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THE GLACIAL DEPOSITS OF EASTERN DURHAM

by

Peter Beaumont B.A. (Dunelm)

A thesis presented for the Degree of Doctor
of Philosophy in the University of Durham.

December 1967.



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Introduction

This thesis describes work undertaken on the glacial deposits of Eastern Durham. In the work a series of techniques are employed in an attempt to discover relationships between the various stony clay deposits of Eastern Durham which are not apparent from the normal stratigraphical investigations which have been employed previously in the area. Many of the techniques used are employed for the first time in studying the glacial deposits of north-east England, and some have not been recorded in published work before.

The study is therefore a pioneering effort with no advance knowledge of the pitfalls one may encounter. For this reason it was felt wise to employ a number of different techniques to a limited extent rather than to concentrate on a single technique which might produce negative, or inconclusive results. Some of the methods used did fall within this category, but it has only been possible to show this as the result of detailed work and analysis. It is hoped that workers in other areas will benefit from this knowledge. It was also found that techniques which have proved of excellent diagnostic value in the U.S.A. have been of little value in Eastern Durham.

In this work attention has been concentrated almost exclusively on the stony clays of the area, for it is these deposits, which if they represent sub-glacial tills, hold the key to the sequence and number of glaciations within Eastern Durham. Far too often in the past stony clay deposits have been cited as evidence of a glacial phase without any other contributory evidence being advanced. In an attempt to overcome this problem part of this work has concentrated on an



elucidation of diagnostic properties of a sub-glacially deposited till, and a comparison of these with the properties of stony clays believed to have had different modes of origin.

Finally the work has obtained information on the stony clays as deposits in themselves. Such deposits make up about 70% of the surface exposures of Eastern Durham, and are therefore of considerable importance in the geomorphic evolution of the area. Yet at the same time nowhere in the local literature is any quantitative indication given of the variability of such deposits, nor have attempts been made to calculate the average proportions of the different constituents present in such deposits.

The thesis has been compiled in three sections. Section I is an introductory section and includes a description of the study area, a history of previous research in Quaternary studies in northern England, and a description of the stratigraphy and distribution of the glacial deposits of Eastern Durham.

Section 2 describes the analytical work carried out on the glacial deposits.

In Section 3, using the analytical data together with field observations the modes of origin of glacial deposits in general, and within Eastern Durham in particular are discussed. A consideration of the general sequence of events during the Quaternary era in northern England is also included.

S E C T I O N 1

Introductory

Chapter 1

TOPOGRAPHY AND DRAINAGE

A. TOPOGRAPHY

Introduction.

Eastern Durham forms part of the coastal lowland of north-east England, and is situated between the Pennine Uplands and the North Sea. The region forms the northern continuation of the English Lowlands and links the Vale of York with the coastal plain of Northumberland and eastern Scotland. (Fig 1.)

In northern England the Pennine Uplands form the principal relief feature and consist of a large north to south fault bounded structure which has been tilted to the east. Accordant summits and shelf features are conspicuous elements of the Pennine landscape, and are considered by some authors as evidence of ancient land surfaces adjusted to successively lower base levels. (Linton D.L. 1951, Maling D.H. 1955, Sissons J.B. 1954, Wooldridge S.W. 1950). The Pennine Uplands reach their greatest elevation of 2930 feet above sea level at Cross Fell overlooking the Vale of Eden, and fall gently away to the east in a series of long watershed ridges between the Rivers Tyne, Tees and Wear. These ridges end abruptly at heights of about 700 feet overlooking the Wear Lowlands.

In Northumberland to the north the relief of the Pennine Uplands is much lower with very few areas rising above 1000 feet. Bare moorland forms most of the western area, while to the east thick glacial drift gives rise to an undulating and rather featureless landscape. To the south of the area the Cleveland Hills form a major escarpment which marks the northern edge of the North York Moors.

Figure 1.

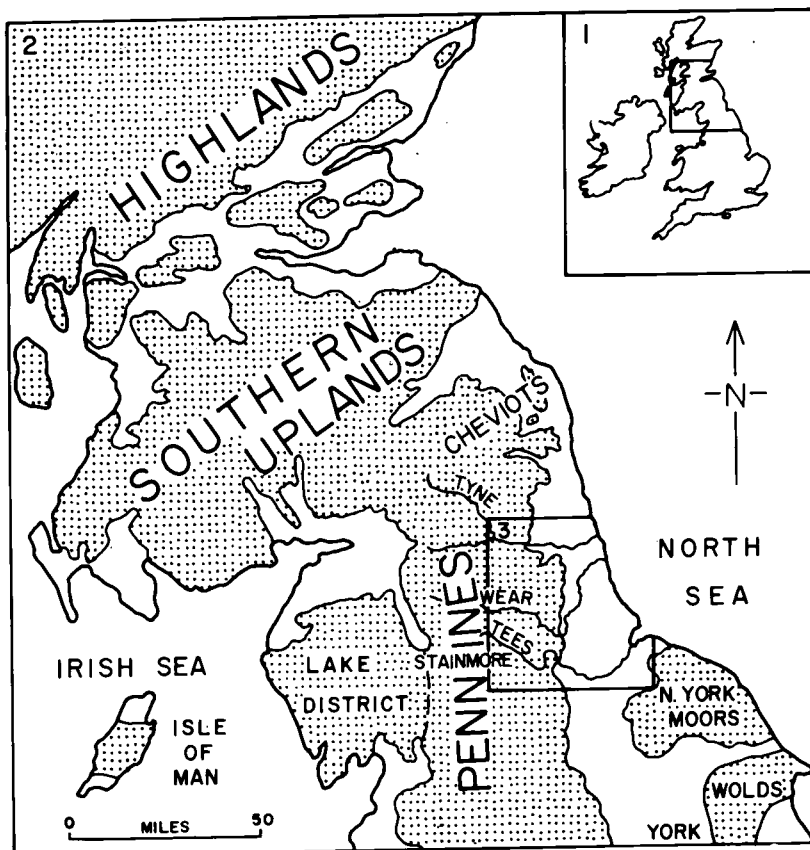
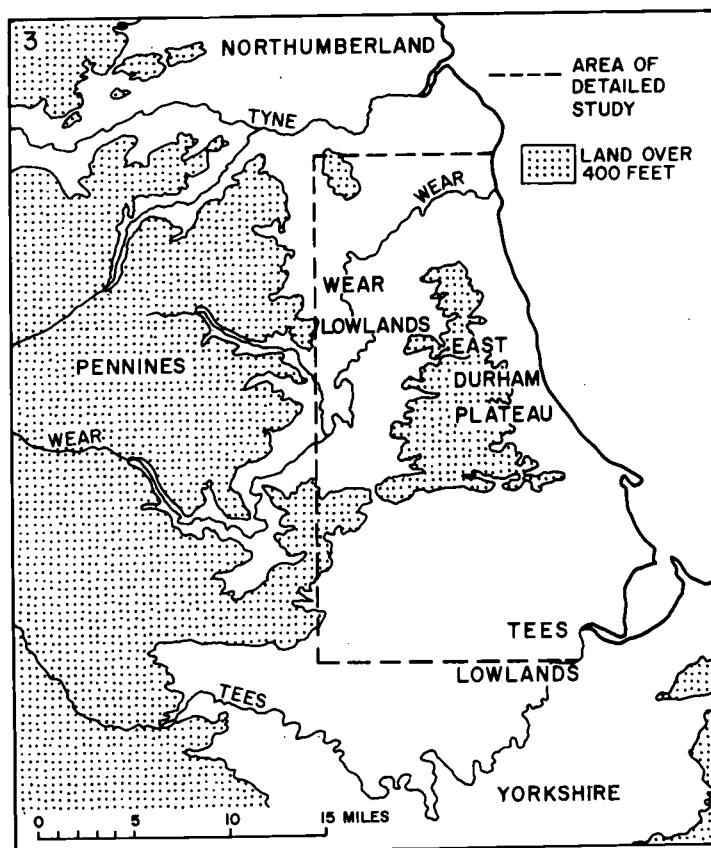


Figure 2.



Eastern Durham.

The relief of Eastern Durham, which lies everywhere below 750 feet can be divided into three topographical regions. (Fig 2 and 3).

- a. The Wear Lowlands
- b. The Magnesian Limestone Escarpment and Plateau
- c. The Tees Lowlands

a. The Wear Lowlands

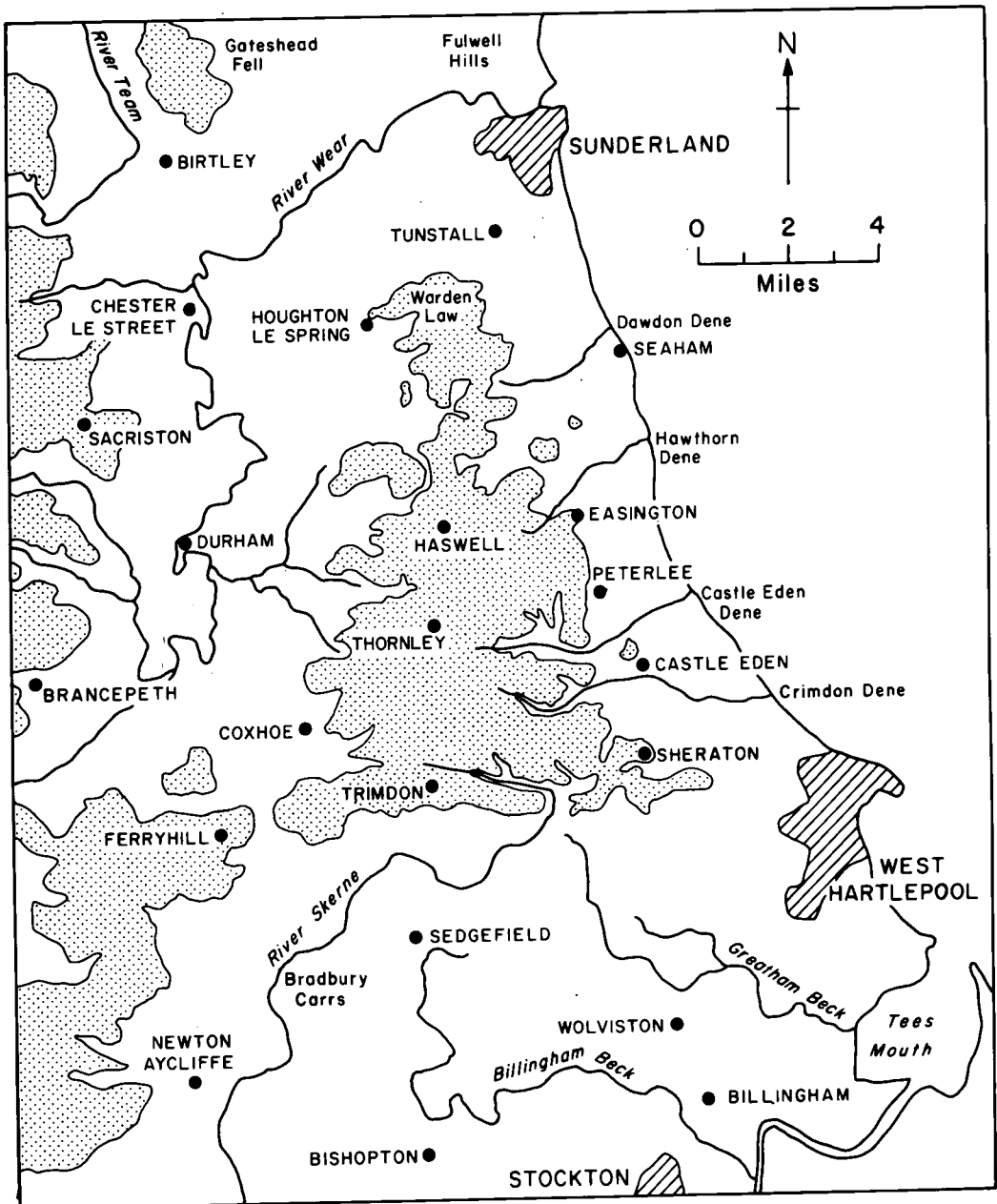
The Wear Lowlands form a north-south corridor of constructional topography dominantly composed of thick glacial sands and clays. Widespread depositional surfaces are a characteristic feature of the area at heights of 280-350 feet to the south of Durham City, and at heights of 140-200 feet around Chester-le-Street.

Into these surfaces the River Wear and its tributaries have incised themselves to form a series of gorge-like channels, interrupted in areas of less resistant material by wide floodplain development. With the exception of these steep valley sides, gentle slopes predominate within the area.

b. The Magnesian Limestone Escarpment and Plateau

The Magnesian Limestone escarpment, rising abruptly from beneath thick superficial deposits, marks the eastern boundary of the Wear Lowlands. It forms a west-facing feature cut in solid rock which stands about 200 feet above the area to the west, and reaches a maximum altitude of around 630 feet in the area near Cassop Colliery.

Figure 3.



Despite fluvial erosion, which has caused its rather dissected form, the escarpment presents a remarkably unbroken feature throughout its length, and is breached completely in only three places. The most spectacular of these breaches is the glacial meltwater channel at Ferryhill.

East of the escarpment on the dip slope of the Magnesian Limestone, the East Durham Plateau forms a triangle of land reaching the present coastline. Locally the plateau exceeds 500 feet in altitude, but in general the higher points show a marked accordance in height between 400-450 feet.

Near the coast a line of low hills from Tunstall to Castle Eden is formed by the outcrop of the more fossiliferous reef limestone, and in the Sheraton area a series of morainic ridges adds relief to an almost flat topography.

The fall of the plateau eastwards is usually quite gentle but near the coast a sudden drop to the coastal plain is seen on the eastern side of the reef knoll features. The coastal plain is rarely more than half a mile wide and is best developed in the area immediately south of Easington.

A series of short west to east streams drain the plateau towards the coastal fringe. In their lower courses these streams are deeply entrenched to form the steep-sided wooded valleys known locally as denes. Castle Eden Dene and Crimdon Dene are the two largest.

c. The Tees Lowlands.

South of the Magnesian Limestone Plateau the altitude of the land drops slowly into the thickly drift covered area of the Tees Lowlands. The western part of this area is drained by the circuitous course of the River Skerne, and includes the large peat filled basins of

Bradbury and Morden Carrs, which until recently were areas of marshland or standing water. Eastwards the hummocky depositional topography slopes down more rapidly towards the wide flat estuarine lands of the River Tees. Along the present course of the Tees a wide floodplain up to one mile in width is developed, with a series of higher terrace features up to 100 feet above the present stream.

B. DRAINAGE.

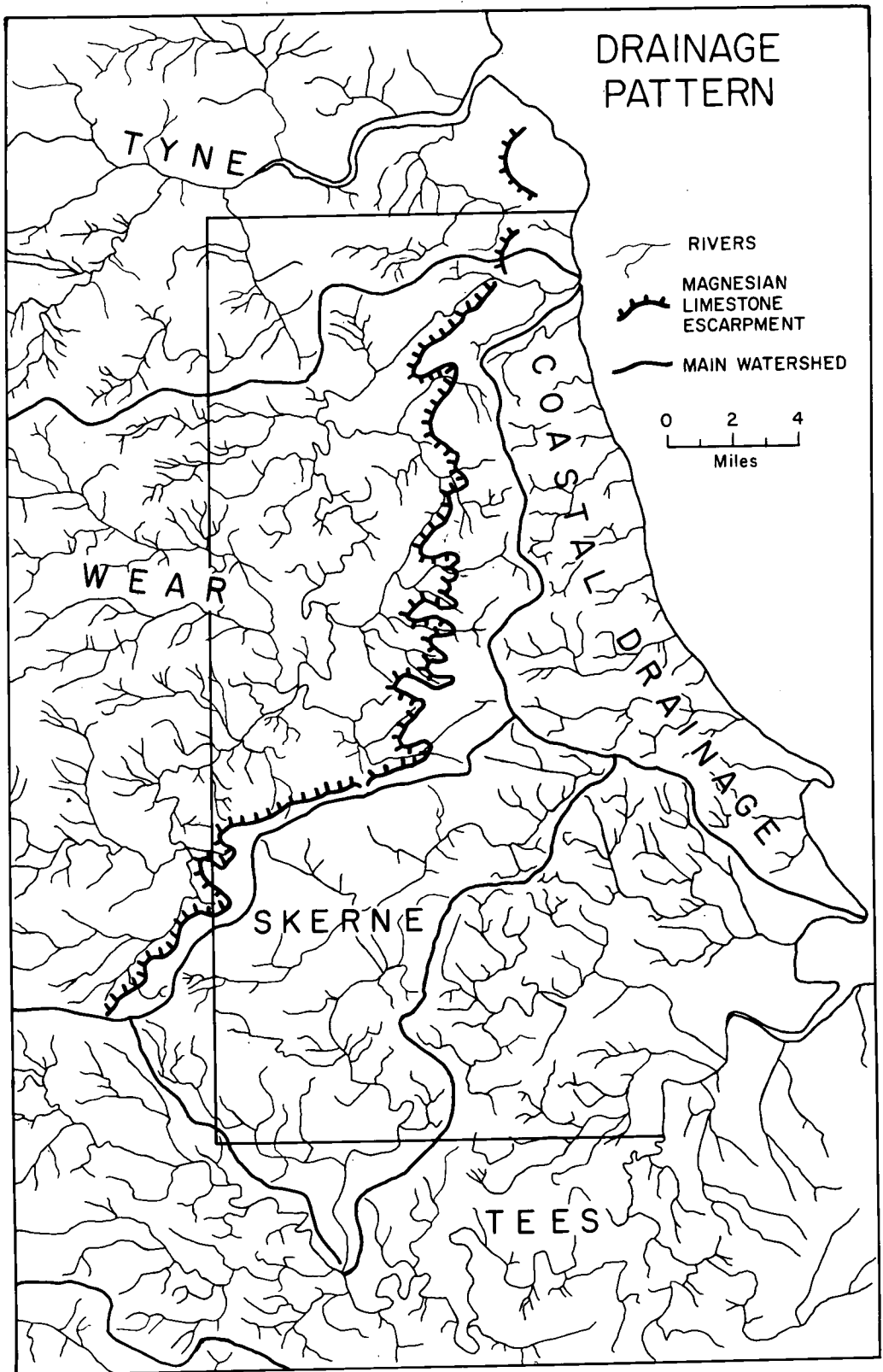
The drainage pattern within the area of Eastern Durham is extremely simple and divisible into three main units. (Fig 4.)

The largest unit comprising the Pennine foothills and all of the Wear Lowlands is drained northwards by the River Wear to its mouth at Sunderland. Within this area only two tributary streams are of any size, and these the Rivers Browney and Deerness drain the Pennine foothills. In the extreme north a small area is drained directly to the Tyne by the River Team and the River Derwent.

The only anomalous feature of the drainage pattern of Eastern Durham is the positioning of the main watershed between the east bank tributaries of the River Wear and the dip slope streams of the East Durham Plateau. This watershed does not as one might expect coincide with the crestline of the Magnesian Limestone escarpment, but has been displaced by the headward erosion of the tributaries of the River Wear to a position between one and three miles east of the line of the escarpment. This has meant that the catchment area of the streams flowing directly to the coast has been reduced to a belt of land between three and eight miles in width. Within this area the two largest streams, Castle Eden Dene and Crimdon Dene occur in the south where the watershed is farthest inland.

The final unit is drained by the River Tees. Its largest tributary, the River Skerne, receives most of the northern

Figure 4.



drainage of the Tees area and carries it through its wandering course to join the River Tees south of Darlington. In the eastern portion of this unit the drainage is effected through the small streams of Greatham Creek, Billingham Beck, and the Hart Burn.

Chapter 2

GEOLOGY

Introduction.

This chapter is a compilation of work described in the following papers :- Anderson W. 1945; Armstrong G, and Kell J. 1951; Armstrong G. and Price R.H. 1954-55; British Regional Geology:- Southern Uplands; Northern England; The Pennines and adjacent areas; East Yorkshire and Lincolnshire. Browell E. and Kirkby J.W. 1866; Daglish J. and Forster G. 1863; Dunham K.C. 1948; Garwood E.J. 1891; Hickling H.G.A. 1931; Hickling H.G.A. 1950; Hickling H.G.A. and Robertson T. 1949; Hodge M.B. 1930; Howse J.W. 1949; Lebour G.A. 1893; Lebour G.A. 1894; Marley J. 1882; Smith D.B. 1958; Trechmann C.T. 1915; Trechmann C.T. 1925; Trechmann C.T. 1954; Wood F. 1950; Woolacott D. 1897; Woolacott D. 1913.

In a study of the glacial deposits of Eastern Durham a description of the solid geology for its own sake is of little relevance. It is from the outcrops of the solid rock and their overlying waste mantle however that the deposits making up the glacial drifts are primarily derived, and for this reason it is essential that the broad pattern of outcrop, and the main lithological characteristics of the solid geology within the surrounding area, should be described.

The geology of northern England is characterised by the predominant outcrop of sedimentary strata of Carboniferous age in a broad belt from the Pennine Uplands to the Northumberland Coast. (Fig 5). Younger rocks are confined to two main areas. The first and most extensive is in south-east Durham and north Yorkshire where the Carboniferous rocks pass under a sequence of Permian, Triassic, and Jurassic strata. Secondly Permo-Triassic rocks also outcrop on the west of the Pennine Uplands in the Vale of Eden and in the Solway Lowlands. Pre-Carboniferous rocks are confined in outcrop to the Cheviot massif, the Lake District and the Southern Uplands. It is also in these areas that the only extensive outcrops of igneous material in northern England are found.

The major lithological characteristics and distribution of the rock types outside Eastern Durham are described first, and then the pattern of outcrop in Eastern Durham is considered in greater detail. (Fig. 5).

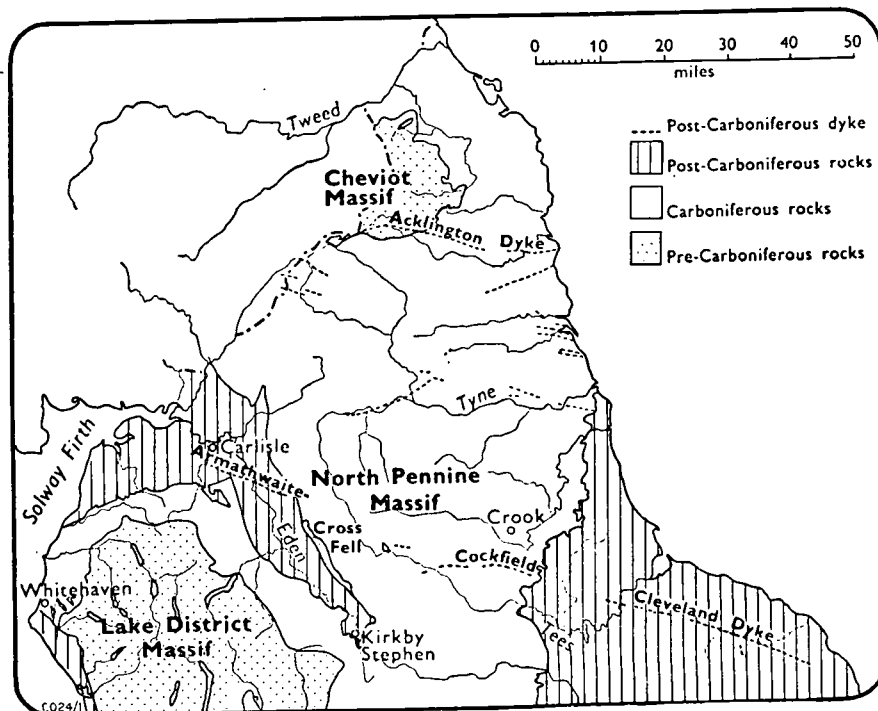
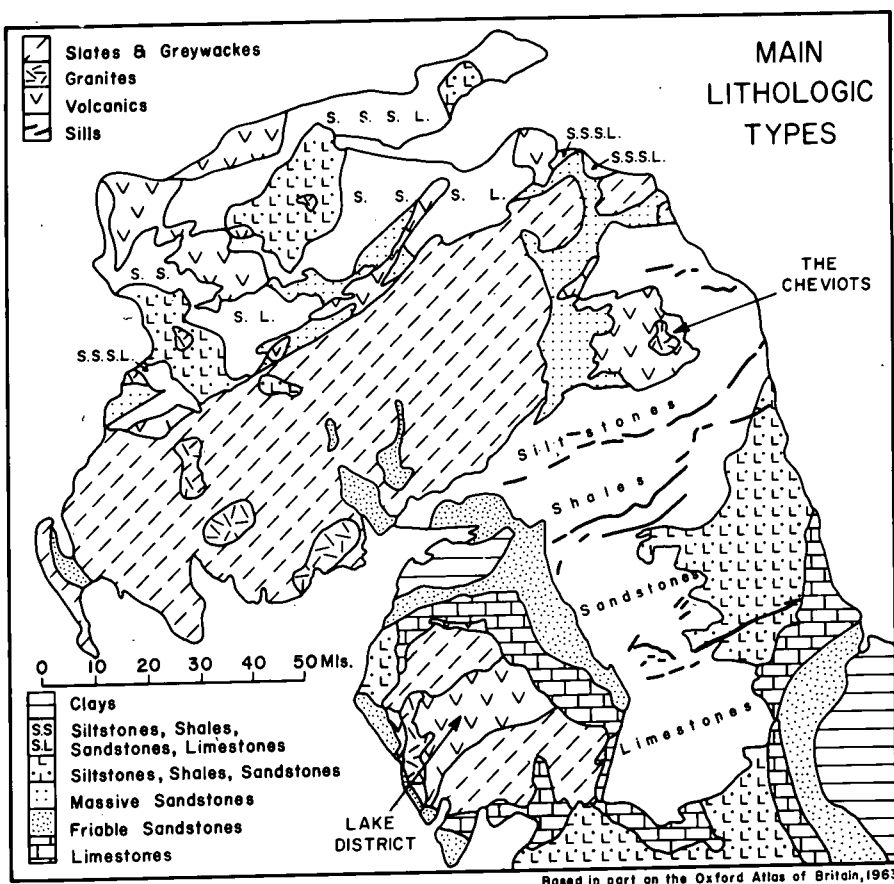
A. NORTHERN ENGLAND.

