerals (principally goethite) (Figs. 110 and 118). Such large scale replacement probably resulted from iron rich mineralizing fluids becoming trapped beneath the overlying shales. These were thus forced to migrate laterally within the top of the sandstone.

MEASURED VERTICAL SECTION THROUGH THE UPPER KNITSLEY FELL GANISTER AND ASSOCIATED STRATA (NZ 09603425)

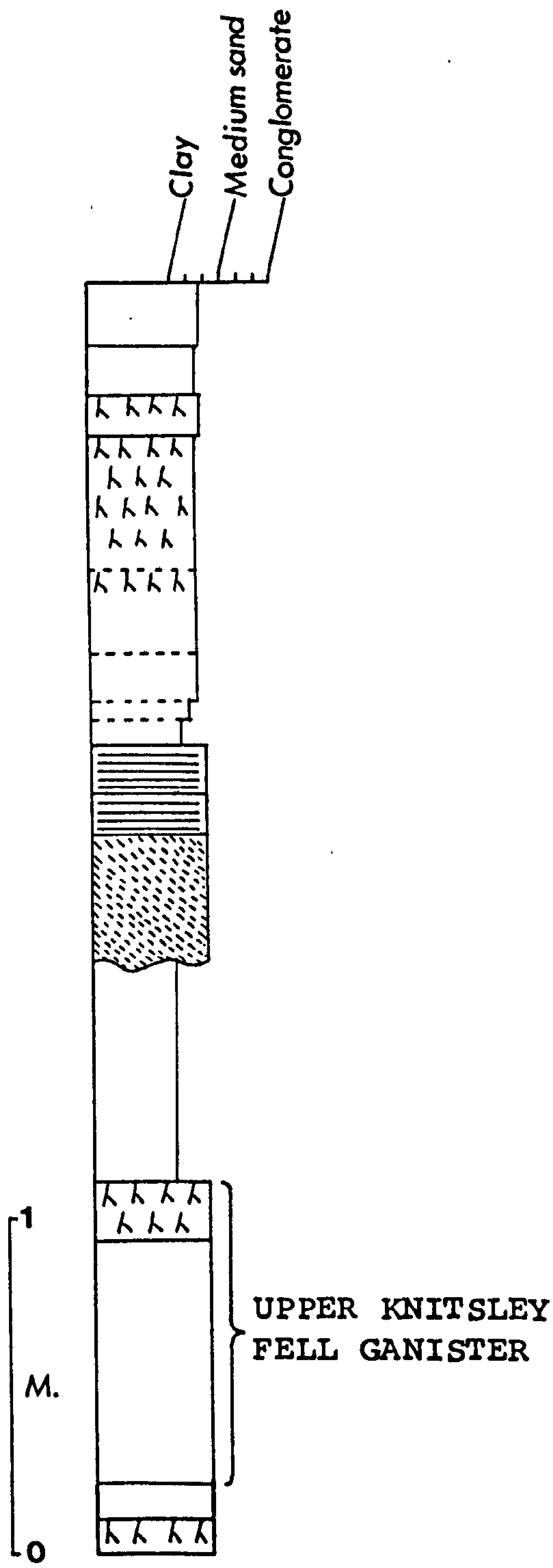

Fig.119

(iii) Interpretation

The absence of features indicative of pedogenesis (rootlets apart), together with the presence of biotite suggest that the rock is not a true ganister. The occurrence of rootlets both at the top, and beneath the quartz arenite indicates rapid sand deposition in a subaerial environment. As in previous examples, e.g. Cross ganister it is suggested that deposition took place along a high energy shoreline, by washover during storm events.

K. Conclusions

A wide variety of sandstones within the Northern Pennines have been termed or worked for ganister. The majority are not pedogenically formed quartz arenites and thus do not qualify as true ganisters. Many appear to have formed by high energy reworking in the shoreline zone. Thin rooted quartz arenites formed in this manner can superficially resemble true ganisters, particularly when exposure is poor.

CHAPTER EIGHT

CONCLUSIONS

A. Origin of Carboniferous quartz arenites and ganisters of the Northern Pennines

(i) Introduction

A significant discovery of this research is that the majority of 'ganisters' in the Northern Pennines are sedimentary in origin and are thus not true ganisters. Many of these horizons attained their mature stable mineralogy by reworking in high energy shallow-marine to shoreline environments. Both the sedimentary quartz arenites and the true ganisters appear to have been derived mainly from less mature fluvial and deltaic sands, and underwent similar amounts of quartz enrichment. The mineralogy of these less mature sands suggests that this was generally $<15\%$.