1. Pre-Carboniferous Rocks

a. The Lake District.

The central part of the Lake District is formed of pre-Carboniferous rocks which have been exposed by denudation following

Figure 5.



From Smailes

Northern England

the dome-like uplift of the area. The oldest rocks, chiefly slates of the Skiddaw Series, are exposed in the northern area around Keswick. To the south these rocks are succeeded by the Borrowdale Volcanic Series, lavas, ashes, and conglomerates which outcrop as a north-east to south-west belt across the central part of the Lake District. The southern boundary of the Borrowdale Volcanic Series is marked by a major north-east to south-west tear fault along which Silurian shales, flags and grits have overridden the Borrowdale Volcanic Series to form the southern part of the Lake District. All of these Lower Palaeozoic strata show an east-north-east to west-south-west "Caledonian Trend" imparted to them by the intense orogenic activity of Lower Palaeozoic times. Associated with these violent earth movements was a series of igneous intrusions which gave rise to the extensive outcrops of the Ennerdale Granophyre and the Eskdale Granite, and the minor, though still famous, masses of the Shap and Threkald Granite.

b. The Cheviot Massif

The Cheviot Massif is the result of vulcanicity during the Devonian Period. This vulcanicity led to the formation of a large series of andesitic lavas into the centre of which a granitic mass was later intruded. At the present day the pattern of igneous outcrop^{is} an area of about 200 square miles, roughly circular in plan to the south-west of Woller.

c. The Southern Uplands.

The Southern Uplands are characterised by north-east to south-west trending belts of Lower Palaeozoic rocks of Silurian and Ordovician age. These rocks are dominantly of sedimentary origin and have been subjected to intense folding by earth movements associated with the Caledonian Orogeny. Considerable lithological variation in

the strata is a feature of the area. However very widespread outcrops of both greywackes and conglomerates are characteristic of the area as a whole.

In Ordovician times igneous activity was extensive and gave rise to a whole sequence of lavas, tuffs, and agglomerates. During Old Red Sandstone times the intrusion of granite took place, of which the most famous example is the Criffel Granite.

2. The Carboniferous Rocks.

The Carboniferous rocks of northern England consist of an alternating sequence of marine, shallow water and deltaic deposits. The most meaningful distinction in this series is between the Lower Carboniferous with thin but often pure limestone beds, and the Upper Carboniferous, completely lacking any limestones, but which is characterised by the occurrence of productive coal seams. A transitional series, though not pronounced, does occur between the Upper and Lower Carboniferous in which neither limestones nor coals are well developed. In Yorkshire this group is known as the Millstone Grit, but in County Durham this series is classified mainly as part of the Lower Carboniferous.

The Lower Carboniferous strata outcrop in a broad north to south belt through northern England. The sediments show considerable lateral variation and it is difficult to construct a detailed succession which is applicable to the whole area. The major lithological division in the Lower Carboniferous is found along the line of the Stublick Fault, which itself parallels the line of the Tyne Valley. To the north the Carboniferous succession is represented by a whole series of shallow water deposits comprised dominantly of sandstones, shales, and occasionally coals, which appear in successively younger outcrops around the volcanic material of the Cheviot Massif. The oldest strata are the Cementstone Shale Group, which are in turn succeeded by the coarse massive sandstone of the Fell Sandstone Group. The overlying

strata of the Scremeston Coal Group are up to 2000 feet in thickness and composed dominantly of soft sandstones and shales. They form very extensive outcrops in the area south-west of the Cheviot Massif.

Throughout this early Carboniferous sedimentation the Pennine Uplands south of the Tyne valley were still undergoing sub-aerial weathering. When they were finally submerged much less deposition occurred upon them than on the area to the north. The deposits so produced, known as the Yoredale Series, are marked by the rhythmic succession of limestones, shales, sandstones and coals. Persistent massive limestone beds are found in this sequence, but they are less well developed than in the area of the Yorkshire Dales to the south. In the Northumberland and Durham areas the limestones only make up about 10 per cent of the total sequence.

Upper Carboniferous strata outcrop in a triangular area to the east of the Lower Carboniferous rocks to form the Northumberland and Durham Coalfield. The total thickness of this strata is more than 2000 feet, and in all more than 20 workable coal seams are known. Sandstones, siltstones and shales are the dominant lithologies with the coal seams making up less than 5 per cent of the total sequence.

Intruded into these Carboniferous rocks of Northumberland and Durham is the Whin Sill, a mass of quartz dolerite which forms extensive north facing escarpments within northern England.

3. Post Carboniferous Rocks.

The post Carboniferous rocks rest unconformably on greatly eroded Carboniferous strata. Deposits of the Permian are found on both sides of the Pennine Uplands, but the two areas are characterised by markedly different lithologies. In the Vale of Eden land deposition under desert conditions gave rise to the thick Penrith Sandstone, while in County Durham about 800 feet of Magnesian

Limestone were deposited in a desiccating inland sea. In the upper part of the Magnesian Limestone sequence a series of thick salt and anhydrite beds is found.

Overlying these beds in County Durham is a series of red marls which passes upwards into the thick red Bunter Sandstone and Keuper Marls of the Tees Lowlands. In the Vale of Eden the counterparts of the Bunter Sandstone and the Keuper Marls are the St. Bees Sandstone and the Stanwix Shales.

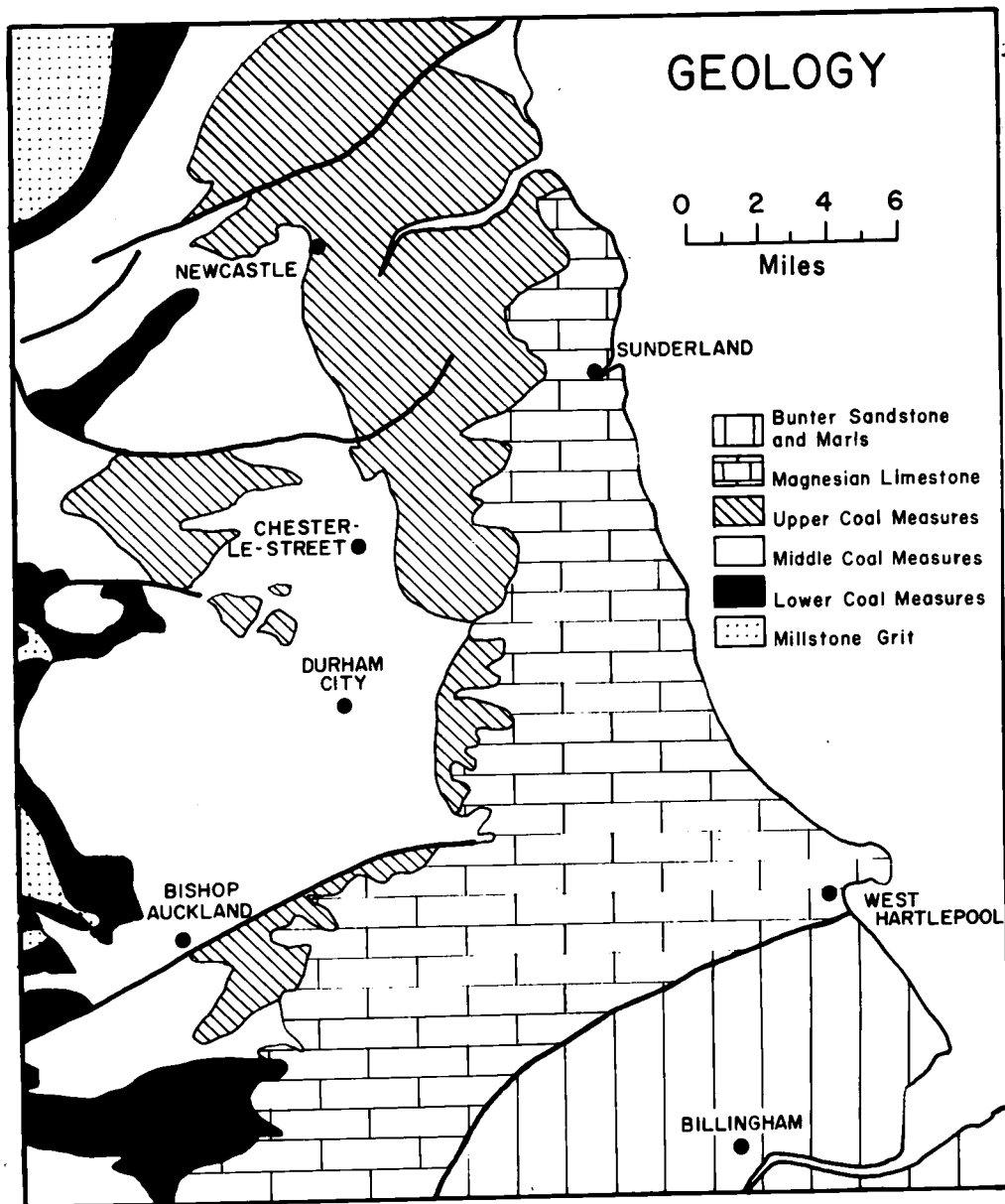
The youngest of the solid strata of northern England are the Triassic and Jurassic rocks of the North York Moors. They are characterised by shales and massive and flaggy sandstones, although thin coal seams, limestones and ironstones are also found.

B. EASTERN DURHAM (Fig. 6)

The rocks outcropping within Eastern Durham are of Upper Carboniferous, Permian and Triassic age. With the exception of a few igneous dykes found in the Coal Measures all these rocks are of sedimentary origin and have not been subjected to the intense orogenic activity experienced by other parts of the British Isles. As a result the dips of the strata are gentle with a marked component to the east and south-east.

Within Eastern Durham there are two lithological changes in the strata which are of the greatest glacialogical significance. In the centre of the area the outcrop of the Magnesian Limestone commences as a west facing escarpment and rocks of this age cover all the eastern parts of the area. To the south of the Magnesian Limestone Plateau, a major fault line known as the West Hartlepool Fault downthrows Bunter Sandstones and marls against the Magnesian Limestone.

Figure 6.



As a result of these two main structural elements three main lithological divisions can be distinguished in Eastern Durham.

- a. In the north and west the yellow, grey, and black sandstones, siltstones, shales and coals of Carboniferous age
- b. In the east the yellow dolomitic Magnesian Limestone
- c. In the south the bright red Bunter Sandstone, and the red and green Keuper Marls.

a. The Carboniferous rocks of the north and west.

The oldest strata in Eastern Durham, of Coal Measures age outcrop in the north and west in the Pennine Foothills and the Wear Lowlands to form part of the Northumberland and Durham Coalfield. The Coal Measure sediments are found in the form of a north-west to south-east synclinal basin which has its deepest point buried beneath Permian rocks in the vicinity of Sunderland.

Most of these strata, with the exception of the higher ground of the Pennine Foothills, are buried beneath thick deposits of glacial drift and are exposed only along the courses of rivers, or where some of the sandstones form pronounced topographical features.

The majority of the Coal Measures strata were deposited under shallow water conditions, with occasional sub-aerial environments indicated by the presence of coal and its seat earth. The deposits as a whole represent periods of cyclical sedimentation which persisted from the Lower Carboniferous through to Coal Measures time. Each cycle or cyclothem is characterised by a series of deposits which reccur again and again, except where local conditions have caused a member of the cyclothem to be missing or of restricted occurrence.

A typical Coal Measures cyclothem includes the following strata :-

Coal
Sandy shale
Sandstone
Sandy shale
Mudstone and shale
Shale with marine phase at the base.

On lithological grounds the Coal Measures can be divided into three groups.

1. The Lower Coal Group consists dominantly of sandstone and gannisters with only a few coal seams and mudstones. This division outcrops only in the extreme western part of the area.

2. The Middle Coal Group, or Productive Coal Measures occupy most of the western outcrop of the exposed coal field in Eastern Durham, from the Team valley in the north to the Magnesian Limestone escarpment in the south. The total thickness of this group is of the order of 800 feet and includes between 15 and 20 important coal seams. Sandstones, shales and mudstones are associated with each of the cyclothem, and there is a marked tendency for the arenaceous component to increase upwards in the series. The coal seams are the most reliable members of the sequence, while the associated sandstones show a marked tendency to wedge out laterally.

3. The Upper Coal Group reaches a thickness of 1200 feet in the concealed coalfield beneath Sunderland. In its exposed portion in north Durham it is an arenaceous sequence, and no marked lithological break occurs between it and the underlying Middle Coal Group. The emphasis is decidedly on sandstones with individual beds more than 50 feet in thickness, separated by sub-ordinate argillaceous zones of sandy shale and fireclay. The thicker sandstones, known as the High Main Post, and the Grindstone Post, form a ridge of high ground in the

Gateshead area, from which the once famous Newcastle Grindstones were quarried. The upper part of the Upper Coal Group represents a marked lithological change being predominantly argillaceous. The sandstones where present in this upper sequence are always thin.

b. The Permian rocks of the east.

The Permian rocks of Eastern Durham were deposited on highly eroded strata of Carboniferous Coal Measures Age, and show wide areal and lithological variations, from wind blown sand to beds of gypsum, anhydrite and rock salt. The yellow dolomitic Magnesian Limestone does however form the vast majority of the total outcrop. It outcrops almost continuously along the Durham coast from the River Tyne to Hartlepool, and in the west forms a marked escarpment overlooking the Coal Measures of the Wear Lowlands.

The sequence of the Permian outcrop in Eastern Durham is as follows :-

Upper Magnesian Limestone

Hartlepool and Roker Dolomite
Concretionary Limestone
Flexible Limestone (local)

Middle Magnesian Limestone

Brecciated Limestone
Reef Limestone

Lower Magnesian Limestone

Marl slate

Yellow Sands

To the south of the West Hartlepool Fault the buried Permian succession changes considerably, and in the upper division beds of salt and anhydrite are extensively developed. Such rocks do not however form a surface outcrop within the area. (The full Permo-Triassic sequence of south of the West Hartlepool Fault is

listed in section c.)

1. Yellow Sands.

The basal formation of the Permian is the false bedded deposits of the Yellow Sands. They fill hollows in the denuded surface of the Coal Measures and are generally considered to be at least in part sand dune deposits fringing the subsiding margin of the Permian Sea. Their outcrop is limited to the base of the Permian escarpment from South Shields to Ferryhill.

2. The Marl Slate.

The Marl Slate is believed to be a lagoonal or estuarine laminated mud, deposited by the encroaching Permian Sea over the basal Yellow Sands. In many respects it represents a passage bed from the arenaceous beneath to the calcareous beds above. It is generally only 3 to 5 feet in thickness, but is very persistent and characterised by a great number of fish and plant remains.

3. The Lower Limestone.

The Lower Limestone outcrops in a belt 1 to 2 miles wide along the western edge of the East Durham Plateau and is generally covered by drift deposits. The only large surface outcrops are to be seen in the Quarrington Hill and Coxhoe areas, where the bedding is distinct and regular and the colour yellow or yellowish brown.

4. The Middle Limestone.

Beds of the Middle Limestone form an interrupted north to south chain of reef knolls in the coastal area from the Tunstall Hills to Blackhall Rocks. The reef appears to have originally formed as a bank of shells some 10 to 12 miles seaward of the western shore of the Permian Sea.

West of the reef the Middle Limestone consists of regularly bedded undisturbed dolomites, while to the east the reef

thins and is replaced by unfossiliferous and highly brecciated strata which forms low ground in much of the coastal area from Salterfen Rocks to Horden Colliery.

5. The Upper Limestone.

The Upper Limestone rests on, or to the east of the Reef and is believed to have been deposited in an eastward shrinking sea. It is divisible into three main formations.

The Flexible Limestone is a persistent bed in the north and is visible in Marsden and Fulwell Quarries.

The Concretionary or Cannon Ball Limestone is characterised by the rare development of large concretionary structures. It attains a thickness of between 50 to 200 feet and is best developed in the Sunderland area.

The Hartlepool and Roker Dolomites are stratigraphically the highest beds of the Permian which outcrop in the area of the East Durham Plateau. Their most extensive outcrop is found near Sunderland and Hartlepool, where they vary in character from massive friable oolitic dolomites, to porous and thinly bedded dolomites.

c. The Triassic rocks of the south.

To the south of the West Hartlepool Fault in south-east Durham the solid rock outcrop is composed of the Bunter Sandstone and the Permo-Trias Marls. The Triassic rocks are thickly covered with glacial drift and surface exposures are rare. Lithologically they consist of bright red sandstone with partings of red and grey green variegated marls, and appear to pass downwards without a break into the much more argillaceous Saltiferous Marls.

The full Permo-Triassic succession is as follows

Triassic Sandstone	
Permo-Triassic Marls	300-350 feet
Upper Anhydrite	10
Marl	20
Main Salt	100
Main Anhydrite	45
Upper Magnesian Limestone	75
Lower Salt	60
Lower Anhydrite	
Lower Magnesian Limestone	600-700
Basement Beds	Variable

Chapter 3.

HISTORY OF PREVIOUS RESEARCH IN NORTHERN ENGLAND.

In the present work the author has had to place considerable reliance on the description, distribution, and interpretation of the glacial deposits as put forward by workers in northern England within the last one hundred years. It is therefore important that at this stage the main findings of such work should be described and the evolution of ideas on Pleistocene history be outlined. In this brief sketch no attempt is made to include the work of every author, but only those who in the author's opinion have made significant contributions to the knowledge of the glacial deposits within the area. (Local works of lesser importance are however recorded in the bibliography).

Owing to its northern position within the British Isles and its relative isolation, County Durham has never attracted Pleistocene geologists to an extent seen in the more famous localities of East Anglia and Holderness. Yet the coastal sections of County Durham compare favourably as regards quality of exposure with both these previously mentioned areas. As a result Durham has lacked a continuity of study of the Pleistocene deposits, and has been characterised by a few important works separated by long periods of relative inactivity. Isolation has also meant that many of the local workers were not fully aware of the modern views on glaciation which were being put forward in the south of the country. As a consequence Durham has always seemed to some an isolated backwater from which very few new ideas on glacial theory have evolved.

Interest in the glacial deposits of County Durham is well over one hundred years old and seems to have been initiated by the spread of coal mining eastwards into the drift covered lands of the Wear Valley.

As early as 1863 mining engineers such as Wood N. and Boyd E. had traced the approximate lines of the large drift filled valleys, which had proved such a hinderence to mining activity, but at the same time had paid little attention to the origin of the deposits themselves.

At a time when the "Glacial Theory" was just gaining widespread acceptance within the British Isles, Howse R. (1864) working in Northern England was one of the first people to recognise the significance of land based ice sheets and their erosive power. His work in the lower Tyne valley led him to recognise three glacial till deposits which he concluded from striae and erratic content had been derived from Scandinavia, the Lake District, and Cheviot areas respectively.

On the western side of the Pennine Uplands Goodchild J.G. (1875) in a long and detailed paper further discredited the idea of boulder clays as water-lain deposits. His work led him to conclude that at maximum glaciation the Vale of Eden was filled with a large ice sheet which flowed eastwards over the Tyne Gap and Stainmore depression to form one of the till sheets which Howse had previously described.

It was also during the 1870's that the Geological Survey commenced its survey of the lower Tees area. As a result of this work the geologists Howell H.H. Cameron A.G. and Barrow G. produced a series of drift maps of the area, but no memoir was ever published. They distinguished two boulder clays separated by sand and gravels, but the lack of a memoir has meant that the exact interpretation of these deposits is extremely difficult.

By the beginning of the twentieth century a general picture of the distribution of the glacial deposits of northern England had been built up. It was however in the first twenty five years of the twentieth century that a special interest was shown in the glaciation of the area, and it was in this period when most of the key discoveries were made.

In 1902 Kendall P.F. published his classic paper on the deposits and features of the Cleveland Hills. In this work he described a threefold division of the deposits into an Upper Red Boulder Clay, Middle Sands and Gravels, and a Lower Blue Boulder Clay. This succession was similar to that described by the Geological Survey Officers, Barrow G. and Foxe-Strangeways C. working respectively in the North Cleveland and Northallerton areas. Kendall thought that the first ice to reach the area was from the congested Irish Sea Basin, and that this, as Goodchild had earlier envisaged, had flowed over Stainmore and out to sea at the Tees estuary. The second phase of glaciation he claimed was marked by the diversion of this Tees ice sheet into the Vale of York with the growth of the Scandinavian ice sheet. Kendall was at this period uncertain whether the Scandinavian ice sheet ever reached the east coast of England, but concluded that if it did, it was soon pushed offshore by the southward moving Cheviot ice. This Cheviot ice sheet he thought coincided with the period of maximum glaciation.

At the same time that Kendall was working in the Cleveland Hills, Derryhouse A.R. (1902) was conducting research along the larger river valleys of the Alston Block. In the Tees valley he identified a tripartite division of the deposits similar to that of Kendall and was also able to distinguish between local ice originating in Teesdale and ice from the Lake District over Stainmore. Even at the period of maximum glaciation Derryhouse considered that the highest parts of the Pennine watershed were not ice covered. As a result Weardale, in which the main drift was described as a stiff blue boulder clay, was considered to have been an area of only local ice. To the north the southern tributaries of the River Tyne were plastered with a blue boulder clay similar to that of Weardale. Yet in the Tyne Gap a reddish gravelly drift was more common, which Derryhouse thought was continuous with drift in the Vale of Eden. He considered that in the Tyne Gap ice sheets from the Pennines and the Vale of Eden coalesced, and then moved eastwards as a single glacier to the mouth of the Tyne, where they became confluent with ice moving south from the Cheviots.

In the early part of the twentieth century the local geologist Woolacott D. commenced a whole series of publications on the glacial deposits of County Durham. In agreement with Kendall to the south, he recognised a tripartite division of the deposits, with a Lower Stony Boulder Clay, capped by widespread sands and gravels, and finally in a number of places only an Upper Clay. The basal member of the succession, the Lower Boulder Clay was well exposed resting on Magnesian Limestone south of Sunderland, and this clay from its erratic content was considered to have been derived from the north and west. The Upper Clay which possessed few stones and a remarkable prismatic jointing was considered to represent a boulder clay washed and resorted by the sea, and deposited under tranquil conditions at a time during or after the retreat of the ice.

The gravel deposits associated with these stony clays were considered by Woolacott to be indicative of a series of post-glacial raised beaches which pointed to a maximum submergence of the coastline of 150 feet. The highest beach, at 150 feet, was described around the Cleadon, Tunstall, and Fulwell Hills, with a lower beach at 100 feet being found along the coast from Seaham Harbour to Castle Eden Dene. The formation of the upper beach was regarded by Woolacott as the period when the upper part of the Lower Boulder Clay was eroded and redeposited as the Upper Prismatic Clay.

One of the most detailed descriptive papers on the glacial deposits was that of Merrick E. (1909), based on observations in quarries and brick pits throughout northern Durham. In this work he described a sequence of nine deposits having widespread occurrence in the lower Tyne and Wear valleys, which were to be used as the basis of research by many later workers.

Brown Clay. Yellow Clay. Rotten Loam.
 Common Clay.
 Surface Leafy Clay.
 Black Clay.
 Bottom Leafy Blue Clay.
 "Scarp".
 Sand.

The detail of Merrick's paper has much to commend it. Yet at the same time it suffers from a series of serious drawbacks. In it he fails to acknowledge, probably through a lack of pedological knowledge, that many of the features, such as colour and jointing, which he used to distinguish the deposits could have been produced solely through the weathering of a single deposit. Insufficient account was also taken of the fact that a number of the upper clays could have been recent solifluction deposits which have slumped over existing ground surfaces. The fact that a number of buried land surfaces do exist in the sequence seems beyond doubt from Merrick's evidence. The real problem is the date of their origin and the cause of their subsequent burial.

It appears that only one deposit, the "Scarp" can be regarded unquestionably as a boulder clay. Similarly only the leafy clays can be regarded as true lacustrine deposits. It is with the Common, Brown, Black and Yellow Clays that the problems of origin are greatest. The fact that they vary so much seems certain proof that they do not represent true boulder clays. They appear in part or in whole to have been derived from the "Scarp" or Leafy Clays, a fact which partially helps to account for their similarity to one or other of these deposits. As many of the pits where Merrick made his observations are now abandoned, the original evidence for this sequence is no longer available. From a consideration of the evidence presented by Merrick it seems reasonable to assume that the upper clays he described are derived from deposits formed by the washing or slumping of earlier deposits, perhaps under periglacial conditions. This would explain the chaotic nature of some of the deposits and the proximity of stoneless and stony clays.

Furthermore it would appear likely that in the upper part of the sequence the differentiation of the deposits on the basis of colour is more apparent than real, and merely represents a distinction between weathering horizons of a single clay.

The north-western part of County Durham was the subject of research in a paper by Herdman T. (1909) on the glacial phenomena of the Vale of Derwent. In this he described the lowest member of the glacial succession as a reddish brown or blue grey boulder clay, containing a large number of local and foreign stones. The key question is whether two separate clays exist or whether these two clays are lateral variations of the same deposit. The evidence of Derryhouse (1902) would suggest that the red clay is possibly of Lake District origin, while the blue clay is derived from local Carboniferous material. However Herdman does not distinguish between the two deposits and this to some extent diminishes the value of his work.

The Pleistocene succession of Northumberland was outlined by Smythe J.A. (1912) in a paper in which he claimed two clays of differing areas of origin to be present within the area. The typical boulder clay was a blue grey plastic clay charged with limestone, sandstone, and Whin Sill rocks. It occurred over the whole area apart from the Cheviot Massif, and was generally the deposit resting on rock head. A reddish clay with fewer stones was seen to overlie the typical bluish grey clay, and was traceable as far south as the River Wansbeck. From their rock contents it appeared that the lower grey clay had a western origin, while the red clay stemmed from a more northerly^R_A direction.

In explanation of the deposits Smythe argued that, at the beginning of the glacial period, the hills between the North Tyne and the Cheviot Massif radiated ice streams in all directions. With time the pressure of the western ice from the Vale of Eden increased, diverting

the local glaciers, until at maximum glaciation it seemed probable that this western ice held complete sway almost to the east coast. After the maximum of the glaciation, pressure from the North Sea ice became the prime factor diverting the Tweed and local ice along the coast in a southerly direction.

Smythe's findings in agreement with Kendall's some fifty miles to the south, show that western ice from the Lake District was the first to reach the east coastal fringe. Both also stress that Cheviot ice was the last ice sheet to leave the area, and that this occurred at the very close of glacial conditions. It appeared that the clay of western origin in Northumberland bore more resemblance in colour to the local boulder clays of the Pennine valleys than the reddish clay coming over Stainmore from the Lake District. The deposit derived from the Cheviot area however was essentially identical in visible characteristics in both Northumberland and in the Cleveland.

The discovery and recognition of a Scandinavian Clay on the Durham coast was made by Trechmann C.T. (1915, 1931). The possible existence of such a deposit has long been suspected as a number of Scandinavian erratics had been found along the coasts of both Northumberland and Durham, although Howse, Kendall and Woolacott had been of the opinion that the Scandinavian ice sheet had never actually reached the coastal area. The shelly basement clay with Scandinavian erratics, as Trechmann described the deposit, filled a pre-glacial depression in the Magnesian Limestone at Warren House Gill, and was considered to be a true glacial deposit laid down on the edge of the North Sea ice sheet. In agreement with Lamplugh G.W. (1906, 1907) in Holderness Trechmann believed that the North Sea ice sheet had attained its maximum extension before local ice had reached the east coast, and that it represented an independent and early phase of glaciation.

Overlying the Scandinavian Drift was the Main Cheviot Drift which Trechmann considered to have been formed by the mixing of ice streams from Scotland, the Cheviots, the Lake District and the Pennines. In the earlier stages of glaciation the Scottish ice was regarded as having had freer access to the east coastal region, than at a later period when the Cheviot and Pennine glaciers predominated. The Main Cheviot advance was regarded as the product of maximum glaciation. Trechmann therefore concluded that the maximum glaciation of the east coast was later than on the west of the Pennines where maximum glaciation was thought to have established an easterly ice flow over Stainmore and the Tyne Gap. Trechmann considered that the Cheviot ice had only invaded the coastal areas of Eastern Durham and that its western limit was marked by a series of kames in the Sheraton area. West of this Cheviot limit a clay with abundant Lake District and Scottish rocks was found. Such a clay was described by Trechmann as covering most of the Magnesian Limestone Plateau area.

In the period up to 1915 very little evidence had been found indicating undisputed intervals in the glaciation of County Durham. Within the next ten years this position was considerably changed with the discovery of a series of deposits indicative of sub-aerial or marine conditions in the glacial sequence. As a result, these findings led to a spate of reinterpretations of the glacial deposits in terms of interglacial and interstadial periods.

Fossiliferous clays and a "loess" deposit, both associated with the Scandinavian Drift were described by Trechmann in 1919. The clays which appeared to be the oldest glacial deposits in the area, were found in a series of fissures in the coastal region. They possessed a Pliocene or Early Pleistocene flora and appeared to have been torn up by the advance of the Scandinavian ice, and rammed into fissures in the Magnesian Limestone. The "loess" deposit was found at

Warren House Gill directly overlying the basal Scandinavian Drift. It was considered by Trechmann to be identical with European loessic material, and to indicate an interglacial period between the deposition of the Scandinavian Drift and the arrival of the ice sheet which deposited the Cheviot Drift.

With the reopening of the coastline after the First World War, a raised beach deposit resting on a shelf cut in the Magnesian Limestone was discovered by Woolacott D. (1920) at Easington. It possessed a rich temperate shelly fauna and was considered to have had the same origin as the sands and gravels which stretched some twelve miles along the Durham coast. The date of origin was considered Late or Post Glacial by Woolacott, although Trechmann thought of it as a remnant of an interglacial or interstadial beach.

In the light of these new findings a comprehensive interpretation of the Durham Pleistocene succession was outlined by Woolacott (1921), in which he indicated the existence of four glacial periods separated by intervals of varying importance. The oldest deposit was considered to be the Scandinavian Drift, deposited by an ice sheet from Scandinavia. This was followed by an interval, possibly interglacial, in which the "loess" was deposited. The next glacial episode was marked by the advance of Scottish ice down the coastal area of Northumberland and into Eastern Durham. An interval of unknown duration then ensued, followed by the invasion of ice of western or Lake District origin. Finally following a further interval Cheviot ice advanced and was diverted south along the east coast by offshore ice lying in the North Sea Basin. With the melting of this ice climatic conditions ameliorated and Post Glacial conditions followed.

In the 1920's the Geological Survey of North Western England was completed by the geologists Trotter F.M. and Hollingworth S.E.

In this area and especially in the Vale of Eden, a sequence of glacial deposits almost as complex as those of the east coast was discovered, with the evidence pointing to two major and one minor glacial phases. The earliest or Scottish glaciation was considered to be associated with the growth of an ice sheet in south west Scotland which advanced through the Tyne Gap and southwards up the Vale of Eden, where it diverted Lake District ice over Stainmore. This advance deposited the Lower Boulder Clay of the Vale of Eden. Throughout the area this clay was overlain by the more widespread Upper Boulder Clay, which was believed by Trotter and Hollingworth to represent the product of maximum glaciation. This boulder clay was deposited from Lake District ice moving northwards down the Vale of Eden to unite with Galloway ice flowing through the Tyne Gap. The final, or Scottish Readvance was found only in the northern part of the Vale of Eden, and was represented by only a thin till masking earlier deposits. This they concluded was the product of a late and minor glacial phase.

A correlation of these deposits with Woolacott's (1921) succession for Eastern Durham was outlined by Trotter and Hollingworth in a later work (1932). (Fig 7). In this they described the Main or Lake District glaciation as the time equivalent of the ice sheet which deposited the Main Cheviot Drift of the Durham area, and the Early Scottish Glaciation as the equivalent of Woolacott's stage three in which western ice had uninterrupted access to the Durham coastal region. Deposits of the Scottish Readvance, a very weak glacial phase, were not considered to be present on the east coast.

The most comprehensive summary of knowledge of the glacial deposits was outlined by Raistrick A. (1931) as part of a symposium by the Geological Association on the Geology of Northumberland and Durham. (Fig 8). In this work he attempted to construct a detailed picture of the pattern of events in the Pleistocene, and to describe the topographical features to which they gave rise. Following the work of

Figure 7.

TABLE SHOWING THE CORRELATION OF THE GLACIAL DEPOSITS
IN THE NORTH OF ENGLAND
(after Trotter and Hollingworth 1932)

	WEST		EAST	
	Southern Part of the Irish Sea Basin	Lake District and the Solway Firth	Northumberland and Durham	Yorkshire
FIFTH GLACIAL EPISODE		Retreat Phenomena: lakes, channels, sands and gravels, and laminated clays Scottish Readvance Boulder Clay	Not represented	Not represented
FOURTH GLACIAL EPISODE	?Upper Boulder-Clay of Liverpool District	Retreat Phenomena: lakes, channels, sands and gravels, and laminated clays, (=Middle Sands of Carlisle). Boulder-clay of Lake District-Edenside Maximum and N. Pennines	Retreat Phenomena: lakes, channels, sands and gravels Prismatic Boulder-Clay Cheviot and Scottish Ice with Western Ice in the west	Retreat, Phenomena: lakes, channels, sands and gravels Hessle Clay and its inland equivalents
THIRD GLACIAL EPISODE	Middle Sands and Gravels ?Lower Boulder-Clay of Liverpool district	Gravels and laminated clays Boulder-clay of "Early Scottish Glaciation" (including Lake District Ice).	Gravels and laminated clays Boulder-clay of Western Ice.	Gravels etc. Upper Purple Clay
SECOND GLACIAL EPISODE			Gravels Boulder-clay of Scottish and Western Ice	Gravels Lower Purple Clay
FIRST GLACIAL EPISODE	Represented farther south	?Weathered Boulder clay of Upper Caldew Valley	Loess Scandinavian Clay	Basement (Scandinavian) Clay

Trechmann and Woolacott, Raistrick agreed that ice first arrived from the North Sea area bringing with it clays containing the remains of a Pliocene/Pleistocene flora, and that this was followed by a period of interglacial weathering. During the next glacial phase Raistrick considered that ice streams from the Pennines initially invaded the area and deposited a dark coloured boulder clay. At a later stage in this glaciation, with the growth of the Scottish glaciers ice congestion in the North Sea area became more severe, and the Cheviot and Forth ice was deflected south along the coast acting as a buffer between the Pennine and Scandinavian ice. At the same time ice congestion in the Vale of Eden led to ice streams pouring over the Tyne Gap and Vale of Eden to further complicate the pattern of ice movement in eastern England.

The first ice to retreat at the end of this composite glaciation was the local ice in the Pennine valleys. This left the mid-Durham valleys hemmed in by Lake District ice in the north and west, by Cheviot ice in the east, and Tees - Stainmore ice in the south. At an early stage in this retreat Raistrick envisaged lower Weardale as a lake (Lake Wear) fed by glacial meltwater and held up against the Magnesian Limestone escarpment and the Pennine foothills by ice in the north and east. This lake overflowed to the south across the Permian escarpment, via the Ferryhill meltwater channel, and deposited sands and gravels in a second lake held up by Tees ice against the dip slope of the Magnesian Limestone. This second lake was drained in turn by a meltwater gorge through Aycliffe. Lake Wear was dependent for its existence on the blockage of the mouth of the Tyne, and the low ground east of Gateshead Fell by Cheviot ice. With the shrinkage of this ice sheet to the north a pre-glacial col in the Sunderland area was exposed, over which Raistrick claimed Lake Wear^o overflowed to form the present gorge of the River Wear and to complete the final drainage of the lake.

The Cleveland and Lower Tees areas were the subject of research once more in a paper by Radge G.W. (1939). His work confirmed the views expressed earlier by Kendall (1902) that the first ice to invade this area did so from a westerly direction and deposited what he described as the Lower Brown Boulder Clay. Overlying this was the Red Cheviot Boulder Clay which Radge thought was traceable as far south as Redcar and Saltburn. Associated with the Cheviot clay and forming the surface deposit over much of the Lower Tees valley was a series of laminated clay deposits, which Radge regarded as having been deposited in a lake held up by the Cheviot ice during the later stages of glaciation.

At a similar period work on north western Durham was published by Anderson W. (1939, 1940) in which was described a series of meltwater channels and fluvio-glacial deposits graded to a height of 190 feet O.D. Anderson postulated that there was considerable evidence to suggest a high Late Glacial sea level of 190 feet O.D. in northern England, and also lower but related levels at 140 feet and 100 feet. It is undoubtedly correct that surfaces do occur at these altitudes, but their origin must still be regarded as open to conjecture. The lack of any faunal remains would appear however to testify against a marine origin.

Following on from the work initiated by Anderson a series of papers appeared dealing with the interpretation of glacial meltwater channels in Northern England, and the general problem of whether these were of sub-glacial or sub-aerial origin. Peel R.F. (1949, 1956) described "up and down" channels in Northumberland at Beldon Cleugh and East Dipton, which in his earlier work he considered to be of sub-aerial origin formed by lake overflows in different directions at different periods. In his later work he suggested a possible sub-glacial origin for the channels. This idea of a sub-glacial origin for meltwater channels was later used extensively by

Sissons J.B. (1958) to explain the formation of many of the meltwater channels, both large and small, of the Tyne Gap area.

The introduction of the "Undermelt Hypothesis" as a possible origin for the glacial deposits of Northern England was made by Carruthers R.G. (1939), and amplified in later works (1940, 1953). The idea that a composite sequence of glacial deposits could be formed by the melting of a single ice sheet was not Carruthers own, but the regional interpretation by this method certainly was.

The basic premise of the theory was that the melting of an ice sheet took place by the process of "bottom melt", under the pressure of stagnant ice above. Carruthers believed such bottom melt led to a characteristic sequence of deposition consisting of till, laminated clays, silts and sands.

The basal till Carruthers regarded as the ground moraine of other workers. The laminated clays however he considered in no sense water lain, but rather "banded dirt" produced by the shearing of englacial detritus within the ice, and deposited undisturbed by the process of undermelt. The silts and sands, obviously the product of running water, were thought of as having been formed by the re-sorting of either basal till or the banded dirt in a sub-glacial environment. Even the upper tills of the area he regarded as merely sheared up basal tills. Nowhere, Carruthers claimed, was there any evidence of a readvance of the ice, and all the deposits of Northern England, both the many tills and the interbedded sediments he regarded as having their origin in the melt out of a single stagnant ice sheet of Saale age. Although in the light of modern work this might seem a rather extreme interpretation, there is no doubt that Carruthers' unorthodox idea of monoglaciation made other workers more critical of the evidence of multiple glaciation, and provided a necessary stimulus for glacial geology.

In the early post war period little research was undertaken in the Durham area, and it was not until the 1950's that papers on the glacial deposits of the area began to appear once more.

In 1952 a review article was published by Trechmann C.J. in which his final views on the Pleistocene history of Eastern Durham were set down. (Fig 9). These views did not include any information which had not previously appeared in the literature, but did provide a useful synthesis of Trechmann's work.

In the Lower Tees area Agar R. (1954) published the detailed results of observations made over a number of years in connection with civil engineering constructions around Middlesborough. In this work he distinguished three boulder clays which he correlated with the Hessle, Purple, and Drab clays of Holderness, and also a series of high Post-Glacial sea levels at 60 to 80 feet, and 25 to 40 feet.

In the mid 1950's Maling D.H. (1955) completed a Ph.D thesis at Durham University on the Geomorphology of the River Wear. This dealt mainly with the Tertiary landforms in Upper Weardale, but from observations in the area of the Middle Wear, Maling concluded that there was no evidence for more than one glaciation. He further suggested that true boulder clay was less extensive than was formerly thought, and that many of the superficial clays of the area were the products of insitu weathering or periglacial erosion.

Remarkably little published work dealing with the Pleistocene chronology of north-east England has appeared since this date. One exception was an interesting paper on the surface and rockhead relief of the Northumberland Coalfield published in 1960 by Anson W.W. and Sharpe J.I. In this work they outlined the form of the sub-drift relief using detailed borehole information obtained by the opencast executive of the National Coal Board. As a result they were

SEQUENCE OF PLEISTOCENE EVENTS ON THE DURHAM COAST

(after Trechmann, 1952)

Coastal Area		North Sea Area
Holocene	Sand dunes on surface with Neolithic and later remains	Cliff Erosion, storm beaches. Forest bed becoming submerged.
Mesolithic	Prismatic and laminated clay. Peat with Elk at Neasham	North Sea becoming marine. Forest growth, calcareous marls with land shells, blue clay with marine and estuarine shells. Mesolithic flints.
Post-Glacial	Uplift of rocky coast, cutting of gorges	Slow submergence of North Sea area.
Late-Glacial	Kaims, morains, and gravel spreads deposited	
Cheviot drift	Ice movement to S. and S.W. from North England and S.E. Scotland	North Sea occupied by ice sheets.
Tyne drift	Ice movement carrying Galloway and Lake District stones, later confluent with the Cheviot ice stream	
Western drift	Ice stream from Westmorland with Shap granite and Brocknam, to south of Hartlepool	
Beach period	Formation of beaches of which patches remain at Easington and Blackhall Rocks. Arrival of some northern ice	Occupied by temperate sea, with shells whose fragments occur in the Cheviot drift.
Interglacial	Some valley erosion. Uplift and slickensiding near Beacon Hill. Rotting of boulders, calcretion of conglomerate. Loess concretions.	
Scandinavian drift	Deposition of loess-like drift. Arrival of shelly clay with Norwegian stones. Red marl filling up fissures.	Occupied by Scandinavian ice sheet.
Pre-Glacial and Cromerian	Land topography uncertain but rock surface probably more level than at present	Swamps with freshwater shells. Forest bed not far away. Clay with arctic marine shells.
Pliocene	Probably land off the present coast	Crag Sea in East Anglia and off Aberdeenshire?

able to recognise a series of drift plugged channels formed by two differing sets of conditions. They considered a number of large east to west channels to be the pre or interglacial courses of the main river systems of the area, while a series of north to south channels, more sharply defined and less continuous, was regarded as representing buried meltwater channels. During the course of their research they visited many opencast sites, and from the exposures studied concluded that the "Prismatic Clay" of northern England was a solifluction mantle, and that periglacial activity in Late Glacial times had had a greater effect on the glacial deposits than had previously been recognised. Little attempt was made however to explain the mechanism by which such widespread solifluction deposits were distributed, or to explain the fact that such deposits were often of a different colour from the true till-like deposits from which they must have been derived.

Since 1954 the Geological Survey have been resurveying parts of north-east England. In the Durham area the work of E.A. Francis and D.B. Smith has already resulted in the publication of a series of 6" to the mile solid and drift maps, and it is hoped that a memoir of this work will appear in the near future.

Although working in contiguous areas these two geologists arrived at differing interpretations of the glacial sequences. In the eastern area Smith D.B. claimed that there was clear indication of three glaciations, while in the Wear Lowlands Francis E.A., in agreement with Maling's earlier work stated that there was no evidence for more than one glaciation.

The Pleistocene sequence as outlined by Smith in Eastern Durham is as follows.

"Prismatic Clay"
 Morainic Drift
 Upper Boulder Clay
 Middle Sands Upper Division
 Lower Division
 Lower Boulder Clay
 Loess
 Scandinavian Drift

In agreement with Woolacott and Trechmann, Smith regarded the Scandinavian Drift as the oldest glacial deposit within the area, and as having been formed by ice impinging on the Durham coast. Following this glaciation, a prolonged period of sub-aerial weathering, possibly representing the Hoxnian interglacial, was considered to have taken place, during which time the loess accumulated, and many of the deep buried valleys of the coastal area were eroded.

The Lower Boulder Clay ice sheet was thought to have been a major ice sheet which covered the whole district and moved in a southerly direction. Evidence for the dating of this glaciation is not conclusive, but Smith tentatively suggested that it might represent the Saale Glaciation of North Western Europe.

The Middle Sands were divided into an upper and lower division, with the latter being regarded as the sub-aerial outwash from the waning Lower Boulder Clay ice. The upper division on the other hand was interpreted as outwash from, or partly beneath the advancing Upper Boulder Clay ice. A time interval of considerable duration and possibly represented by the Eemian Interglacial was thought by Smith to exist between these two divisions.

The Upper Boulder Clay, a product of the Weichsel Glaciation was regarded as moving southwards down the Durham coastal area, leaving a line of morainic features from Easington to Sheraton. At its maximum extension this ice sheet was believed to have blocked

the dip slope streams of the Magnesian Limestone Plateau, forming a series of lakes in which laminated clays were deposited. These lakes were regarded as overflowing westwards through a series of impressive channels, breaching the Permian escarpment at Town Kelloe.

In the Central Durham area Francis described a sequence of :-

Upper Stony Clays
Middle Sands, gravels and clays
Lower Boulder clay

The Lower Boulder Clay in this area was regarded as being continuous with the Lower Boulder Clay of the coastal region. Some if not all of the Middle Sands, Gravels and Clays were regarded by Francis as being formed during the decay of the Lower Boulder Clay ice, and could thus be correlated with the lower division of the Middle Sands in the coastal area. In the Wear area, however, Francis claimed that there was no evidence for any interval corresponding to that between the upper and lower division of the Middle Sands of the coastal region. This meant that no certain correlation could be made between the Upper Stony Clays of the Wear Lowlands and the Upper Boulder Clay of the coast. Indeed, Francis was more of the opinion that the Upper Stony Clays of the Wear Lowlands were more likely deposited during the glaciation that deposited the Lower Boulder Clay. He did however consider the possibility that patches of these Upper Stony Clays may have been formed by differing processes, including both sub-glacial deposition and periglacial action.

This summary illustrates that the pattern of glaciation outlined by workers in North East England has changed little in the last one hundred years. Since the mid-nineteenth century the east coastal region has been correctly regarded as an area of conflict and intermingling of ice sheets derived from sources to the east, west, and north.

Howse R. (1864) was the first person to suggest the presence of Scandinavian ice offshore, and the conflict of Lake District and Cheviot ice masses in the coastal areas of Northumberland and Durham, - ideas which have been modified only slightly in the intervening period.