The geographical distribution of quartz arenites in the Northern Pennines exhibits a distinct correlation with the extent of the Alston Block. This may at first appear artificial, particularly in the eastern part of the region which was extensively searched for quartz arenites due to its proximity to the iron and steel producing centres. However, even taking this bias into account, texturally mature quartz arenites appear more abundant on the Alston Block than in adjacent troughs. This suggests that the restricted subsidence on the block during deposition often allowed reworking to take place in the high energy environments which occasionally existed. In the troughs subsidence was greater, reworking less, and thicker texturally less mature sandstones accumulated, often in stacked units.

Quartz arenites on the Alston Block are divisible into 4 main types based on their mode of origin. These are described in the following sections.

(ii) True ganisters

True ganisters represent quartz arenites containing >95% quartz which achieved this degree of quartz enrichment by leaching in a palaeosol profile (p. 5). The dominant process in Carboniferous examples appears to have been downward mechanical eluviation of clay material, although occasionally iron compounds and carbonaceous material have been translocated. They are thus fossilized equivalents of the A_2-horizon of modern podzols and podzolic soils. Formation of these soils requires freely drained conditions and an excess of precipitation over evapotranspiration. This leads to leaching and quartz enrichment in the A_2-horizon, which may become a ganister if cemented by quartz during diagenesis. The recognition of such an origin for a texturally mature quartz arenite depends on the occurrence of several of the following criteria:-

(1) The presence of roots and rootlets; these commonly decrease in abundance with depth.

(2) Indications of soil horizons. Commonly palaeosol profiles containing a quartz arenite exhibit a carbonaceous top which may be overlain by a thin coal (thick coals are uncommon). Beneath the quartz arenite horizon there is often a clay enriched zone (this varies from a kaolinitic clay to a sandstone which in the topmost metre or so shows a decrease in clay content with depth).

(3) Cutans beneath the quartz arenite horizon. These commonly occur as clay coatings and pore linings (argillans),

and are generally restricted to zones where sandstone underlies the quartz arenite. Preferential development of these features in certain areas may give rise to clay rich laminae such as the ripple-like structures from the Firestone Sill (p. 87).

(4) A sharp or transitional basal contact to the quartz arenite. In the latter case the quartz arenite commonly passes down into texturally and mineralogically less mature sandstone. Sharp contacts are generally very irregular and give rise to a "knobbly" base to the quartz arenite with undulations up to a few 10's cms. deep. These undulations lack any features indicative of loading, and are similar to the tonguing contacts seen in modern podzols and podzolic soils.

(5) Absence of sedimentary structures. This is generally due to destruction by rootlets and soil organisms as well as obliteration by other pedogenic processes.

(6) The quartz arenite is commonly thin, generally <1 m., but up to 2 m. in extreme cases.

(7) Large variations in the thickness of the quartz arenite horizon, generally due to the irregular basal contact.

(8) Vertical and lateral changes in the lithology of the quartz arenite horizon due to variations in leaching.

(9) Absence of any marine fauna in the quartz arenite.

(10) Lack of features indicative of high energy reworking e.g. well rounded, well sorted grains.

Of these characteristics, the lack of sedimentary structures, and the presence of rootlets and a highly irregular basal contact are often diagnostic of a pedogenic origin for a quartz arenite (ganister) containing >95% quartz. In addition the quartz arenite is generally very fine to medium grained, and lacks features indicative of silcretes e.g. TiO_2 rich cloudy areas.

Ganisters may form isolate sandstone layers or the tops to thicker sandstone bodies. This depends on the thickness and lithology of the sandy parent material from which they developed, the time available for leaching, rate of leaching, and the depth to the water table. The amount of quartz enrichment which occurred during pedogenesis is often hard to ascertain unless some parent material has been preserved. Obviously ganisters will develop more rapidly on sandstones already enriched in quartz to some degree. Consequently most examples appear to have undergone <10% quartz enrichment during pedogenesis. Sandstones containing >95% quartz prior to pedogenesis and leaching cannot classify as ganisters (p. 5) and constitute sedimentary quartz arenites.

The thickness of the ganister A_2-horizon developed during pedogenesis will reflect a variety of factors including time, parent material, rate of leaching etc. One of the most important factors in this respect is the depth to the water table, as this represents the lowest limit to which the ganister A_2-horizon can develop.