Controversies it is true have arisen, particularly concerning the nature of the intervals between the till deposits. On the one hand Carruthers R.G. (1939, 1940, 1953) regarded the glacial sequence of North East England as the product of a single glaciation, while Woolacott D. (1921) suggested a pattern of four separate glacial phases separated by intervals of unknown duration. Most other workers have identified at least two glacial phases, although considerable differences of opinion occur as to the complexity of each phase.

Although considerable work has been carried out dealing with the stratigraphy of the glacial deposits, it is remarkable how little work has been undertaken with the idea of attempting to synthesise the stratigraphy with the landforms produced by glaciation. Only Raistrick's work can be said to attempt this difficult task on anything but a very general scale.

Similarly, without exception, all the interpretations outlined above have been reached as the result of field mapping and stratigraphical interpretation. Quantitative analysis of the deposits

as an aid to the interpretation of the deposits is virtually unknown, and limited in published work at least to a series of stone counts by Herdman T. (1909) and Trechmann C.T. (1915).

It is with these final points in mind that the present work was undertaken.

Chapter 4.

GLACIAL DEPOSITS AND FEATURES

Introduction.

The description of the distribution of the glacial deposits outlined in this chapter follows the work of Smith D.B. and Francis E.A. (in press) for the central part of the area; Woolacott D. (1921) and Trechmann C.T. (1915, 1919, 1953) for the northern area; and Trechmann C.T. (1915, 1919, 1953), Kendall P.F. (1902) and Agar R. (1954) for the area of the Tees Lowlands.

Most of the area of Eastern Durham is covered by glacial drift varying in thickness from zero to more than 300 feet. The drift is thickest in the lowland areas, and is often absent in areas above 500 feet on both the Permian Escarpment and in the Pennine Foothills.

In the coastal area, the Wear Lowlands and in the Tees Lowlands a composite sequence of deposits is found, while on the Magnesian Limestone Plateau and on the Pennine Foothills only a single till sheet with associated gravels is present.

A. Stratigraphy of the deposits.

In this section the stratigraphy of the glacial deposits is described under five regional sub-headings. These are :-

1. the Coastal Area.
2. the Magnesian Limestone Plateau Area.
3. the Tees Lowlands.
4. the Wear Lowlands.
5. the Pennine Foothills.

1. The coastal area.

Pleistocene succession (after Smith D.B.)

"Prismatic Clay"	0 - 6 feet
Morainic Drift	0 -50
Upper Till	0 -40
Middle Sands	
Upper Division	0 -20
Lower Division	0 -80
Lower Till	0 -50
Sands and gravels	0 -20
"Loess"	0 - 6
Scandinavian Drift	0 -14
Fissure deposits	

It is in the coastal area where the most complete glacial succession exists, and where the type sequence of the area is found.

Fissure deposits.

The oldest glacial deposits are a series of clays and breccias filling fissures in the Magnesian Limestone of the Durham coast, and were first described by Trechmann C.T. (1915, 1919) in the area between Crimdon and Hawthorn Denes. Most of the fissures were filled solely with limestone breccia, but, in some fissures, grey and brown freshwater clays with organic material and non-marine mollusca of early Pleistocene age were found.

In one of the fissures near Blackhall Colliery peaty wood and tree trunks were recovered from the foreshore zone, while in one close by mammalian bones were obtained. Almost all the fossiliferous material was found in the foreshore exposures of these fissures, and is no longer available for re-examination owing to the tipping of coal waste on to the beach.

The Scandinavian Drift.

The exposure of the Scandinavian Drift is now almost completely buried beneath Horden pit heap. The deposit was first described by Trechmann filling a buried valley at Warren House Gill, and extending along the coastline at the base of the cliff for almost a quarter of a mile.

The clay itself was dark grey and compact, and occasionally coloured yellow by the inclusion of Magnesian Limestone material. It was devoid of the typical erratics of Northern England, and more than 85% of the far travelled stones were of igneous or metamorphic origin. The majority of these were regarded by Trechmann as post-Silurian eruptives from the Christiana district of Southern Norway. Thick shelled fragments of lammellibranchs and gastropods were common in the deposit, and included many arctic forms which were now extinct in British seas. This fauna was claimed by Trechmann to be similar to that of the Bridlington Crag on the Yorkshire coast.

Near its northern limit the clay reached a maximum thickness of 12 to 14 feet, but thinned rapidly as rockhead rose. Its upper surface was described as undulating and as having been disturbed by the ploughing action of later ice sheets.

The deposit has not been recorded anywhere else within the area, although a boulder of laurvikite unearthed during constructional work for the railway viaduct at Castle Eden Dene (Trechmann C.T. 1915 p.54; Woolacott D. 1921 p.64) suggests its possible existence in other of the coastal buried valleys.

Overlying the Scandinavian Drift at Warren House Gill, and banked against the southern side of the buried valley was a brown

silty deposit claimed by Trechmann (1919 p.174) to be "loess". It was up to 6 feet in thickness, homogeneous, and without sign of stratification. A series of elongate concretions occurred throughout the deposit, but no land shells or calcareous vegetable structures similar to those found in the loess deposits of Europe were discovered. At the northern part of the exposure the upper layers of the loess were regarded as having been redeposited by water, and in places the loess was interbedded with the Scandinavian Drift. No exposure of undisturbed loess is visible at the present day.

Lower sands and gravels.

Beneath the Lower Till is a series of sand and gravel deposits in depressions in the surface of the Magnesian Limestone. Most of these deposits are only a few yards across, and commonly less than 10 feet in thickness. They vary in composition from fine grained red sands to coarse gravel deposits. In all these deposits, Carboniferous material including limestone sandstone and coal, together with Lake District and Southern Upland erratics are common. No undisputed Scandinavian material has yet been discovered in these deposits. At Limekiln Gill, north of Crimdon in a coarse gravel deposit below the Lower Till, abraded shell fragments were found.

Lower Till.

In the coastal area the Lower Till is the most widespread deposit resting on the Magnesian Limestone. It is rarely more than 30 feet in thickness and is particularly persistent in outcrop, being absent only from the higher outcrops of solid rock, or from where it has been removed by post-depositional erosion.

The clay is grey ^{or} dark brown in colour, and an

extremely tough and compacted deposit. Throughout its outcrop it contains many pebbles of Carboniferous sandstone, limestone together with material derived from the Lake District and Southern Uplands. Occasional sandy lenses and streaks are found in the clay, but over most of its outcrop it conveys the impression of great uniformity.

Smith D.B. (1962) divided the Lower Till into four sub-divisions in the coastal area.

Dark Grey Brown Boulder Clay	4 to 12 feet
Red Silty Clay	0 to 6 feet
Dark Grey Brown Boulder Clay	2 to 5 feet
Dark Grey Boulder Clay	1 to 8 feet

These divisions can be traced along the cliff sections, but inland appear to die out rapidly. The red silty clay, although very thin is remarkably persistent in outcrop. The stone contents of these sub-divisions of the Lower Till is similar, and indicates derivation from the west.

Middle Sands.

The lower division of the Middle Sands overlying the Lower Till in the coastal sections between Hawthorn and Crimdon Denes is a red sand deposit with interbedded silts and clays. In places these sands contain small lenses of fine gravel. In the lower part of the deposit thin beds of stony clay up to 2 feet in thickness, and up to 20 feet in length, closely resembling the Lower Till, are seen interbedded with the red sands. In some exposures the Lower Till appears to pass by interdigitation up into the red sands, but more commonly a thin iron stained gravel is found at the junction of the two deposits.

The upper division of the Middle Sands consists mainly of gravel with subordinate brown and yellow sands. The gravels are

often calcreted to form a particularly hard and resistant bed, which is well exposed in the cliffs south of Seaham Harbour. These gravels appear to transgress across the surface of the red sands in a southerly direction, and in Castle Eden Dene mouth rest directly on the Lower Till. Throughout most of their exposure the gravels maintain an approximate height of between 40 to 70 feet O.D. When the junction between the upper and lower division of the Middle Sands was visible, Smith noted that a sharp contact could be seen.

To the south of Castle Eden Dene the upper division of the Middle Sands rests directly on the Lower Till. The junction appears erosional and is sometimes marked by a stone horizon, composed of material derived from the Lower Till.

The Easington Raised Beach (Woolacott D. 1920) is found beneath the upper division of the Middle Sands. Its relationship towards the lower division of the Middle Sands is uncertain.

Upper Till.

In the coastal cliffs south of Chourdon Point the uppermost deposit is the Upper Till. It varies in thickness from 5 to 40 feet, and is reddish or purply-brown in colour. Cheviot porphyritic lavas are found within the deposit, and Smith noted a higher proportion of Upper Magnesian Limestone fragments than in the Lower Till. Lake District and Southern Upland material is also found. The Upper Till is almost always found overlying sand and gravel deposits, with little evidence of disturbance or incorporation of these deposits. Ripple marks are sometimes preserved in the underlying sands, while at other exposures interbedding of sand and till is seen. Occasionally as near the mouth of Hawthorn Dene the Upper Till rests directly on rockhead.

The distribution of the Upper Till is not uniform throughout the coastal area. In the north around Sunderland it appears to be completely absent, except at a few localities. (South Hylton Quarry). To the south it outcrops in inland exposures near Seaham Harbour and Cold Hesleden. Its western limit is only well defined in the Easington Sheraton area where it appears to be associated with a series of kame and morainic mounds. To the north and south of these points it is extremely difficult to plot an exact margin, as the deposit appears to feather out onto the Lower Till. In the south the Upper Till outcrop can be traced into the Tees Valley south of Sedgfield.

Morainic Drift.

In the central part of the coastal area between Hawthorn and Sheraton the Upper Till is overlain by morainic drift. This is well exposed in the Peterlee district, where it is seen to be a highly variable deposit, but generally with a high gravel content. The lithology of the erratics is similar to that of the Upper Till.

Prismatic Clay.

The "Prismatic Clay" (Woolacott D. 1921) is found mainly to the north of Seaham Harbour, where it can be seen for great distances forming the highest deposit along the cliff sections. It is a brown, fine-grained deposit and contains only a very few small pebbles. It is rarely more than 6 feet in thickness, and generally overlies sands or roughly laminated silts with a gradational junction. On drying it exhibits prismatic jointing, and it is from this characteristic that its name is derived.

2. Magnesian Limestone Plateau area.

Glacial succession

Stony and stoneless clays	0 to 24 feet
Laminated clays	0 to 100 feet
Gravels and sands	0 to 150 feet
Lower Till	0 to 100 feet

Lower Till.

Over most of the Magnesian Limestone Plateau the glacial deposits are thin, although locally along the line of buried valleys, (Ludworth Colliery, drift thickness 120 feet) thickness of drift of more than 100 feet do occur. The Lower Till is the basal deposit and is the lateral equivalent of the Lower Till of the coastal region. It is the only deposit which is continuous in outcrop over large areas of the plateau, and even it is sometimes absent along the line of the escarpment. At quarry exposures within the region this till is rarely more than 12 feet in thickness, and can show rapid variations over short distances. At Tuthill Quarry the maximum drift thickness is 16 feet, but at the same quarry depths of less than 3 feet are common. The clay is yellowish brown or brown in colour and is characterised by the presence of Carboniferous coal, sandstone and limestone, together with Borrowdale Volcanic Series material, and greywackes derived from the Southern Uplands. Even when no drift occurs overlying the Limestone, its former presence is indicated by the high coal content found within the soil profiles.

Sands and gravels.

Overlying the Lower Till is a series of sand and gravel masses of varying sizes. Some of these as at Grindon, Warden Law, and Battar Law are extremely large with more than 100 feet of deposits overlying the Lower Till in places. Other gravel deposits are much smaller. Some seem to be associated with meltwater channels

(south of Eppleton Colliery), while others at Kelloe Law and Southern Law are found bearing no apparent relationship with any other landform feature.

Laminated Clays.

Laminated clays and sands are found overlying the Lower Till at Sheraton, Wingate, and Shotton Colliery. The basal junction of these deposits is rarely seen but when exposed shows little or no disturbance or erosion of the underlying Lower Till. The laminated clays which are up to 100 feet in thickness in the Shotton area, become more sandy in composition to the east and appear to have been derived from this direction. Stratigraphically they are found at a similar level to the gravel deposits of the plateau area, but a section showing the exact relationship between the two deposits is not known. At Sheraton the Upper Till is seen overlying at least part of the laminated clays. Smith concluded that the laminated clays were largely of lacustrine origin associated with a water level at c. 450 feet.

Stony and stoneless clays.

Although any one of the deposits so far described, can and frequently does form the surface exposure, the stratigraphically youngest deposit is a series of stony and "stoneless" clays. These are only found in the lower eastern parts of the plateau, overlying sands, laminated clay, or the Lower Till itself. They are usually less than 5 feet in thickness, though they can be over 20 feet in thickness, as at Shotton Colliery Brick Pit. Some of these clays appear locally homogeneous, while others show considerable lateral variation over short distances. Their contact with underlying material can show either a gradational or an erosional and disturbed junction.

3. The Tees Lowlands.

Succession

"Warp"	
Upper Stony Clay (Upper Tees Clay)	0 to 12 feet.
Laminated clays and sands	0 to 40 feet
Upper Till	0 to 30 feet
Middle Sands and gravels	0 to 100 feet
Stainmore Till	0 to ?30 feet
Lower Till	0 to 40 feet

To the south of the Magnesian Limestone Plateau the ground drops gently into the Tees Lowlands, and the glacial deposits thicken progressively. A complex glacial succession similar to that of the coastal area is found. The drift deposits are uniformly thick with depths of between 50 to 200 feet being relatively common. Exposures of the drift deposits are few and confined to gravel pit sections along the line of the incised stream courses. As a result much of the glacial succession is based on borehole information, with the consequent difficulties of interpretation to which this gives rise.

Lower Till.

Within the area sections of the basal deposits are everywhere poor, and it is only along the Tees channel itself that exposures are found. At one of these, Rockcliffe Scar, a succession is seen similar to that revealed in many of the borehole records. The basal deposit is a dark grey till, about 4 feet in thickness. It is a very stony clay, particularly rich in Carboniferous Limestone and sandstone, and closely resembles the Lower Till of the coastal and plateau regions. Overlying this along a well marked erosional junction outcrops a thick red till, more than 20 feet in thickness containing Shap Granite and other diagnostic Lake District erratics. This clay, named by the author the Stainmore Till, is not exposed in the area of

detailed study to the north, but from borehole records and occasional erratic finds, its existence at depth seems probable. The northern limit of this clay is unknown, but it is certain that it does not occur north of a line from Heighington through Sedgefield to Hart. The section at Rockcliffe suggests that the Stainmore Till is in part at least younger than the Lower Till of the area to the north. It may however represent a lateral equivalent of the Lower Till deposited at a later date in the same glaciation.

Middle Sands and Gravels.

The Middle Sands and Gravels are only poorly exposed throughout the region, and their contact with the Lower Till is not seen. They show considerable lateral and vertical changes in grain size, and current bedding of the sands is often well marked. Triassic Sandstone is a common constituent of these gravels, especially in their lower parts. A two-part division of these sands and gravels has so far not been recognised, and it is possible that even more complex conditions during deposition existed here than in the area to the north.

The Upper Till.

The Upper Till appears from borehole records to be present throughout the area, and to be identical with the Upper Till of the coastal sections. Surface exposures of this Till are however rare.

Laminated clays and sands.

Overlying the Upper Till is a series of laminated clays and sands. These are low lying deposits and well exposed over large areas near Billingham and Haverton Hill. The clays are reddish brown in colour, with very fine laminae which can show remarkable contortion, slump and shear structures on both a micro and macro scale. Rock fragments are extremely rare within these deposits.

Upper Stony Clay (Upper Tees Clay)

The surface deposit over much of the higher ground of the Tees area is a bright red clay with very few included stones. It is generally less than 10 feet in thickness and overlies laminated clays, sands and gravels, and the Upper Till. When it overlies the Upper Till the junction appears gradational, and is virtually invisible. The deposit contains nodular calcareous concretions at depths of 1 to 6 feet, which appear to have been formed by weathering processes. This deposit mantles most of the Tees Lowlands below 250 feet. O.D.

Warp.

Overlying all the glacial deposits at heights below 60 feet. O.D. are deposits of "Warp" formed in post glacial times under estuarine conditions.

4. Wear Lowlands.

Succession after Francis E.A.

Upper Stony Clay (Upper Wear Clay)	0 to 15 feet
Middle Sands and Gravels and Laminated	
Clays	0 to 250 feet
Lower Till	0 to 100 feet

Lower Till.

In the Wear Valley a complex glacial sequence is found. Outcrops of solid rock are infrequent except along the post glacial channel of the River Wear and its tributaries, and the basal glacial deposits are poorly exposed. The Lower Till is a grey brown stony clay with many Carboniferous rocks, and material from the Lake District and Southern Uplands. It contains no Magnesian Limestone and appears to be continuous with the Lower Till of the Magnesian Limestone Plateau and

the coastal area. It is a persistent deposit averaging c. 25 feet in thickness in borehole records, and is absent only from the sides of the deeper buried valleys. Good exposures of this deposit are seen in the Wear Gorge near Finchale Priory, and at quarry sites near Chester-le-Street.

Middle Sands, Gravels, and Laminated Clays.

Overlying the Lower Till is a very complex sequence of thick sands, gravels and laminated clays, which at Low Newton have a total thickness of more than 250 feet. These deposits are poorly exposed and much of the information regarding them has been obtained from borehole records. As a general rule sands tend to be the dominant deposit west of the Wear and laminated clays to the east. The laminated clays seem to be the most frequent deposit overlying the Lower Till. In these clays Francis noted that the laminae could be as fine as 1/500 of an inch, and that in places these clays passed laterally into sands and gravels. They are worked extensively for brick making, particularly in the Birtley area.

Some of the gravel beds in this sequence, for example those at Durham Gravel Pit, show extremely poor sorting which seems indicative of ice contact conditions. These deposits do not appear to have been formed solely from the Lower Till as they contain considerable proportions of Magnesian Limestone material.

In contrast, exposures north of Durham along the A.1. show beds of well sorted sand more than 40 feet in thickness.

Throughout these deposits no orderly succession can be discerned, and one is led to conclude that they are the result of deposition under very rapidly changing and complex environmental conditions.

Upper Stony Clays (Upper Wear Clay).

The Upper Stony Clays form the surface deposit over considerable distances. They are mostly less than 8 feet in thickness and contain variable amounts of stones. Rock types other than those of Coal Measures origin are rare. The deposits showed considerable lateral variation, and locally concentrations of angular sandstone in a clay matrix are found. Elsewhere large and small abraded fragments of coal, and little else are found mixed in the clay. In a borehole between Shincliffe Colliery and Croxdale Hall, Francis claimed that these clays reached a thickness of more than 50 feet.

Within the area of the Wear Lowlands any of the described deposits can form the surface exposure.

The deposits in the extreme northern part of the Wear Valley are much less fully known, and little attention has been paid to them since Merrick's work (1909). Recent work by Smith D.B. and the present author would however suggest that the glacial sequence of this northern area is basically similar to that of the south, and simpler than Merrick implied. The basal deposit here as elsewhere appears nearly always to be the Lower Till, and overlying this is the complex sequence of sands and laminated clays which seem typical of the deposits filling the buried valleys. Finally mantling most of the region is a stony clay 4 to 7 feet in thickness.

5. Pennine Foothills.

On the Pennine Foothills and on Gateshead Fell in the north, the laminated clays, sands and gravels associated with the larger buried valleys wedge out laterally as rockhead rises, and the Lower Till becomes the surface deposit. On the higher ground above 500 feet O.D. quarry exposures show that even the Lower Till is absent and

that the superficial deposit is formed of frost shattered angular sandstone material. Occassional patches of sand and gravel are found.

B. Buried channels, meltwater channels and glacial landforms.

1. Buried Channels.

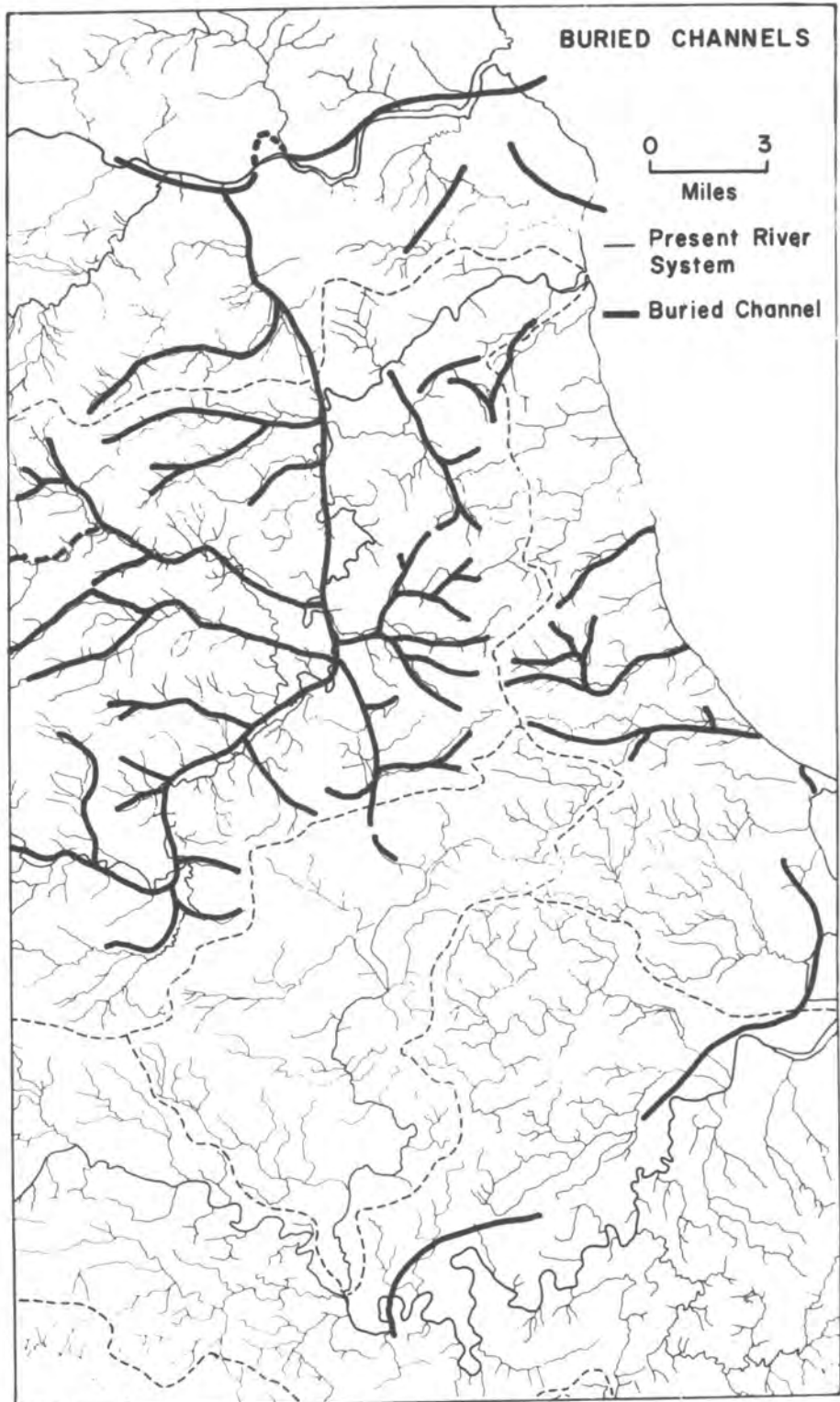
Amongst the most impressive and yet least visible features of Eastern Durham is the system of buried channels cut in the solid rock which exists beneath the drift cover.

These valleys are found associated with all the present day major streams, and seem to represent partially at least an original sub-aerial drainage pattern which has been overwhelmed by glacial deposition. Within the study area their pattern is best known from the Wear valley where a considerable boring programme for coal exploration has been undertaken. In the Tees valley buried channels also exist, but lack of boring evidence does not allow their centre lines to be plotted with any certainty. (Fig 10).

The channels form part of a topography with a much greater amplitude of relief than that of the present day, and appear to have been eroded relative to a base level at c. -140 O.D. The largest buried channels are associated with the present main streams of the River Wear and Tees, and form large features more than a mile wide and 200 feet deep.

The form and lines of the buried channels have been studied for more than 100 years, and in places an extremely detailed knowledge of them has been obtained. (Wood N. and Boyd E. 1864; Woolacott D. 1905, Trechmann C.T. 1915, Armstrong G. and Kell J. 1951,

Figure 10.



Maling D.H. 1955, Anson W.W. and Sharpe J.I. 1960. Francis E.A. and Smith D.B. in press). This work has shown that the long profiles of such channels possess certain irregularities which do not seem explicable in terms of normal stream erosion. For example an enclosed hollow descending to more than -170 feet O.D. was found in the buried channel of the River Team near Newcastle. Some workers (Hickling H.G.A. and Robertson T. 1949 p.38) have claimed that such features were due to glacial overdeepening by ice flow channelled by topographic features. In Central Durham Francis did not think such an explanation was applicable and here sub-glacial meltwater was considered a more likely agent of erosion in forming these irregularities. (Francis E.A. in press).

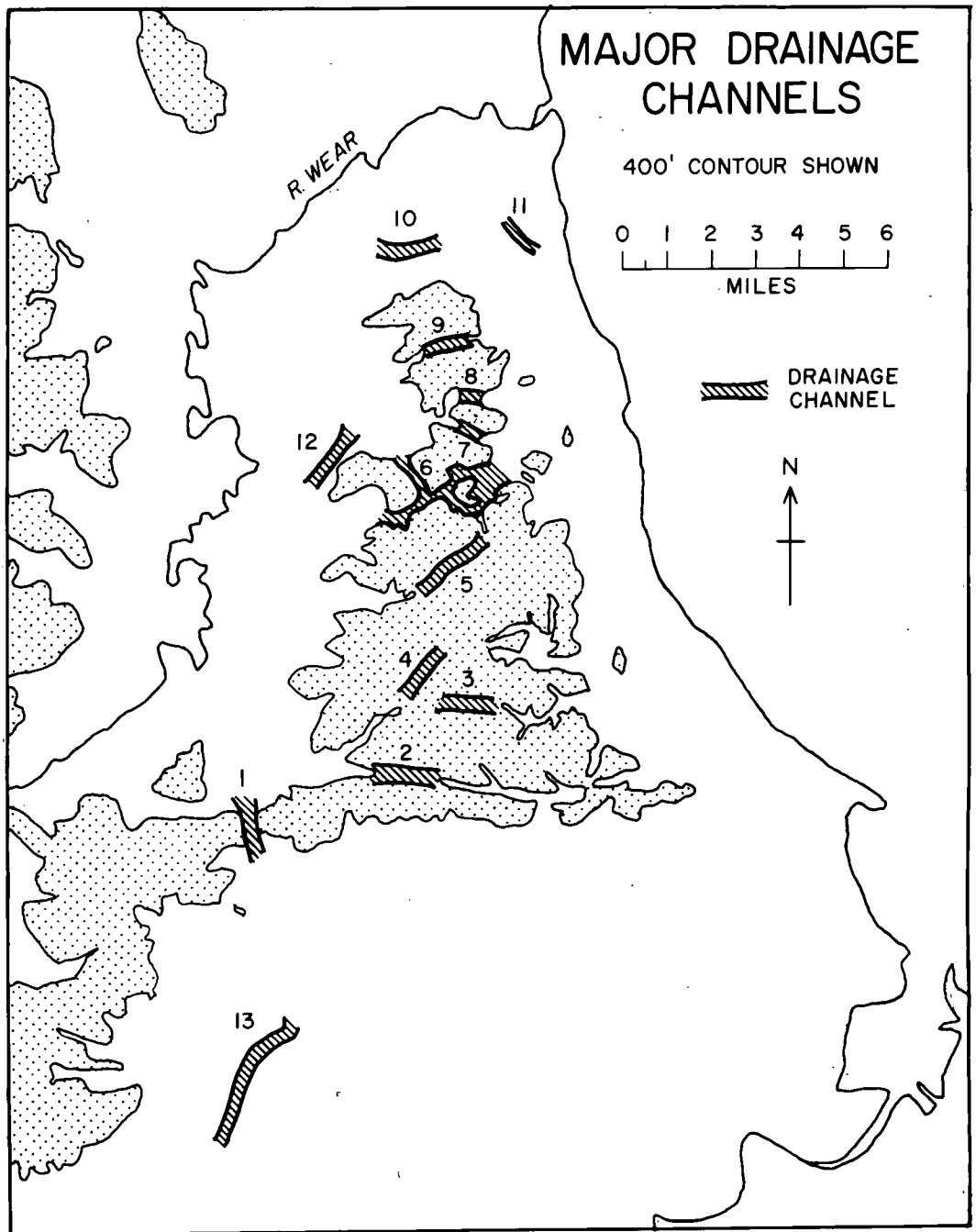
It is along the line of the buried channels that the glacial deposits reach their maximum thickness. In the Wear area a maximum recorded thickness of 272 feet has been recorded at Newton Hall, and in the Tees valley more than 300 feet at Ten O'clock Barn, south of Sedgfield. In north-west Durham thickness of more than 300 feet of drift have been recorded in the Derwent valley.

2. Meltwater Channels.

In the upland areas around Eastern Durham meltwater channels have been widely described in the past :- Best R.H. (1956); Boer de G. (1944); Derbyshire E. (1961); Derryhouse A.R. (1902); Gregory K.J. (1965); Gresswell R.K. (1952); Herdman E. (1909); Hollingworth S.E. (1931); Kendall P.F. (1902); Peel R.F. (1949,1956); Price R.J. (1960); Raistrick A (1931); Sissons J.B. (1958); Trotter F.M. (1929).

In Eastern Durham with the exception of the large meltwater channel at Ferryhill, (Maling D.H. 1955) meltwater channels

Figure 11.



1. Ferryhill	6. South Hetton	12. West Rainton
2. Trimdon	7. Easington Lane	13. Aycliffe
3. Deaf Hill	8. Hetton-le-Hole	
4. Town Kelloe	9. Warden Law	
5. Ludworth	10. East Herrington	

have rarely been described systematically in the literature.

In the area of the Magnesian Limestone Plateau there is a series of large channels breaching the main watershed between the coastal and the Wear drainage. None of these features carry significant amounts of water at the present day.

The largest is the Ferryhill channel running north to south through the Permian Escarpment. It is c.150 feet deep and more than 100 yards across, with a present floor level at c. 300 feet O.D. From borehole information however it is known that 150 feet of glacial drift lies beneath this present channel floor.

North of this channel is a series of eight cols in the Magnesian Limestone, with heights between 350 to 450 feet. A number of these seem to have been filled by westerly flowing water at some stage during glaciation. Many of these channels are now partially filled with superficial material of unknown thickness. In one of these channels more than 120 feet of drift was proved at Ludworth Colliery. Finally the most northerly channel in the plateau is a broad col like feature passing through East Herrington. Its floor is at c.250', and to the west this col appeared to connect with the large Tunstall channel.

In the Wear Lowlands large meltwater channels are less commonly found. A large col is seen south west of West Rainton with a floor level at c. 250 feet, but this is the only large channel in the region. Smaller channels are cut in superficial deposits and solid rock at Pity Me and Croxdale respectively.

In the Tees valley only one certain channel exists and this is the gorge of the present River Skerne cutting through the Magnesian Limestone near Aycliffe. Elsewhere in the Tees valley a series of channel like depressions do occur cut in the superficial deposits, and these features may well have carried meltwater at some stage late in the glaciation.

3. Glacial landforms.

Glacial topographic features are not well developed in Eastern Durham, and over most of the region glacial deposition has left a rather dull and featureless landscape.

It is only in the extreme eastern part of the area that the topography developed on the glacial deposits can be described as having a fresh appearance. In this area from Seaham Harbour through Sheraton, Sedgefield to Braffeton there occurs a belt of hummocky topography characteristic of ice marginal deposition. Near Peterlee and Sheraton kame like mounds up to 150 feet in height are found along this belt, but elsewhere these features exist on a less impressive scale.

With the exception of this morainic belt other "constructional" topography is only spasmodically developed, and nearly always associated with sands and gravels. On the Magnesian Limestone Plateau a whole sequence of sand and gravel mounds is found in large complex near Warden Law, while to the north a linear ridge of sand hills is exposed near Grindon.

In the Wear valley "constructional" topography is rare and found chiefly in the area around Durham City. It is especially well developed in the Kimblesworth, Shincliffe, and Whinney Hill areas. However in the Wear valley a series of depositional, and possibly partly erosional surfaces are well developed. The largest of these is the 320 feet surface of Maling, which consists of terrace-like fragments between 270 to 380 feet O.D. They are best developed on the margins of the Wear valley and found east and west of Durham City. These terraces are formed mostly of sand and laminated clays, and are often capped by the Upper Stony Clay (Upper Wear Clay). In the West Rainton area the terrace appears to be at least partly cut in the solid rock.

To the north near Houghton-le-Spring a similar terrace-like feature is found at c. 190 feet O.D., and at the mouth of the Wear and in the coastal zone, a lower surface between 80 and 140 feet O.D. is sometimes developed.

In the Tees valley widespread lacustrine flats with associated thick peat deposits are found north of Sedgfield at Bradbury and Morden Carrs.

SECTION 2

Analytical results

Analysis of the stony clays has been concentrated on those portions of the profile which have not been subjected to intense weathering action. These include the "C" horizon of pedology, or the Zones IV (oxidised but unleached), and Zone V (unoxidised and unleached), of Leighton M.M. and MacIntock P. (1930).

Brief descriptions of the methods of analysis are included in the text, but when any detailed information on techniques is felt necessary, this is included in Appendix form.

The terminology used to describe the stony clay deposits in this section is as follows:-

Upper Tees Clay
Upper Wear Clay
Upper Till
Lower Till

Upper Tees Clay.

A reddish brown relatively stoneless clay, which forms much of the surface exposure in the Tees Lowlands.

Upper Wear Clay.

A dark brown deposit, which possesses both stony and stone free facies. It forms the surface deposit in parts of the Wear Lowlands.

Upper Till.

A red brown to dark brown stony clay which forms the surface deposit along parts of the coastal area. It appears to pass below the Upper Tees Clay in the Tees Lowlands, and is not found on the higher parts of the Magnesian Limestone Plateau.

Lower Till.

A dark brown or dark grey stony clay which forms the basal superficial deposit over most of Eastern Durham. It can be subdivided into three provinces.

1. Lower Till of the Wear Lowlands.
2. Lower Till of the Magnesian Limestone Plateau area.
3. Lower Till of the coastal area.

Chapter 5

GLACIAL STRIAE AND TILL MACRO-FABRICS

Introduction.

One of the most important methods of distinguishing between ice advances is to prove different directions of ice movement. The two major methods of determining actual ice movement at a given locality are by the measurement of glacial striae, and the fabric analysis of glacial till.

A. Striae.

Glacial striations are made by debris being dragged along the sole of a glacier, and form the most common and conspicuous sign of glacial abrasion. (Flint R.F. 1957 p.56). They are generally accepted as indicating directions of ice movement during the period in which they were formed, but in some cases their interpretation needs special care. Flint (1957 p.61) pointed out that strong divergences in the trends of striae are produced by lobation of the ice and topographic irregularities, and that most striations are made near glacial margins during deglaciation and therefore do not indicate the direction of ice flow at maximum glaciation.

The occurrence at a single locality of 2 or 3 sets of striae with discordant trends is not uncommon. (Flint R.F. 1957 p.61). This can be caused by changes in direction of flow of a single ice lobe, due to ice thinning and allowing topographical irregularities to exert increased influence, or a shift in the position of the centre of outflow of the ice. Therefore, evidence of a considerable time lapse between the making of successive sets of striae is a prerequisite to the interpretation of crossed striations as the product of successive glacial episodes. (Flint R.F. 1957 p.61-62).

Further difficulties arise with the dating of striated surfaces. If a striated pavement is exposed without a covering of glacial deposits at the present day, it is almost impossible to ascribe such a surface to any particular glacial episode. On the other hand, if a striated bedrock is overlain by a glacial till, one cannot be certain that the striations are associated with that particular till sheet.

Finally, striations are not uniformly distributed throughout an area. Such haphazard distribution is due to many factors including lithology, pre-glacial weathering and the condition of the sub-drift surface, post glacial weathering, concealment beneath drift cover, the debris content of the ice and variable observation. In northern England, as elsewhere, striae are selectively preserved as a result of a combination of these factors.

The most favourable rocks lithologically for the preservation of striae in north east England are the limestones of the Lower Carboniferous, followed by the Whin Sill dolerite, and the various sandstone formations mostly of Carboniferous age. The Magnesian Limestone is particularly unsuited to striae preservation, as under stress conditions the rock exhibits a strong tendency to break down to a rubbly or powdery debris.

Post glacial weathering has obviously been an important factor in the removal of striae. The Carboniferous limestone is particularly susceptible to sub-aerial weathering, and detailed etchings such as striae are rapidly obliterated under the attack of acidulated rain water when exposed. Similarly the cement of many of the sandstones, and the Whin Sill dolerite, is susceptible to ground water and rain water attack, leading to a crumbling and flaking away of the superficial markings.

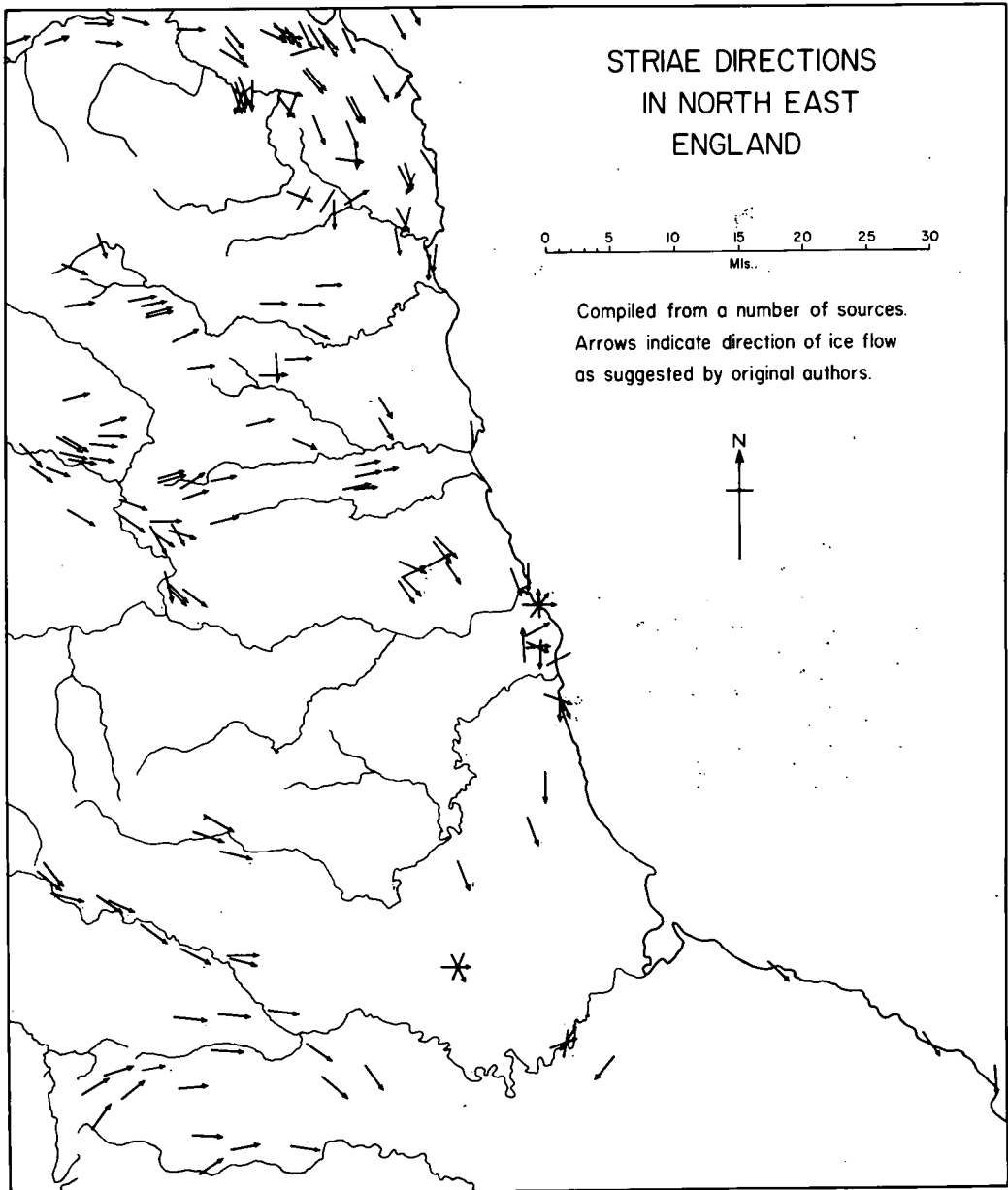
In north-east England many workers have compiled records of striae in the course of their research. (Howse R. 1864; Barrow G. 1888; Kendall P.F. 1902; Dwerryhouse A.R. 1902; Smythe J.A. 1912; Trechmann C.T. 1915; Woolacott D. 1921; Raistrick A. 1931; Radge G.W. 1939; Carruthers R.G. 1939. Figure 12 is a map compiling the results of these observations. The map shows the concentration of striae observations in the upland area where the drift cover is generally thin, and the paucity of observations in the thickly drift covered lowland areas of coastal Northumberland and Durham.

In the Cheviot Massif observations recorded by Smythe J.A. (1912 p.89-90) indicate a direction of ice movement around the eastern flank of the Cheviot Hills. Ice movement was initially north-eastwards down the Tweed Valley, changing to a southerly direction in the coastal plain between Bamburgh and Alnmouth. Further to the south, along the valleys of the rivers Coquet, Wansbeck and Blyth the striae indicate a west to east direction of movement for ice originating in the Northumberland Fells. Finally in the Gosforth region striae with dominantly north to south trends were described. These were thought to have been formed at a later date than the west to east ones, by ice moving south from the Cheviots.

In the Pennine area the majority of the striae observations were described by Dwerryhouse in 1902. In the valley of the North Tyne striations are relatively common, and consistent in direction (Dwerryhouse A.R. 1902 p.599-601). They indicate ice movement from the west with a marked southerly component being introduced along the lower reaches of the North Tyne Valley.

The area of the Alston Block is singularly lacking in striae observations. In Weardale (Dwerryhouse A.R. 1902 p.593) and in Teesdale (p.582) striae observations indicate a down valley easterly ice movement. Across Stainmore striae indicate the passage of Lake District

Figure 12.



ice from the congested Vale of Eden to the Tees Lowlands. In the Tees Lowlands, owing to the great thickness of glacial drift, striae have only rarely been recorded. Barrow G. (1888) recorded grooves running NW to SE at Hob Hill, while near Eaglescliffe, Kendall P.F. (1902), Trechmann C.T. (1915) and Radge G.W. (1939) recorded striations passing NE to SW. Along the North Yorkshire coast a few striae passing SE and S were noted by Kendall P.F. (1902).

In Eastern Durham it is only in the northern part that striae observations are common. Howse R. (1864 p.169 to 170), recorded striations near South Shields radiating between north and east. He claimed that these indicated ice movement from the land towards the sea, and further pointed out that in many areas the striae followed the general slope of the land, rather than conforming to a single general direction. A few miles to the south at Roker, Kendall P.F. (recorded in Woolacott D. 1921 p.27) noted striae with a W.S.W. trend, while nearby at Fulwell Quarry Woolacott D. (1921 p.27) recorded southerly trending striae.

In the central part of the Magnesian Limestone Plateau, the area of detailed study of the author only three striae observations are recorded in the literature. These are all quarry observations. Two were described by Woolacott D. (1921 p.27) at Haswell and Wingate respectively, and one by Trechmann C.T. (1915 p.78) at Ferryhill. All three indicate southerly directions of ice movement.

Further west at Aycliffe, Trechmann C.T. (1915 p.78) described striations passing in three directions to the east, east-south-east, and south-south-west, which he considered to represent the erosion of three separate ice sheets.

In the course of this work the author has not observed any glacial striations on the parent rocks of Eastern Durham.

Taken together the pattern of striae indicate a general west to east movement in the upland area, particularly in central Northumberland and over Stainmore, and a southerly movement around the flanks of the Cheviots and in the southern part of coastal Northumberland. Elsewhere and especially in Eastern Durham observations are so few, and the patterns so divergent, that no general deductions of ice movement can be made. It is in this area however that the conflict and intermingling of ice sheets from the Pennines, the Lake District, the Cheviots and Scandinavia was greatest, and it is here that directions of ice movement might have been expected to shed most light on the patterns and sequence of glaciation. It was with this point in mind that fabric studies on the glacial tills were undertaken.

B. Fabric analysis.

Hugh Miller in 1884 seems to have been one of the first persons to realise that the stones embedded in a glacial till showed a preferred orientation of their long axes corresponding to the direction of ice movement. Richter K. (1932, 35, 36), was the first to investigate stone orientations using statistical methods, while the most comprehensive early work on the subject was published by Holmes C.D. (1941) as the result of a Ph.D study. Since this date a series of studies has been completed dealing partly or completely with the results and interpretations of stone and fine particle orientations, (e.g. Krumbein W.C. 1939; Dapples E.C. and Rominger J.F. 1945; Lundquist G. 1948; Virkkala K. 1951; Hoppe G. 1952, 53; Dreimanis A. and Reavely G.H. 1953; Sitler R.F. and Chapman C.A. 1955; West R.G. and Donner J.J. 1956; Glen J.W., Donner J.J., and West R.G. 1957; Harrison P.W. 1957;

Wright H.E. 1957; Dreimanis A. 1959; Stevens L.A. 1959; Norris G. 1962; Catt J.A. 1963; Ostry R.C. and Deane R.E. 1963; Andrews J.T. 1964; Catt J.A. and Penny L.F. 1966).

Most of these studies have used the technique of stone orientation in an effort to discover directions of ice movement. Others such as Holmes C.D. 1941; Karlstrom N.V. 1952; Glen J.W., Donner J.J., and West R.G. 1957; Harrison P.W. 1957 and MacIntock P. 1959, have considered the technique itself, and the means by which the stones become orientated.

Although most of this work has been concentrated on Pleistocene tills, work by Richter K. (1936); Hoppe G. (1953); Glen J.W. Donner J.J. and West R.G. 1957; and Harrison P.W. 1957, have shown that similar orientation patterns parallel with the direction of ice movement are to be found in deposits associated with present day glaciers.

Techniques.

In sampling for fabric analysis it is essential to ensure that the exposure at which the orientation measurements are made has not been disturbed by post depositional soil creep or periglacial activity. Preliminary work in Eastern Durham showed that in some cases preferred orientations within the till could be obtained to within 2 feet of the present day ground surface, while at other exposures the till fabrics had been disturbed to depths of between 4 to 5 feet. In this work therefore orientation measurements were never attempted within 5 feet of the present ground surface.

Two methods were employed for determining stone orientation measurements in the field. The first was that described by Karlstrom T.N.V. (1952), and which was itself, based on earlier work by

Wadell H. (1936), and Krumbein W.C. and Pettijohn F.J. (1938). This method required the construction of an orientation template, which was used for marking the stones in the field exposure. The stones were then removed to the laboratory where the parameters of direction and dip of the major and minor axes could be measured and recorded.

The second method, a modification of that used by West R.G. and Donner J.J. (1957) involved the measurement of the long axes with a compass. This proved more rapid than the Karlstrom method and permitted all analysis to be carried out in the field.

Field Methods.

Only stones with long axes more than double the length of the intermediate axes were measured in the field. Triangular and rhombohedral stones were discarded, owing to the difficulty of deciding which was the long axis. The stones varied in length from $\frac{3}{4}$ to 4 inches. Stones of suitable shape for long axes study varied from between 5 to 50% of the total sample, and, in general terms, showed a relationship inversely proportional to the amount of Magnesian Limestone present. Igneous rocks and greywackes produced the best shaped material for orientation analysis.