Ganisters thus reflect freely drained conditions; the thickness of the ganister will indicate the minimum possible depth to the water table during formation of the soil profile.

(iii) <u>Barrier island quartz arenites</u>

Carboniferous barrier island quartz arenites in the Northern Pennines are divisible into mesotidal and microtidal types. Mesotidal forms appear fairly common in the Dinantian and generally consist of moderately thick (<20 m.) laterally extensive regressive deposits. Microtidal barrier island quartz arenites occur principally in the Namurian where they tend to form thinner sequences, generally <10 m. thick.

Mesotidal barrier deposits are dominated by tidal inlet, tidal channel, tidal delta, and washover sediments; beach and shoreface sands seem to be rare. The barriers appear to have developed during the maximum extent of a transgression; subsequently they prograded southwards. Generally during progradation relative sea level was rising (probably due to subsidence), which together with tidal scouring often maintained a backbarrier lagoon. Progradation was not a single event, and was probably interspersed with phases of *in situ* aggradation and landward migration. Generally, however, unless subsidence or sea level rise was rapid, during the last period of progradation laterally migrating tidal inlets reworked previous deposits. Consequently the last progradational event is commonly the only one preserved, particularly on the Alston Block where subsidence was limited. In the Stainmore Trough increased subsidence often resulted in greater preservation of depositional events, giving rise to stacked sandstone sequences. Preservation of these regressive barrier island deposits requires a fairly rapid sea level rise subsequent to their formation, as the extent of reworking by the transgression which preceded deposition of the overlying limestone is generally limited, and shoreline features associated with the transgression are absent.

Carboniferous microtidal barrier island deposits studied by the author are dominated by washover sediments. These are broadly divisible into thin transgressive deposits produced mainly during delta destructive phases, and thicker (several metres or more) stillstand/progradational barrier sediments. Preservation of the latter may be due to deposition of an overlying fluvio-deltaic sequence, or a rapid relative rise in sea level.

Carboniferous barrier island deposits in the Northern Pennines thus reflect periods of low to moderate sand supply in areas downdrift or alongshore from the main contemporaneous zones of fluvial input.

(iv) Shallow-marine quartz arenites

In the Northern Pennines quartz arenites produced in a shallow-marine environment are principally storm-dominated in origin. Tide-dominated examples may exist, but are probably restricted to the Dinantian where the tidal regime appears to have been more suitable for their formation.

Storm-dominated shallow-marine deposition reached its peak during Namurian E_1 and E_2 times. In this period a variety of moderately small (<9 m. high, up to a few kms. wide and several kms. long) sand bars appear to have formed. Generally these were asymmetric in profile with their steepest face in the direction of migration which was commonly northwards. The mode of formation of these bars is unknown, but it is quite likely that they were produced in an environment different to that into which they migrated. Most bar deposits are overlain by a marine band, and appear closely associated with the events which led to its deposition. Low angle depositional dips are common in bar sediments, and reflect washover style deposition during storm events. Sedimentary structures are dominated by parallel lamination and hummocky cross-stratification, and only locally is cross-bedding important.

The generally landward directed palaeocurrents obtained from bar deposits suggest that sand was derived from adjacent shelf regions rather than directly from the shoreline zone. Reworking took place principally on the seaward side of the bars and resulted in their quartz arenite lithology.

Sequences through the sand bar deposits are variable, but sections through the centre generally coarsen and thicken upwards, and are overlain by a reworked zone and marine band. The thickness of the coarsening and thickening upward sequence when fully preserved approximately reflects the height of the sandbar above the adjacent muddy shelf surface. Preservation of these bars appears in many cases to result from drowning *in situ* , and/or rapid shoreline progradation (commonly deltaic) across the shelf.

Other shallow-marine quartz arenites include those from Park Burn which appear to represent storm-dominated channel infills. Reworking to produce the quartz arenitic lithology in this case appears to have taken place in the shoreline zone.

(v) Wave-dominated shoreline[1] quartz arenites, excluding those of barrier island origin

In the Northern Pennines quartz arenites studied by the author, which were produced by wave reworking in the beach environment (excluding barrier island beaches), are not particularly well exposed and generally consist of thin lenticular sandstone bodies. Thicker, laterally extensive progradational beach deposits occur, but are commonly more

1. This includes beaches, cheniers and strandplains/wave-dominated deltas.

texturally immature in response to the greater rate of deposition that took place in such environments. These generally show a coarsening upward sequence capped by a rootlet bed. The thickness of this sequence commonly represents the depth of water into which the beach prograded (Klein, 1974).

Swash lamination in the beach sediments appears to be rare, probably due in part to lack of recognition and destruction by rootlets soon after deposition. In prograding examples swash lamination should normally be present due to beach face accretion. However, in transgressive beach sediments washover style deposition is probably more important; beach and shoreface erosion takes place, and consequently little swash lamination is produced or preserved.

Beach deposits generally form topographic highs which are readily colonized by plants. Pedogenesis commonly takes place, and due to the freely drained conditions may result in a leached soil profile if sufficient time is available. Therefore providing the parent material contains <95% quartz, ganisters can develop in this environment. Such soil profiles will generally only be preserved during regressive events.

B. Quartz arenites and ganisters - implications for Carboniferous depositional environments in the Northern Pennines

(i) Dinantian and Namurian

Dinantian and Namurian sedimentation in the Northern Pennines was dominated by the deposition of Yoredale cyclothems. Generally these consist of a limestone or marine band overlain by a coarsening upward sequence capped by a rootlet bed and occasional thin coal. The coarsening upward sequence has generally been interpreted as forming by delta progradation, however, similar sequences can be produced in a wide variety of environments including prograding beaches/ barriers, tidal deltas, and washover fans, and laterally migrating shallow-marine sand bars. All these environments appear to have been present during deposition of the Yoredales, and contributed to the preserved clastic sequences. Cyclothems also vary markedly in their composition and include a variety of different sequences produced in other depositional environments such as laterally migrating tidal inlets, fluvial channels, distributaries etc. At any one locality individual sequences may form the whole of the clastic interval of a cyclothem, or occur stacked with other sequences. Laterally these sequences often vary. Consequently a wide variety of depositional environments may lead to the development of a cyclothem.

Although some clastic sequences were probably produced by constructive and destructive phases of a fluvial-dominated deltas, others appear to have developed outside the main zone of deltaic influence. This is particularly true in the Upper Brigantian where 2 major strike-fed barrier island systems appear to have developed.

It is thus suggested that the Mississippi type delta model for the clastic portion of the Yoredale cyclothems is an oversimplification, and that a variety of environments have resulted in the preserved sedimentary sequences. During the Brigantian prograding barrier island systems appear to have been important in the development of the Yoredale clastics on the Alston Block. Limestones separating these clastics are generally fairly thick (several metres or more), and indicate long periods of virtually no terrigenous input.

Namurian cyclothems on the Alston Block contain a large proportion of texturally immature sandstones, many of which are fluvial or fluvial-dominated deltaic in origin. Limestones in these cyclothems (apart from the Great) are fairly uncommon and those that are present tend to be thin (generally <3 m.). It is therefore suggested that of the well developed Yoredale cyclothems on the Alston Block many did not develop in a fluvial-dominated deltaic setting.

The formation of deltaic sequences on the Alston Block appears to have commenced close to the Dinantian-Namurian boundary. Above this deltaic sediments increase in abundance and at the same time limestones gradually die away. This reflects the increased terrigenous input to the Alston Block during Namurian times. Such an increase in sediment supply may result from a westward shift in the major distributary channels or rejuvenation in the source area. Periods of virtually no sediment supply during this period were rare and short lived, and only sporadically did limestones develop. Also the marine zone was gradually being pushed southwards, consequently its influence on the region diminished throughout Namurian time.

The development of fluvial-dominated deltaics thus heralded the end of limestone deposition and Yoredale cyclothem formation on the Alston Block. Formation of the clastic sequences of well developed Brigantian examples appears to have taken place principally in prograding barrier islands.

The relationship of these deposits relative to the pene-contemporaneous deltaic deposits on the Askrigg Block (Moore, 1958, 1959, 1960), may be an interesting subject for future research. Unfortunately time has not allowed the author to investigate this aspect.

The beginning of the Namurian also coincided with a probable change in the tidal regime of the shallow shelf seas that occasionally encompassed the Alston Block. Micro-tidal conditions appear to have prevailed throughout the Namurian. A result of this was that storm deposition became a much more important factor in shallow-marine sedimentation. This led to the relative abundance of shallow-marine storm-dominated deposits of E_1 and E_2 Namurian age. The absence of such deposits higher in the Namurian probably reflects a paucity of shallow-marine conditions later in Namurian times, rather than a reduction in storm energy. This may have been due to rapid deltaic progradations across the Alston Block only allowing limited time for shallow-marine reworking and deposition.