The sampling time required for recording the long axis orientations of 100 pebbles usually varied from 2 to 6 hours, depending on the stoniness of the clay, the frequency of occurrence of pebbles of the requisite shape, and the state of the clay. In winter the saturated and plastic nature of the clay made accurate measurements difficult, while in summer the dry clay proved so hard that the stones could only be removed from the matrix with the aid of a hammer and a cold chisel. The time required for the preparation of the exposure and the sampling of a hundred stones, meant that on average each orientation required at least a day of field work.

Results

This section is subdivided into three:-

1. Sample variation
2. Methods of analysis of data.
3. Fabric patterns for individual till sheets.

1. Sample variation.

Although fabric analysis is now widely recognised as a useful technique in the study of glacier movements, very little work has been attempted to assess the optimum sample size in terms of the number of stone long axes measured at a single exposure, or the variability shown by samples over short distances.

To provide information on these questions 14 till exposures were subjected to detailed analysis. At each exposure between 4 and 6 orientation patterns were recorded at 6 to 10 feet intervals along a single till face. Each of these orientation patterns was made up of the measurement of the long axes of 25 stones. In general between 4 and 6 orientation patterns were obtained at each of the 14 separate exposures.

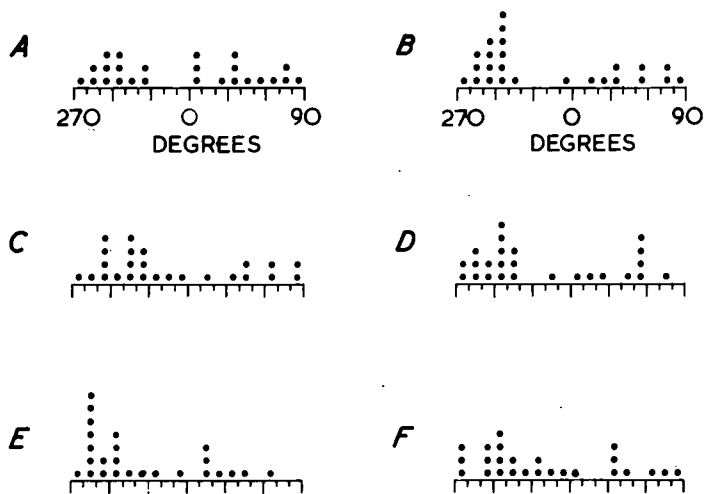
The orientation patterns for each of the samples at an exposure were plotted in a series of histograms, representing angular variation through 180 degrees. Histograms were plotted for each 25 stone sample, and then the data of 2 of these were bulked together to form a 50 stone sample distribution. In turn this was combined to form a total sample distribution for that particular exposure.

The data obtained from the 25 stone orientation samples were subjected to simple numerical analysis in terms of a modal 10 degree sector; a modal 30 degree sector; and a modal 60 degree sector. The centre point of these sectors being recorded in tabular form.

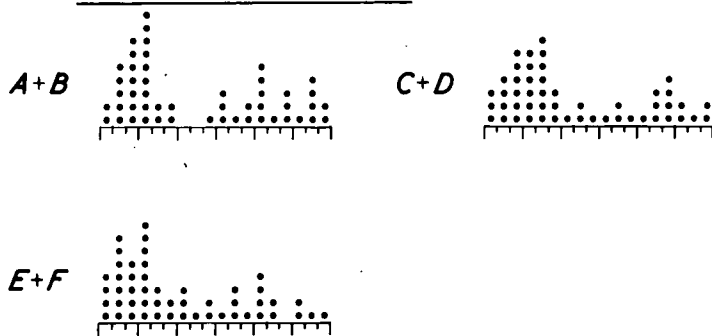
The samples of Westmoor Farm are shown in detail for illustration. (Fig 13). Here 6 orientation patterns of 25 stones each

WESTMOOR FARM

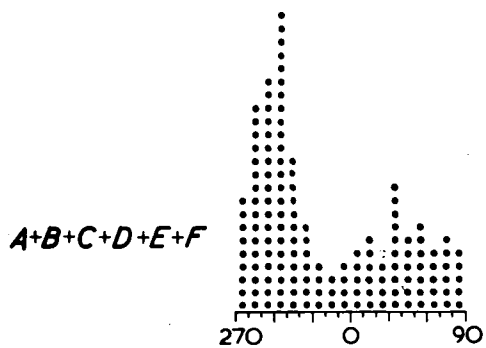
25 STONE ORIENTATIONS



50 STONE ORIENTATIONS



TOTAL ORIENTATION 150 STONES



were made at 6 feet intervals along the till exposure. Histograms were initially constructed and from these data extracted to compile Fig.14. (For full details of 14 sites see Appendix 2).

These data allowed the comparison of variations between,

A. the different methods of analysis, in terms of 10, 30 and 60 degree modal sectors

B. The differences in orientation between each of the 25 stone samples. (A to F).

The horizontal lines illustrated differences between the types of analysis of the same sample, and the vertical columns showed sample differences.

A. Differences in methods of analysis (Fig. 14).

Analysis by the 10 degree modal sector showed that in each sample it is possible to find more than one 10 degree modal sector. (Samples A and C). It is also found that variations within a single sample could be of the order of 90 degrees (A), and that under such conditions it is difficult to discover if the sample does possess a single preferred orientation.

Analysis by the 30 and 60 degree modal sectors shows only a single modal figure. The difference between the mid-point of the 30 and 60 degree modal sectors is generally less than 20 degrees.

Comparisons between the mid-point of the 10 degree modal sector and the mid-point of the 30 or 60 degree modal sectors, shows average variations of the order of less than 20 degrees. However where more than one 10 degree modal sector is found, the differences are often much greater and could approach 90 degrees.

Figure 14.

Westmoor Farm

	1	2	3	
25 stone orientation samples	Mid-point of 10° modal sector	Mid-point of 30° modal sector	Mid-point of 60° modal sector	Maximum difference in degrees between the mid-points of the different sectors for each sample
A	295, 305, 5 35	295	300	90
B	305	295	290	15
C	295, 315	315	310	20
D	305	295	290	20
E	285	295	300	15
F	305	305	320	15

Maximum
difference in
degrees between
the samples
within each
modal sector

90 20 20

Figure 15.

Inter-sample variations at each of 14 exposures. Maximum differences between the mid-points of the modal sectors are indicated.

Differences in degrees	1 10° modal sector	2 30° modal sector	3 60° modal sector
0	0	0	0
10	0	2	3
20	3	5	9
30	2	3	2
40	3	4	0
50	1	0	0
60	2	0	0
70	2	0	0
80	0	0	0
90	1	0	0

These simple tests illustrate very clearly how analysis of the same data by differing methods can lead to widely differing results.

B. Variations between samples. (Fig 14).

The maximum angular difference between the mid-points of the 10 degree modal sectors of samples A to F at Westmoor Farm is 90 degrees. It therefore illustrates that at best the mid-point of the 10 degree modal sector is only a rough method of indicating preferred orientation, and is one to be avoided.

Using the mid-point of the modal 30 and 60 sectors it is found that the maximum difference between the samples A to F is only 20 degrees. From this it can be concluded that analysis in terms of a 30 or 60 degree modal sector for a 25 stone orientation sample gives reasonably consistent results. However it does seem likely that variations of the order of c. 20 degrees are to be expected at any single sampling site. This figure probably represents both the sampling error and the fact that the preferred orientation within the till deposit is not perfectly developed.

A further attempt was made to assess the variation between samples using a more powerful statistical technique. For this purpose the Kolmogorov - Smirnov two sample test is employed. This test indicates whether two independent samples have been drawn from the same populations, by the comparison of two cumulative frequency distributions. (Siegel S. 1956, p.127). The test focuses on the largest deviations between the same intervals for the cumulative frequency curves.

Table of results for individual 25 stone samples.

<u>Westmoor Farm.</u>									
A.	3/25	9/25	12/25	12/25	15/25	16/25	20/25	22/25	25/25
B.	4/25	14/25	15/25	15/25	16/25	18/25	20/25	22/25	25/25
C.	2/25	7/25	14/25	16/25	17/25	18/25	21/25	23/25	25/25
D.	5/25	12/25	15/25	16/25	17/25	19/25	20/25	24/25	25/25
E.	8/25	14/25	16/25	17/25	18/25	22/25	24/25	25/25	25/25
F.	3/25	10/25	13/25	16/25	18/25	18/25	22/25	23/25	25/25
Max	6	7	4	5	3	6	4	3	0
Difference									
K_D									

With this method the numerator of the largest difference between two cumulative frequency curves has to equal or exceed 12 (12/25) before the null hypothesis that the samples are obtained from the same population can be rejected at the 0.01 level of significance. In this example the maximum difference between any two cumulative frequency curves is 7. One must therefore conclude that any differences in observations are due to random deviations within the same population distribution, and that the orientation patterns are similar.

Further information on the variability between samples using the three different methods of analysis is seen when the data from the 14 detailed sampling sites is considered in total. (Fig 15). In Fig. 15 the maximum intersample variation at each of the 14 exposures is plotted in terms of the three different types of analysis.

The mid-point of the 10 degree modal sector, as was seen at Westmoor Farm, shows intersample variations between 20 and 90 degrees at the 14 exposures. This technique can not therefore be recommended.

The mid-point of the 30 degree modal sector gives a much lower spread of results with intersample variations at each of the 14 exposures of between 10 to 40 degrees.

It is however the 60 degree modal sector which gives the most consistent intersample results. Here the variation noted is between 10 to 30 degrees, with a concentration of values at 20 degrees.

From this evidence it was concluded that the mid-point of the 60 degree modal sector is the best and most reproducible method of simple analysis. The evidence also proves that if analysis by the mid-point of the 60 degree modal sector is used, a minimum of 25 individual stone orientations can be used to gain approximate directions of ice movement.

Finally the analysis strongly suggested that over horizontal distances of at least 40 feet, till fabric orientations at a single exposure are particularly consistent, and that in the case of the 14 exposures examined showed maximum angular variations at any one site of less than 30 degrees, when examined by the 60 degree modal sector of analysis.

2. Methods of analysis of data.

The technique of stone orientation is also used on a broader scale to determine regional patterns of ice movement. In all a total of 77 orientation fabric analyses were completed on the stony clays of Eastern Durham. Sites were chosen to give as complete a cover of the area as possible. Certain gaps still remain in the pattern however due to a combination of factors. The largest gaps are near the urban areas of Sunderland, Hartlepool, and Stockton where urban development and building have made fabric analysis impossible. South of Ferryhill, in

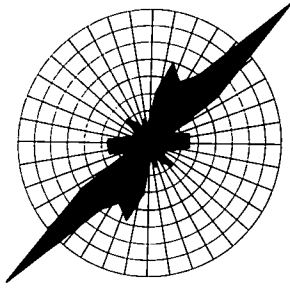
the Bradbury and Morden Carrs area, peat was found up to 40 feet in thickness, while in the Lower Tees area sands, gravels and laminated clays form a thick mantle over the till sheets. In such areas till fabric measurements are totally impracticable.

Wherever possible man-made or natural sections were used for fabric analysis of the till. However in many cases such sections are not available and this necessitated the digging of a pit, or a series of pits to depths of about 7 feet. At each exposure a series of 25 stone samples was taken (as described earlier), at intervals of 4 to 6 feet along a till face. In almost every case at least 100 stones were measured, comprising four separate sub-samples. In this way it was felt that the chances of obtaining an atypical orientation pattern would be reduced to a minimum, as no single small area of till made up the total orientation result.

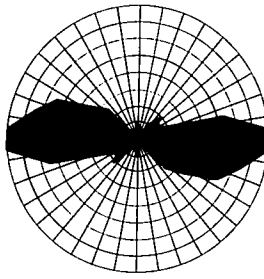
The results of the four or more samples at each exposure were then bulked together, and analysed as a single sample, representing a preferred orientation pattern for that given exposure. Although this method involved considerably more effort and time than the more normal sampling of all stones from a single small exposure, it was felt that it produced more objective and consistent results.

The data collected in the field were tabulated into ten degree columns (Appendix 3) and plotted in histogram form. From these data rose diagrams showing patterns of preferred orientation were plotted. (Fig 16a - g). Most workers in the past have not subjected their fabric analysis data to any form of statistical analysis, and the main peaks of the rose diagrams are generally considered sufficient evidence to indicate a preferred orientation of the long axes of the stones within the till.

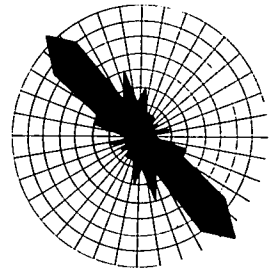
LOWER TILL



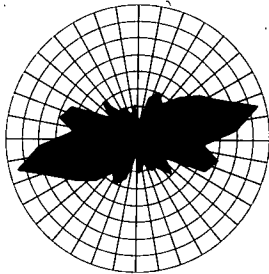
1



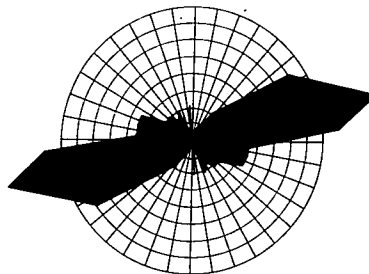
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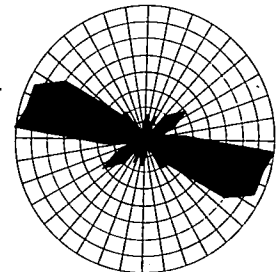
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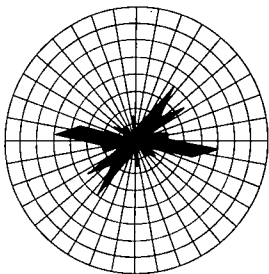
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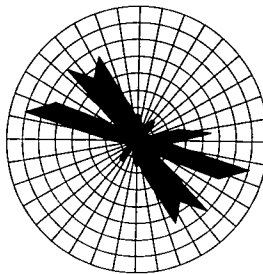
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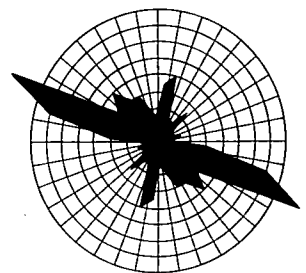
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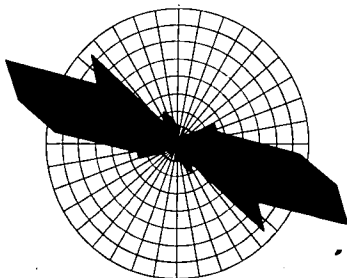
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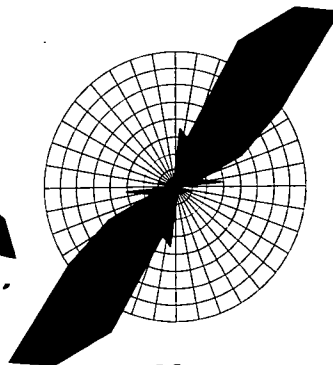
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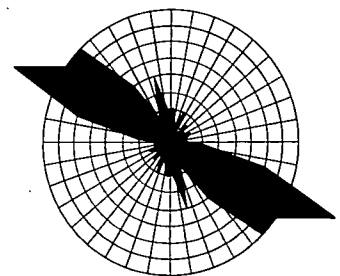
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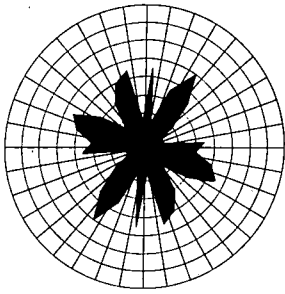
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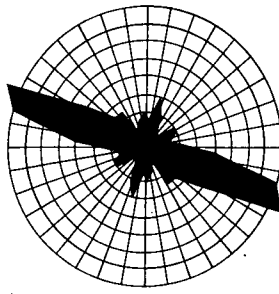
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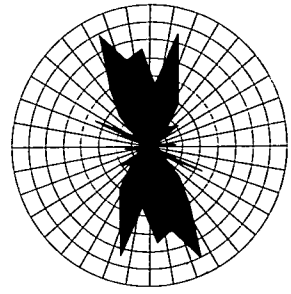
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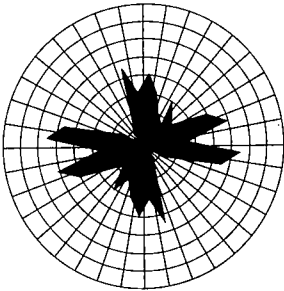
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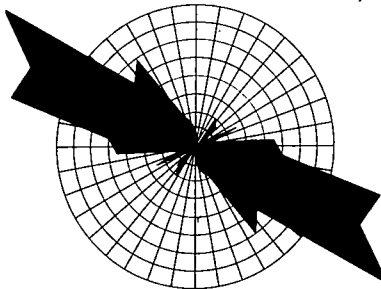
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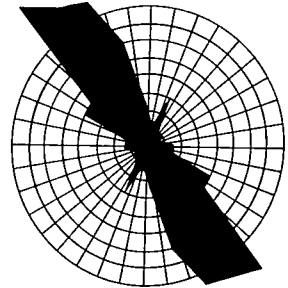
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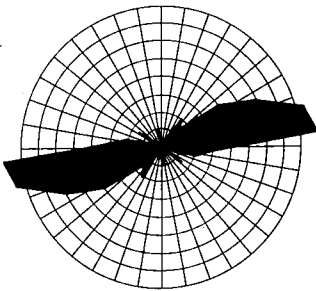
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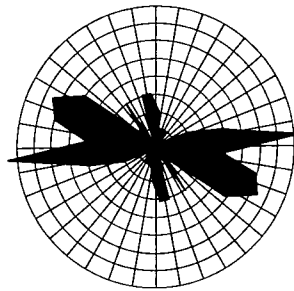
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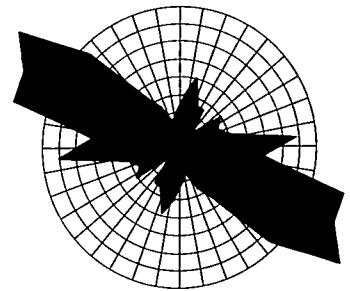
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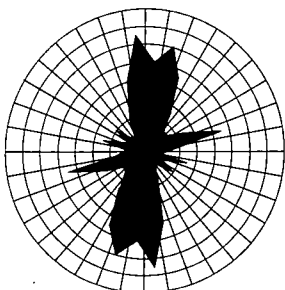
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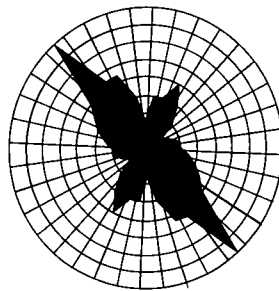
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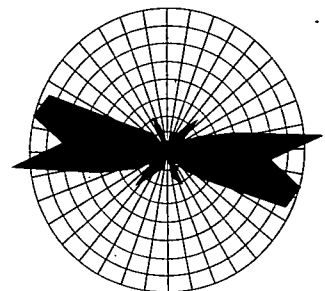
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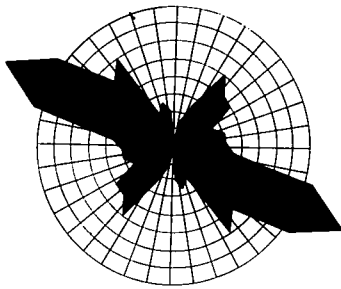


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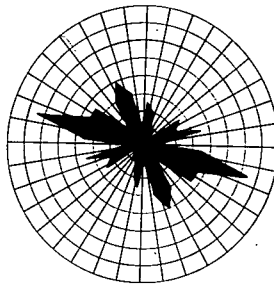


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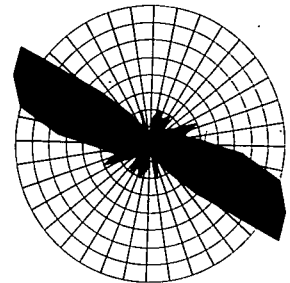
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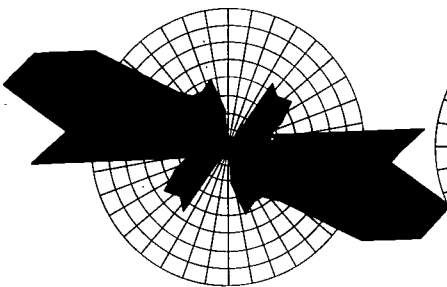
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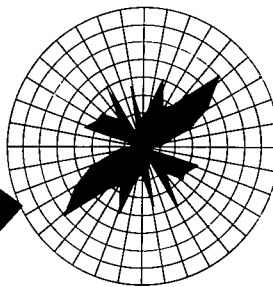
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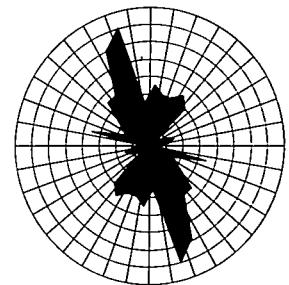
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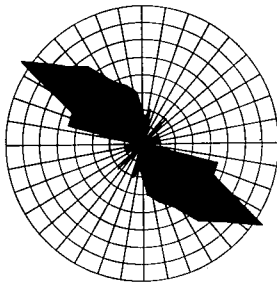
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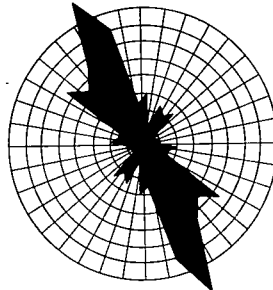
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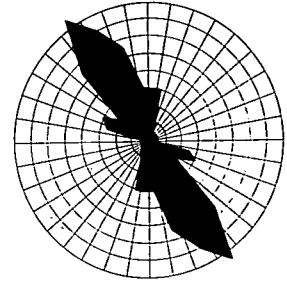
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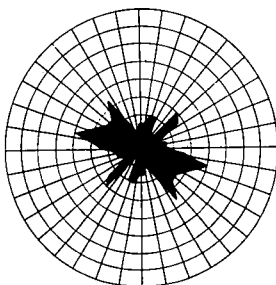
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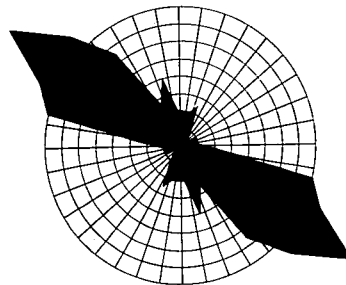
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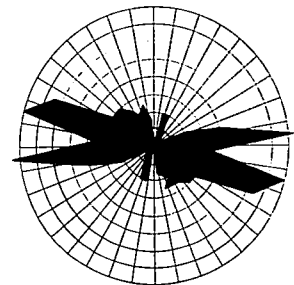
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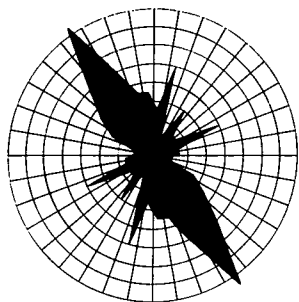
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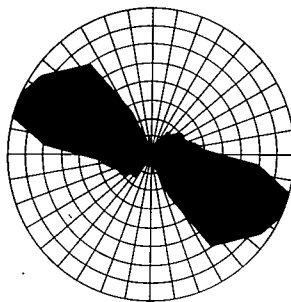
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Figure 16 d.

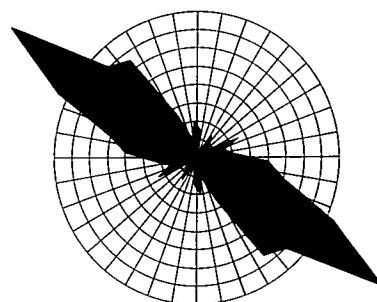
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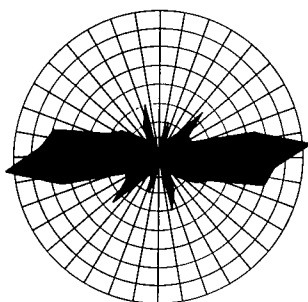
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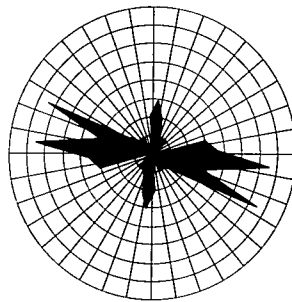
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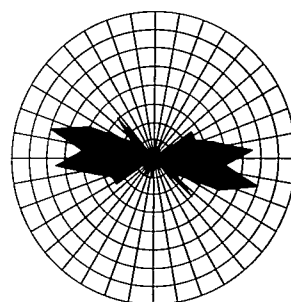
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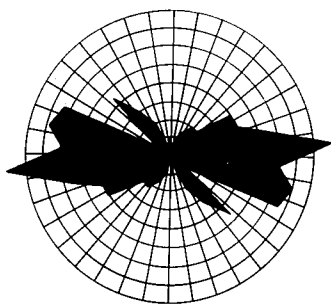
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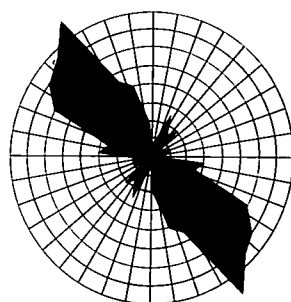
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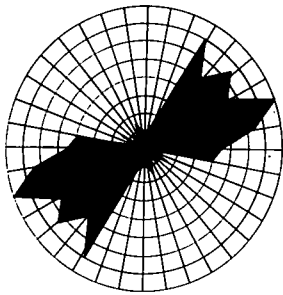


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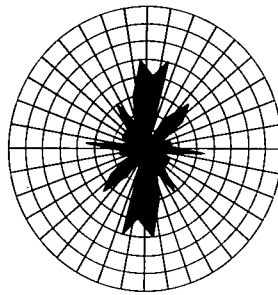


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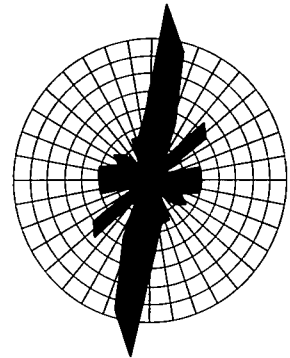
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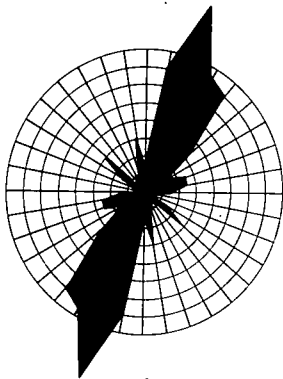
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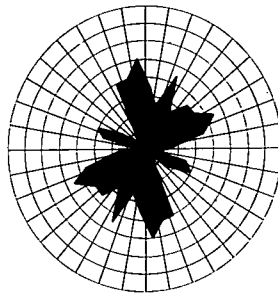
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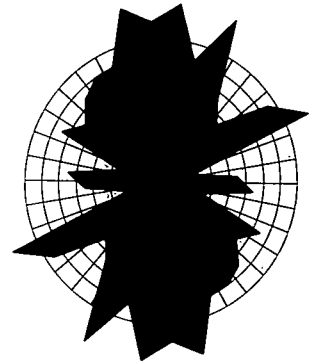
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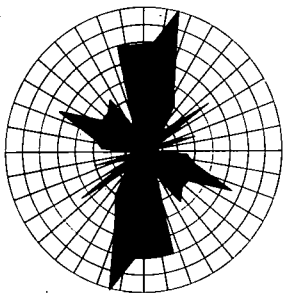
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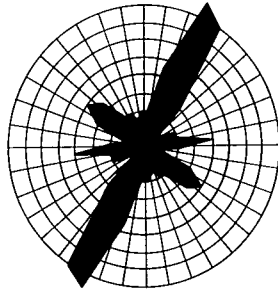
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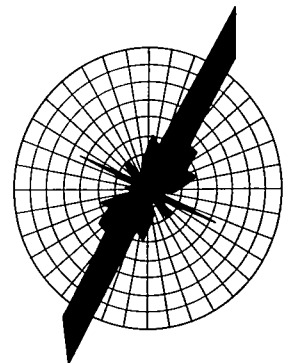
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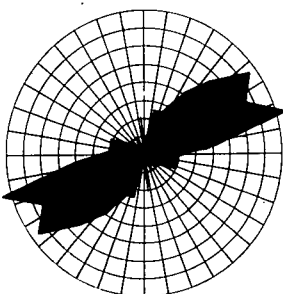
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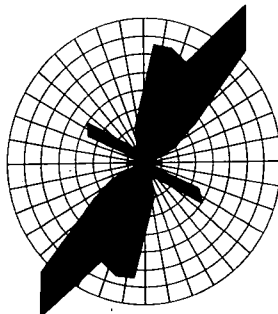
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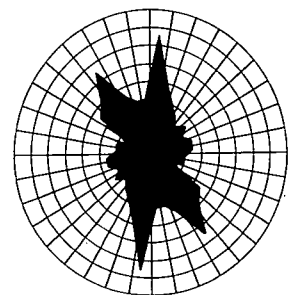
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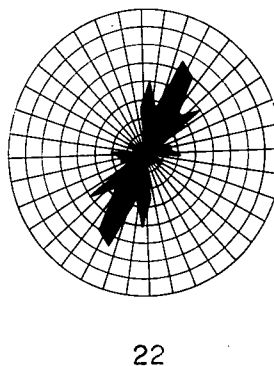
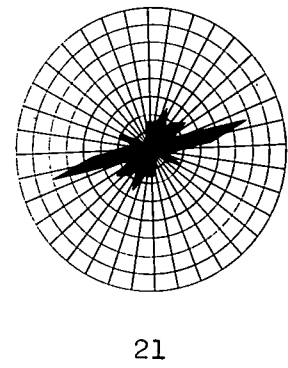
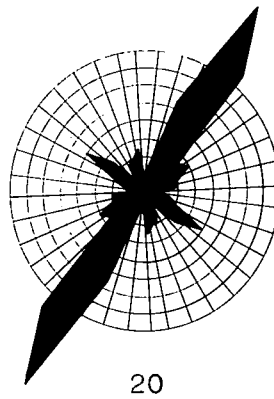
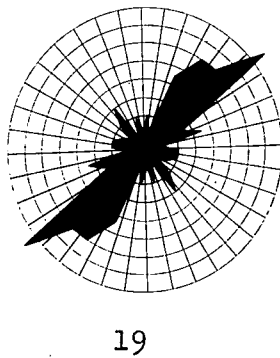
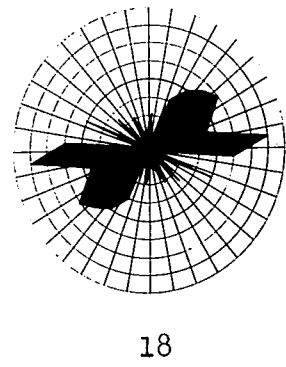
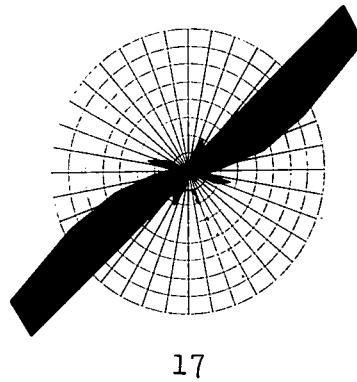
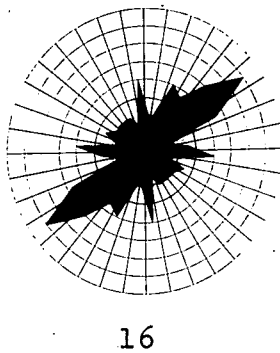
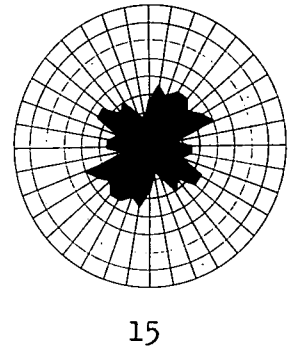
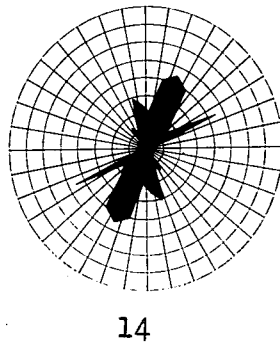
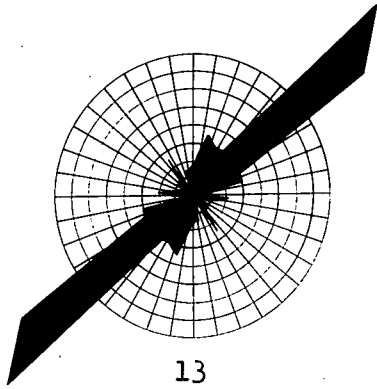


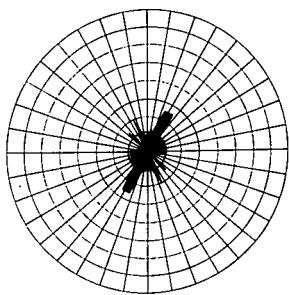
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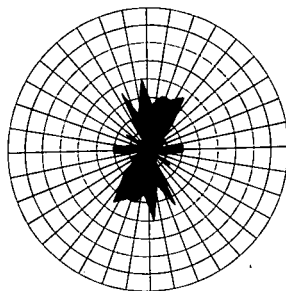
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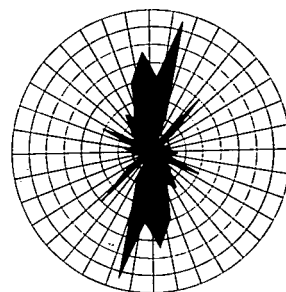




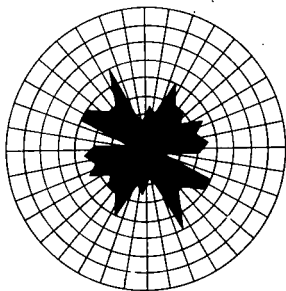
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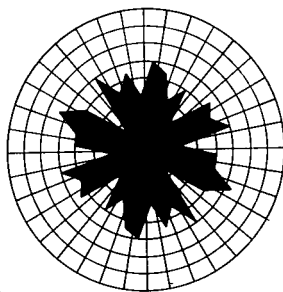
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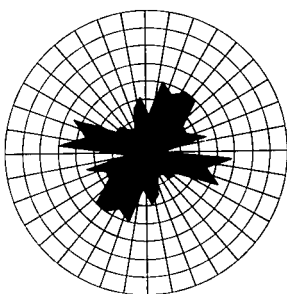


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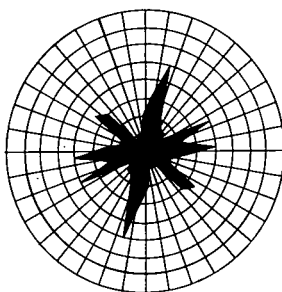


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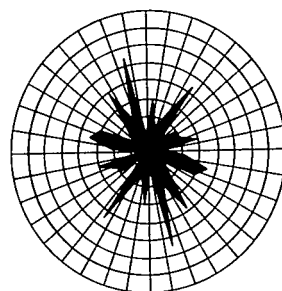
UPPER TEES CLAY



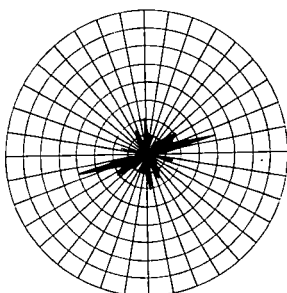
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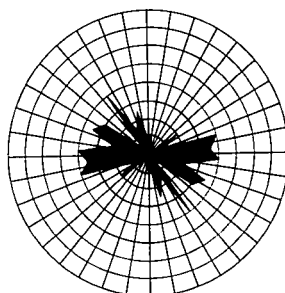
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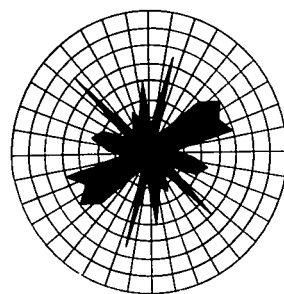
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4



5



6

To test the significance of the observations in this work all the stone orientation data were subjected to statistical analysis by Chi-square. Using this technique it was possible to estimate if the field data were obtained from a randomly distributed population, or from one showing some form of preferred orientation.

For the calculation of Chi-square the data were divided into three 60 degree groupings, of which one was the modal 60 degree sector. A null hypothesis was set up which postulated that the field orientation measurements were drawn from a randomly distributed population. The Chi-square value obtained was a measure of the accuracy of this hypothesis. The results were expressed as probability values. Significance values of .01 or less were taken as almost certainly indicating that a preferred orientation was present. All values above .01 were regarded as inconclusive of any preferred orientation. On this basis more than 75% of the samples analysed showed evidence of preferred orientation. (Appendix 4). The actual Chi-square values for the various samples are shown in Figs 18, 19, 20.

Many workers dealing with stone orientation measurements, besides making no attempt to evaluate the statistical significance of the sample data, also fail to estimate the variability of this data when compared with the total population from which they were drawn. All too often the sample mode or mean has been regarded as the same as the total population mean or mode, and not merely an estimate of it. Many workers (e.g. West R.G. and Donner J.J. 1957, and Catt J.A. 1963) seem to have accepted the 10 degree modal value, or the mean value as an absolute indication of the direction of ice movement, rather than an approximation to it.

In this type of analysis the choice of the mode as a significant average is suggested by its nature i.e. it is a measure of the

most abundant individuals in a population. (Krumbein W.C. 1939). If a number of stones are being deposited under a set of controlled conditions, it would appear that most of the stones would tend to conform to the set conditions, and therefore the modal value would be of great importance. However complexities associated with the size and shape of the stones would cause some deviations from the fixed orientation. These deviations might be significant in terms of their distribution on one side or other of the mode. Deviations however are most conveniently studied in terms of the arithmetic mean of the distribution, by conventional methods of moment analysis. The standard deviation offers a measure of the average spread of the data, and the higher moments afford measures of asymmetry and peakedness. (Improper sampling methods may reflect themselves in a skew distribution, or there may be an actual genetic significance to such measures).

Of the two measures of central tendency, the mode and the mean, the mode is far simpler to calculate, but suffers from the serious drawback that no further statistical calculations can be made from it. The mean on the other hand, is perhaps not as good an expression of the direction of ice sheet movement, but calculations made from it allow the spread of data between samples to be compared, together with estimations of the variance between sample values.

The modal values from each sampling site can easily be seen from the histogram data. The mean value is more difficult to obtain, and this was calculated for each orientation diagram using a technique described by Krumbein W.C. (1939 p.690). The method involves the assembly of the data into histogram form, with 20 degree sectors and setting the origin of an arbitrary scale opposite the largest, or modal class. In as much as there are nine classes in this procedure the modal class has 4 classes on either side of it. This method of rearranging the histogram data is based on the principle that the significant item is the

distribution itself, and not the arbitrary point of breaking the circle into classes. In essence it involves examining the distribution of points about the circle, and building a histogram around the central modal class. From this the mean distribution for each orientation can be easily calculated.

The tabular form of this calculation is as follows.

Hypothetical example:-

Fig. 17

<u>Arbitrary class.</u> (degrees)	<u>Mid point.</u>	<u>Frequency</u>	<u>d</u>	<u>fd</u>	<u>d²</u>	<u>fd²</u>
270 - 290	280	5	-4	-20	16	80
290 - 310	300	6	-3	-18	9	54
310 - 330	320	10	-2	-20	4	40
330 - 350	340	13	-1	-13	1	13
350 - 10	360	22	0	0	0	0
10 - 30	20	14	+1	+14	1	14
30 - 50	40	13	+2	+26	4	52
50 - 70	60	12	+3	+36	9	100
70 - 90	80	5	+4	+20	16	80
		<u>100</u>		<u>+25</u>		<u>441</u>

The columns are summed at the base of the table. The values divided by total frequency (100) yield,

$$n_1 = 25/100 = 0.25$$

$$n_2 = 441/100 = 4.41$$

To find the arithmetic mean azimuth in degrees, n_1 is multiplied by the class interval in degrees (20), and added to the mid point of the $d = 0$ class (360 degrees).

$$\text{Mean azimuth} = 360 + 20 (0.25) = 5 \text{ degrees.}$$

The average spread of the data in degrees about the mean azimuth (the standard deviation) is found from the relationship

$$\text{Standard deviation } (\sigma) = k \sqrt{n_2 - \frac{(n_1)^2}{n}}$$

k is the class interval 20 degrees.

The arithmetic mean azimuth found by this method is the first moment of the arithmetical distribution. It is located at the centre of gravity of the distribution.

The standard deviation is based on the second moment, and measures the average spread of the data about the arithmetic mean.

The mean and modal values of the orientation patterns are regarded as indicating the general directions of ice movement at a given point. (Figs. 18, 19, 20). Comparisons of mean and modal values for the same orientation data show variations between the two values of up to 20 degrees. The closer the sample data approximates to a normal distribution the closer is the correspondence between the mean and modal values. The mean value represents the centre of gravity of the distribution, while the mode expresses the most frequently occurring value. From this it is obvious that differences in the technique of numerical analysis can lead to differing results from the same basic field data.

Having established the direction of preferred orientation in terms of the mean or mode, it is useful also to assess the degree of perfection of this orientation. This gives an indication of the strength of the orientation capacity of the media in which the preferred orientation pattern is gained. It may well be that each media which imparts an orientation pattern does so to a characteristic degree, and therefore by studying the degree of preferred orientation one may be able to learn more of the differing types of origin of certain deposits.

Fig. 18

Lower Till Analytical data from stone orientation measurements.

No.	Mid point of modal 10° sector	Mid point of modal 30° sector	Mid point of modal 60° sector	Mean	Standard deviation	Standard error of Mean	χ^2
1.	45	45	30	39.26	38.10	3.66	43.88
2.	85, 275	275	280	272.40	30.90	3.11	77.86
3.	315	315	320	318.60	38.60	3.84	38.56
4.	75	75	90	78.52	41.88	3.80	21.69
5.	75	75	80	80.17	34.78	3.19	64.35
6.	275	285	290	281.40	36.26	3.65	49.52
7.	275	275	80	84.06	42.16	5.31	14.66
8.	285	325	310	311.60	39.68	3.93	31.05
9.	295	295	300	300.60	44.23	4.27	28.05
10.	295	295	290	294.10	30.34	2.75	90.64
11.	45	35	40	41.44	25.64	2.26	134.14
12.	295	305	300	302.0	36.40	3.41	77.58
13.	35	35	30	-	-	-	0.57
14.	295	295	300	293.80	40.80	4.08	33.86
15.	335	345	350	350.96	36.88	3.68	35.10
16.	35	85	80	219.88	51.42	5.18	12.88
17.	305	295	300	291.54	29.74	2.55	106.72
18.	315	325	320	328.42	32.88	2.93	79.62
19.	85	75	80	75.18	28.38	3.13	75.87
20.	85	295	280	290.28	41.76	4.02	28.76
21.	305	295	300	295.86	48.86	3.77	41.09
22.	355	5	10	8.52	44.80	4.48	24.80

Fig. 18 - Continued :

No.	Mid point of modal 10° sector	Mid point of modal 30° sector	Mid point of modal 60° sector	Mean	Standard deviation	Standard error of Mean	χ^2
23.	315	325	320	319.20	45.10	4.25	15.75
24.	285	275	280	275.20	33.66	3.36	67.47
25.	295	295	300	298.32	37.54	3.29	51.67
26.	285	285	280	289.66	43.58	4.65	11.42
27.	305	295	290	294.92	37.92	3.51	56.37
28.	75	75	80	73.44	34.66	2.55	88.26
29.	45	45	40	-	-	-	8.81
30.	345	335	340	343.00	40.82	4.11	16.64
31.	305	315	310	310.70	37.16	3.72	52.32
32.	335	325	330	335.0	36.80	3.65	49.25
33.	325	335	340	328.72	31.10	3.23	55.05
34.	325	295	300	-	-	-	7.28
35.	305	305	310	310.22	33.58	2.92	86.00
36.	85	275	280	275.66	39.52	3.86	43.62
37.	325	325	330	325.64	45.16	4.32	19.11
38.	285, 295	295	300	297.28	30.34	2.90	91.89
39.	305	305	300	300.00	33.00	3.01	81.05
40.	85	275	280	89.14	38.36	3.77	36.74
41.	275, 285	285	280	285.68	43.44	5.09	33.85
42.	285	275	90	283.62	32.34	3.85	45.58
43.	85	275	90	90.90	35.92	3.28	47.43
44.	325	315	320	321.26	35.68	3.39	60.13

Fig. 19

Upper Till. Analytical data from stone orientations.

No.	Mid point of modal 10° sector	Mid point of modal 30° sector	Mid point of modal 60° sector	Mean	Standard deviation	Standard error of the Mean	χ^2
1.	65	55	50	55.58	34.88	3.33	61.63
2.	355, 15	5	350	357.68	46.02	4.99	10.77
3.	5	5	20	3.48	46.70	4.64	17.55
4.	15	25	30	18.40	36.52	3.45	55.57
5.	355	345	0	10.20	45.96	4.60	12.84
6.	345, 5, 25	355	0	0.34	45.52	2.94	12.68
7.	15	5	10	354.96	44.70	3.92	19.08
8.	25	25	20	26.40	47.40	4.50	15.73
9.	25	35	30	35.80	39.80	3.81	36.40
10.	75	65	60	61.70	33.30	3.26	57.08
11.	35	35	30	37.10	40.68	3.66	63.99
12.	5	15	350	-	-	-	8.00
13.	45	45	40	41.08	35.10	3.35	71.57
14.	25, 65	25	40	23.60	34.10	4.28	29.72
15.	65	55	40	-	-	-	2.18
16.	55	55	40	57.20	40.16	3.90	11.24
17.	45	55	60	60.00	25.30	2.54	104.48
18.	85	85	70	74.86	41.54	4.16	26.52
19.	55	45	50	48.2	40.00	3.98	58.72
20.	35	35	40	29.00	42.40	3.90	38.34
21.	75	75	60	67.22	39.74	5.13	14.40
22.	25	35	30	33.10	35.64	4.26	34.86

Fig. 20

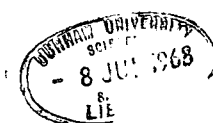
Upper Wear Clay

Analytical data from stone orientations.

No.	Mid point of 10°modal sector	Mid point of 30°modal sector	Mid point of 60°modal sector	Mean	Standard deviation	Standard error of the mean	χ^2
1.	25, 35.	35	50	-	-	-	4.73
2.	355	5	10	4.40	53.80	6.52	10.96
3.	15	5	35	356.14	38.70	4.15	23.03
4.	295	65, 85	280	-	-	-	0.30
5.	335	305	320	-	-	-	2.08

Upper Tees Clay

1.	275	285	40	-	-	-	4.34
2.	65, 85	15, 75	270	-	-	-	2.00
3.	345	335	320	-	-	-	2.55
4.	75	65	60	-	-	-	6.62
5.	315	65	70	-	-	-	2.69
6.	275, 325, 65	85	280	274.48	46.16	5.59	22.52



The average spread of the data around the arithmetic mean is measured by the standard deviation. (c. 66% of the observations lie within + or - 1 standard deviation away from the mean, and c. 95% of the observations lie within + or - 2 standard deviations of the mean).

The standard deviations of 64 orientation patterns which show a preferred orientation pattern are shown in histogram form. (Fig 21). These indicate variations from 25 to 54 degrees and show a marked concentration between 30 to 45 degrees. The modal value is between 30 to 45 degrees. The distribution approximates to a normal distribution, and it appears likely that all these orientation patterns were formed under similar conditions. From the information available it appears that the orientation patterns within the Lower Till are more strongly developed than in the Upper Till. (Fig 21).