During the Dinantian and Namurian true ganisters are relatively rare, and probably only developed on local topographic highs such as beach ridges where freely drained conditions persisted. Elsewhere conditions appear to have been poorly drained and leached soil profiles could not develop.

(ii) Westphalian A

Westphalian A deposition is commonly considered to have taken place on a coastal plain close to sea level. Occasionally this region underwent low energy marine transgressions. Progradation of the shoreline following these events generally took place due to delta growth. The presence of texturally mature shoreline sands suggests that occasionally delta progradation was halted, and wave reworking of the delta front took place to produce cheniers/ beach ridges.

Previously described examples of wave-dominated shoreline sands in the Westphalian A are extremely rare. This probably reflects fairly rapid sediment supply, and limited wave energy available for reworking during this period. Undoubtedly examples occur in other Westphalian A sequences, but have probably not been recognized due to their thin lenticular nature. The thickness of these deposits in the Northern Pennines suggests that the water in which they formed was probably only a few metres deep.

True ganisters are fairly abundant in Westphalian A strata, which is unexpected considering the overall waterlogged nature of the environment. Although topographic highs such as beach ridges or levees may have formed well drained sites, most ganisters do not form the top of sandstone bodies as would be expected in these situations. Local depressions in the water table could have resulted in ganister formation, but the overall nature of the environment argues against such conditions having existed. Small scale tectonic uplift could have caused a fall in the water table relative to the land surface which might have enabled ganisters to form. However, evidence of occurrences of ganister being associated with synsedimentary tectonic movements is lacking. This suggests that many ganisters, particularly laterally extensive ones, probably result from regional changes in the water table such as falls in base level.

Although absolute sea level rises have been suggested for several horizons in the Westphalian A (Duff and Walton, 1962; Anderton, Bridges, Leeder and Sellwood, 1979; Ramsbottom, 1979) absolute falls in sea level are unknown. This is probably due to the lack of diagnostic criteria by which such events could be recognized, rather than their absence. Regionally extensive palaeosol horizons formed under well drained conditions (including true ganisters), may be useful in this respect, particularly where such occurrences are not at the top of thicker sandstone bodies which may have formed topographic highs. True ganisters are thus one of the only indicators of emergent conditions during the Westphalian A. The relative abundance of ganisters in strata of Westphalian A age probably reflects in part small falls in base level. These had pronounced effects on the drainage conditions of a broad flat coastal plain of almost non-existent palaeoslope.

Owing to their freely drained nature, palaeosols containing a ganister horizon did not develop a thick overlying coal. Thick coals above ganisters appear to result from changes in drainage subsequent to ganister formation.

All the studied quartz arenites in the Northern Pennines achieved their mature mineralogy by pedogenic or sedimentary reworking of texturally and mineralogically less mature parent material. Erosion of pre-existing quartz rich source rocks does not appear to have been an important factor. During diagenesis the majority of these quartz arenites underwent a further small increase in quartz content due to cementation by interlocking quartz overgrowths, or microquartz.

C. Economic reserves of quartz arenite (including ganister) in the Northern Pennines

With the development of the iron and steel industry there has gradually been a trend towards the use of higher grade refractory bricks. This has resulted in many of the previously worked quartz arenites in the Northern Pennines being unsuitable for the manufacture of modern silica bricks. Consequently although vast reserves of quartz arenite exist in the Northern Pennines in horizons such as the High and Low Brig Hazles in many instances silica bricks produced from these horizons are not sufficiently refractory for modern usage.

Suitable horizons for the manufacture of modern silica bricks include the Harthope Ganister and Tow Law ganister. The latter horizon is thin (commonly < 1 m.), and has been worked at many of the most accessible localities. Consequently the cost of extraction probably prohibits any further exploitation. Considerable reserves of the Harthope Ganister exist in the vicinity of Harthope Head and undoubtedly this is the most suitable horizon for future refractory use. Other quartz arenites, particularly those in the basal Westphalian A e.g. West Butsfield ganister may prove useful but in many cases are thin and probably uneconomic to extract. Thicker horizons such as the Flinty Quarry sandstone and the Park Burn quartz arenites (except the 3rd Lynnshield quartz arenite) may form useful raw materials for silica bricks, but as yet remain untested on a reasonable scale. Many other horizons exist, but most are too low in quartz content or too remote to be economically useful.

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