Using the data from Fig.21 an attempt was made to establish if the standard deviations of the Upper and Lower Till sheets were drawn from the same population. This is achieved by using analysis of variance for unequal size groups. (Huntsberger D.V. p.212, 224). Initially one sets up a null hypothesis that the two sample means of the standard deviations of the Upper and Lower Till are drawn from the same population. To test this hypothesis an F value is calculated. If the sample F value is less than the Table F value at a given level of significance one must accept the null hypothesis as being valid.

In this case the sample F value = 1.93

From the F table $F_{1 \ 59(.01)} = 7.1$

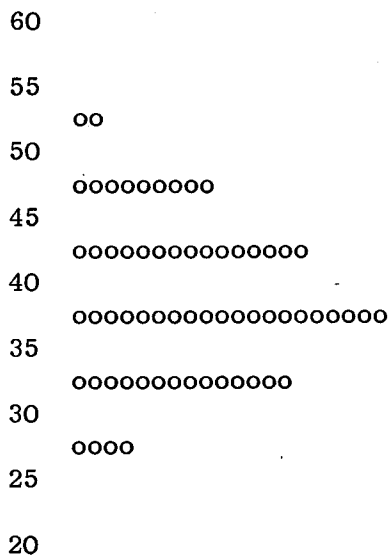
From this it is seen that the null hypothesis cannot be rejected at the 1% level of significance, and therefore the two samples must be regarded as having been drawn from the same population.

Having shown that the stony clays of Eastern Durham do possess preferred orientation of the long axes of their stones, it is clearly of the greatest importance to be able to assess the intersample variations one may expect to find in a single till sheet.

Figure 21.

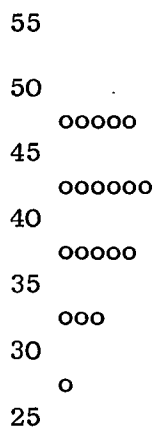
Standard deviations of orientation diagrams in degrees.

TOTAL SAMPLES

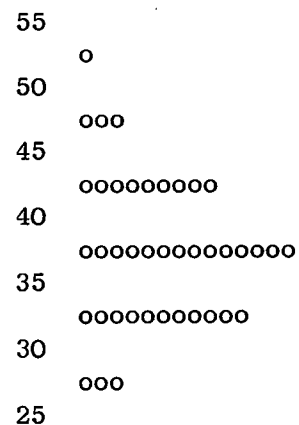


Number of observations

UPPER TILL



LOWER TILL



Each preferred direction of orientation represents a sample mean drawn from an infinitely larger population, and represents an attempt to approximate the true mean of this larger population. The relationship between the sample and the true parameters is partly conditioned by the size of the sample and partly by the method of obtaining the data. Providing that the sample is a random one, the major factor controlling the relationship between the sample and the true population values is the size of the sample. The standard error of the mean is a statistic which measures the likely deviation of the sample mean value, from the actual mean value of the total population. The true mean lies with a 99.7% probability within + or - 3 times the standard error of the mean, from the sample mean.

$$\text{Standard error of the mean} = \frac{\text{Standard deviation}}{\sqrt{\text{Number of observations}}} = \frac{\sigma}{\sqrt{n}}$$

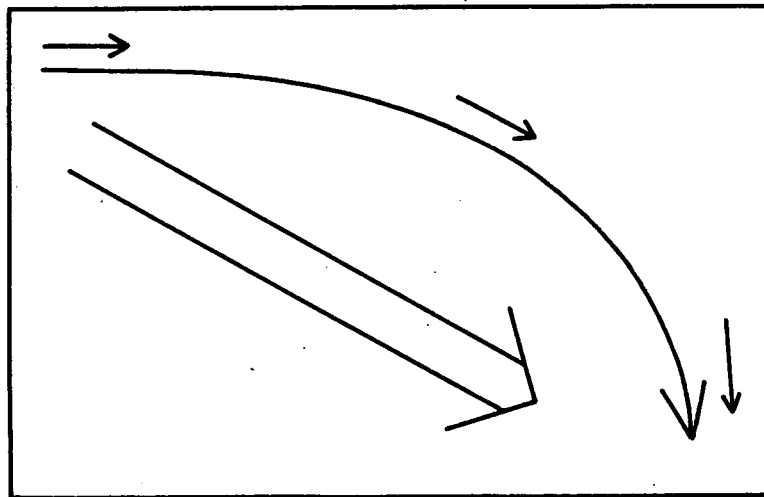
Because the sample size is the key determinant of the accuracy of the standard error of the mean, it is obvious that to halve the standard error one has to quadruple the number of observations.

e.g.

- a. if $\sigma = 40$ and $n = 25$.
therefore the standard error of the mean $= \frac{40}{\sqrt{25}} = 8$
- b. if $\sigma = 540$ and $n = 100$.
therefore the standard error of the mean $= \frac{40}{\sqrt{100}} = 4$
- c. if $\sigma = 40$ and $n = 400$.
therefore the standard error of the mean $= \frac{40}{\sqrt{400}} = 2$

This statistic allows the assessment of whether samples in juxtaposition are derived from the same total population. Certain difficulties do arise as to what one understands by the true mean in terms

of directions of ice movement. In this case one must assume that the true mean represents the direction of ice movement at a given point. Over a large area however total ice movement may not have been constant, and a change in the direction of movement may have occurred, possibly through an arc of c. 90 degrees.



In such a case the true, or resultant mean for the area as a whole can vary by as much as 45 degrees from individual sample means. Equally on a smaller scale minor topographical irregularities can give rise to changes in ice direction.

The difficulties of assessing whether a series of sample means is drawn from the same total population therefore becomes obvious. Bearing this in mind, it is only strictly valid to compare orientation patterns which are close to each other spatially, and not to compare preferred orientations patterns separated by a considerable distance, as the actual mean direction of the same ice sheet may itself have changed.

The technique of the standard error of the mean allows one to say with reasonable certainty whether two orientations in juxtaposition are obtained from an ice sheet moving in a single uniform

direction. If the orientation directions of the two samples are separated by an angular distance of more than three times the standard error of the mean, one can say they are not drawn from a single uniform population. For the preferred orientations of the Eastern Durham samples, figures of three times the standard error of the mean varied from a minimum value of 6.78 degrees to a maximum of 19.56 degrees. (Standard errors of the mean Fig.18,19,20). This means that adjacent orientations within a single till sheet can vary in mean direction between 13 and 40 degrees, and yet still be regarded statistically as being drawn from the same total population mean. In the literature in the past it appears that too little consideration has been given to the assessment of what is a significant difference between two adjacent orientations, and it seems quite likely that different ice directions have been claimed on evidence, which had it been subjected to statistical analysis may have indicated that the differences observed were the results of sample variations within the same total population.

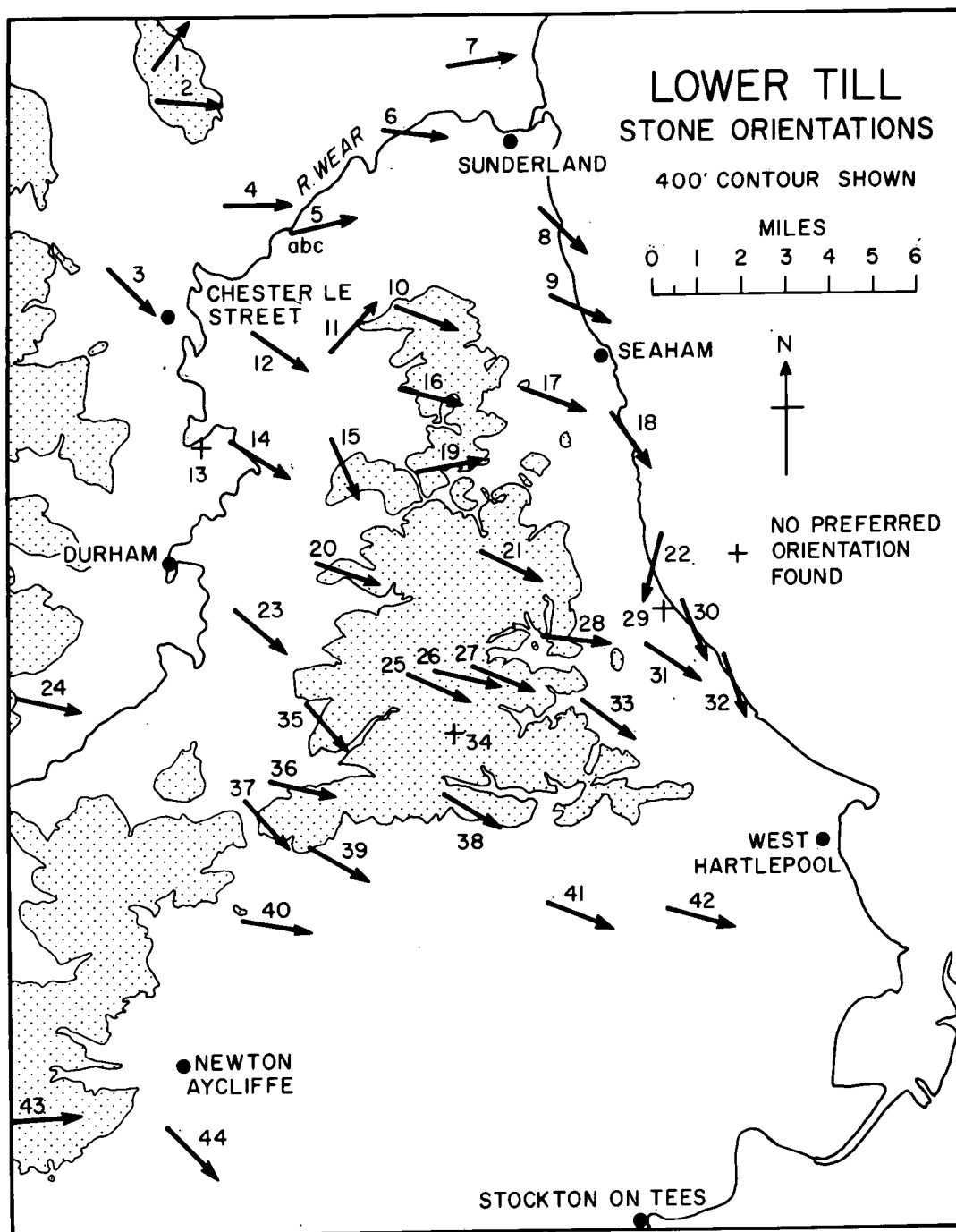
3. Fabric patterns for individual till sheets.

Lower Till

The results of stone orientation measurements at 44 sites within the Lower Till sheet are shown in Fig.22. The arrow heads have been inserted on the evidence that rocks of western origin are found throughout the area, and that no Magnesian Limestone is found in the Lower Till west of the line of the Magnesian Limestone Escarpment.

Of the 44 orientation patterns analysed by Chi square only three are found to be insignificant at the .01 level. The reason for the lack of a pronounced orientation at these sites (Nos. 13, 29, 34), is uncertain as all three exposures appeared to be in completely

Figure 22.



undisturbed till. (Appendix 3).

13. Finchale Priory

29. Mouth of Castle Eden Dene.

34. Trimdon Grange Quarry.

The individual orientation patterns require little comment. In north Durham the preferred orientations indicate an ice sheet which came through the Tyne Valley, overrode Gateshead Fell and continued eastwards out to sea. Orientation patterns at ~~Eighton~~ Banks No. 2; Biddick Burn No. 4; Fulwell Quarry No. 7; and South Hylton Quarry No. 6 indicate an almost due west to east movement. The orientation pattern at Windy Nook Quarry No. 1 provides a slightly anomalous pattern, which may represent a local ice movement.

In the Middle Wear Lowlands the Tyne ice fanned out towards the south into the low lying ground near Chester-le-Street. (Chester-le-Street No. 3; Lumley Brick Works No. 12; and Finchale Priory No. 14). Encroaching upon the Magnesian Limestone Escarpment the basal layers of the ice appear to have been deflected by the very pronounced feature which the escarpment presented. As a result the ice at Penshaw No. 5; and Houghton-le-Spring No. 11 was deflected northwards around westerly penetrating spurs of limestone.

Throughout most of the plateau area from Ryhope to Ferryhill the orientation patterns are particularly constant and indicate a general direction of ice movement to the south-east.

In the southern part of the coastal area south of Chourdon Point (No. 13), there is some evidence that locally ice impinged back onto the coastal region in the lee of the reef knoll ridges, possibly

as the result of increasing ice pressure offshore. (Warren House Gill No. 22; Blackhall Colliery Aerial Flight No. 30; and Crimdon Dene Mouth No.32).

A lack of suitable exposures of the Lower Till in the Tees Lowlands made it impossible for orientation measurements to be carried out in this area.

Taken together these orientation patterns suggest that during the time of the deposition of the Lower Till sheet, Eastern Durham was covered by a single ice sheet which moved in an east-south-east direction.

Upper Till

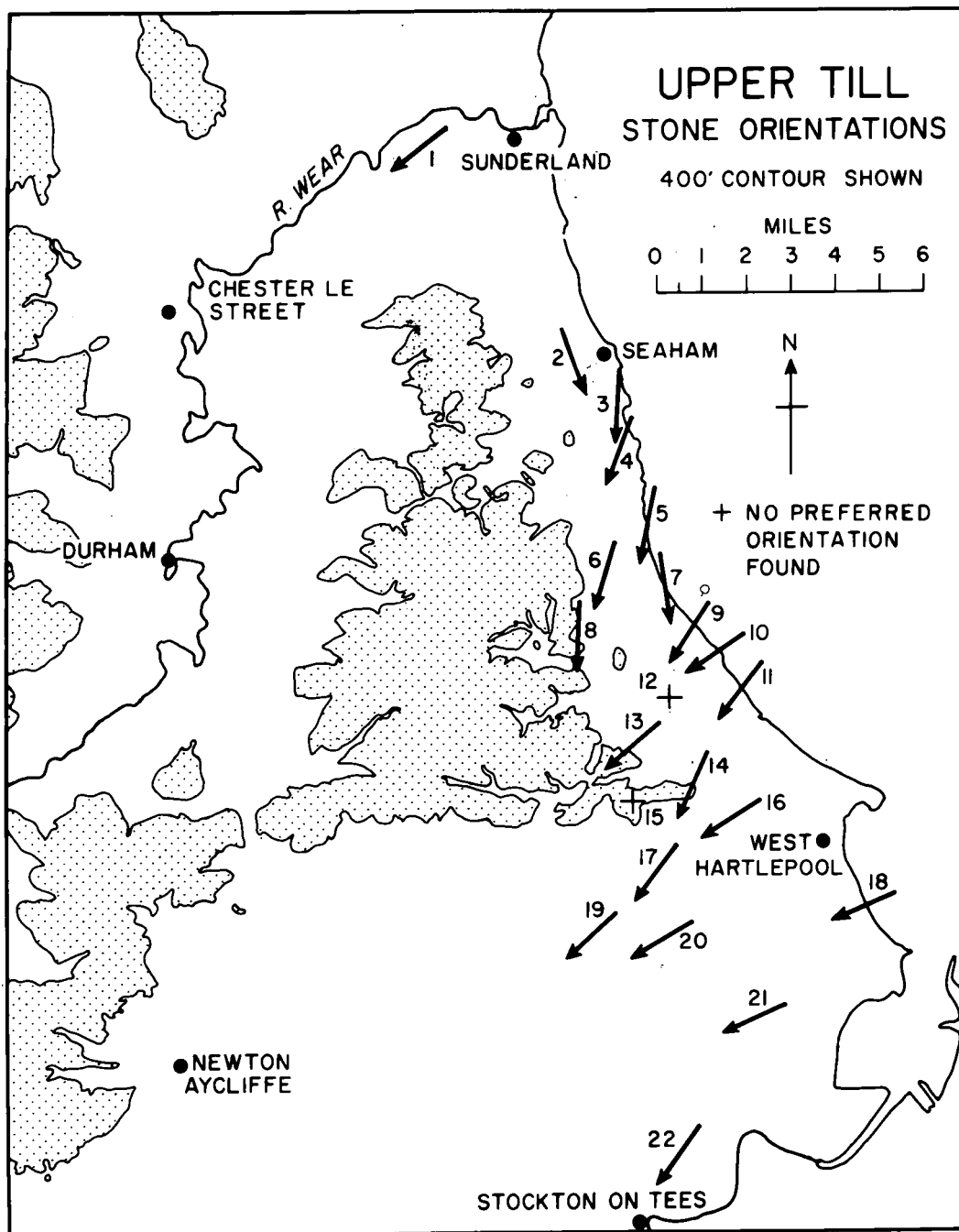
The results of twenty-two orientations obtained from the Upper Till of the coastal area are shown in Fig.23. Of these only two Hesleden Dene No. 12, and Whelly Hill Quarry No.15 proved to have no preferred orientation when subjected to chi-square analysis.

The arrowheads have been inserted on the evidence of the presence of Cheviot rock types within the Upper Till, and the findings of Upper Magnesian Limestone pebbles south of their present outcrop. (Smith D.B. personal communication).

The orientation directions of the Upper Till are particularly constant. The most northerly of the orientation patterns is obtained from an isolated outcrop of the Upper Till at South Hylton Quarry No.1, which indicates a direction of ice movement from the north-east.

Further south along the coast at Seaham Harbour Brick Pit No. 2, and Hazel Dene No.3 the ice directions are almost due north to south. This suggests that the ice was contained in its inland penetration by the relatively steep easterly slopes of the Permian Reef Knolls, which rise to c. 500 feet in the Easington area.

Figure 23.



In contrast further south as the land drops away to the Tees Lowlands the ice sheet appears to have spread as a lobe in a more westerly direction onto this lower ground. (Seaton Carew No. 18; Greatham Beck No. 21; Embleton No.19; A.19 road improvement No.20; Low Stotfield Farm No.17).

A further piece of evidence which confirms the Upper Till ice movement as being derived from a north-easterly direction is found in a new road cutting 80 feet deep at Sheraton.

The succession is :-

Upper Till 18 to 24 feet

Laminated clays and sands 20 to 48 feet

Lower Till 0 to 8 feet+.

In the cutting a large thrust fault was visible in the laminated clays, which did not pass upwards into the overlying Upper Till. The line of the fault which was traceable on both sides of the cutting was orientated at 305 degrees from true north, with the overthrust towards the south west. The feature was interpreted as a thrust feature in what were probably frozen laminated clays, caused by the advance of the Upper Till from a north or north-easterly direction. (Fig.24).

These orientations indicate that at the time of the deposition of the Upper Till, the coastal fringe of Eastern Durham was invaded by an ice sheet from the North Sea moving in a general southerly direction. The fact that this ice sheet appears to move into the Tees Lowlands strongly suggests the presence of a larger and more extensive ice sheet in the North Sea, exerting pressure in a westerly direction.



Figure 24.

One point of general interest is that when the preferred orientations of the Upper and Lower Till sheets are examined in the coastal area between Easington and Crimdon Dene, the mean directions of orientation are remarkably similar. This is probably due to the reef knoll features causing deflection of the ice. When the Lower Till sample from Warren House Gill No. 22 is compared with the Upper Till samples from Foxholes No. 5 it is found that both these samples could have been obtained from an ice sheet moving in a single uniform direction.

Warren House Gill (LOWER TILL)

Mean sample value = 8.5 degrees

Standard error of the mean = 4.5 degrees

Therefore true mean = $8.5^{\circ} \pm 13.5$ degrees with a 99.7 % probability

= 355 to 22 degrees.

Foxholes (UPPER TILL)

Mean sample value = 10.2 degrees

Standard error of the mean = 4.6 degrees

True mean was between 10.2 ± 13.8 degrees with a 99.7% probability

= 356.4 to 23.8 degrees.

However most of the other Upper and Lower Till samples in juxtaposition in the coastal area do suggest differences in ice movement.

e.g. 1. Lower Till Blackhall Colliery No. 30

Sample mean = 343 degrees

True mean = 330.7 to 355.3 with 99.7% probability.

Upper Till Blackhall Colliery No.9

Sample mean = 35.8 degrees

True mean = 24.4 to 47.2 degrees with 99.7% probability.

2. Lower Till Crimdon Dene No. 32

Sample mean = 335 degrees

True mean = 323.9 to 346.1 with 99.7% probability.

Upper Till Crimdon Dene No.11

Sample mean = 37.1 degrees

True mean = 26.0 to 48.2 degrees with 99.7% probability.

These results suggest that there are two differing directions of ice movement within the area of Eastern Durham.

Upper Wear Clay and Upper Tees Clay.

Five orientation patterns were undertaken on the Upper Wear Clay of the Wear Lowlands. Of these only two gave significant orientation patterns when subjected to chi-square analysis. (Railway cutting north of Durham No. 2; High Butterby No.3 Fig.20). The railway cutting exposure north of Durham produced a very weak orientation pattern. Both it and the High Butterby sample indicate a north to south preferred orientation.

Similarly in the Tees Valley, 6 orientations were undertaken in the Upper Tees Clay. After chi-square analysis only one exposure was found to have a preferred orientation pattern. (Portrack Brick Pit No. 5 Fig 20).

Therefore in the case of these clays one appears to be dealing with a mode of origin which can, but in the majority of cases does not, impart a preferred direction of orientation on its included pebbles. In many aspects these stony clays appear to be closely comparable to true-sub-glacial tills. The lack of an orientation fabric in till-like deposits has seldom been reported in the literature before, and yet it seems strange that such features have not been observed in other parts of the British Isles. Whether the Upper Wear and Tees Clays initially possess preferred orientation fabrics, or whether they were deposited by some media which did not impart a preferred orientation pattern is unknown.

Conclusions.

In Eastern Durham stone orientation patterns show that the Lower and Upper Till sheets were deposited by ice sheets possessing different directions of ice movement. They indicate that at the time of maximum glaciation of the area, during the Lower Till glaciation, ice movement was in an east-south-east direction across the county from westerly sources of ice origin in the Pennines, the Lake District, and the Southern Uplands. In contrast the Upper Till Glaciation appears to have only affected the coastal fringe of County Durham. This ice sheet appears to have originated in the Cheviot area of Scotland although its exact relationship with the main western ice sheet is unknown. The preferred stone orientations do not indicate whether these two directions of ice movement took place in the same or different glacial phases. The stratigraphical position of the two tills indicates that the north to south ice movement took place at a later date than the west to east movement.

The stone orientations also explain the anomalous striae directions which have been observed in North East England. It now seems correct to assume that the dominantly west to east trending striae were formed first, and that the north to south trending striae of coastal Northumberland were formed at a later period by ice moving south along the coastal region.

Finally this work has shown that all till-like deposits do not possess preferred orientation patterns at the present day. The reasons for this are unknown.

Chapter 6

STONE COUNTS AND STONE SHAPES

This chapter is divided into two sections:-

- A. Stone counts.
- B. Stone shapes.

A. Stone counts.

Introduction.

The identification of erratic rocks was one of the earliest techniques used in the study of glacial deposits. Its main aim was to distinguish general directions of ice movement based on the distribution of characteristic rock types. It is a purely selective technique based on indicator rock types and little or no attention was generally paid to the other lithological types present within a till.

In north-east England this technique has been employed by the majority of workers studying the glacial deposits. As early as 1864, Howse R. in the Lower Tyne Valley distinguished a boulder clay from the Lake District, and one from the Cheviots on the basis of their erratic assemblage. In the North Yorks Moors, Kendall P.F. (1902) described westerly, northerly, and easterly derived groups of rocks in the tills of the region, and postulated that the easterly derived rocks indicated the presence close offshore of a large Scandinavian ice sheet. In Eastern Durham Trechmann C.T. (1915 and 1952) plotted the western limit of occurrence of Cheviot erratics, and the northerly limit of Shap Granite in the Tees Lowlands, while Smith D.B. (in press) identified fragments of Upper Magnesian Limestone in the Upper Till south of its place of outcrop.

On the other hand quantitative analysis of the total lithologies present within a till sheet has been neglected and only two examples of this type of work are to be found in the literature of Northern England. The first is that of Herdman. T. (1909), working on the clays, and fluvioglacial deposits of the Derwent Valley in north-west Durham, and the second, a single stone count of 500 stones by Trechmann C.T. (1915) from the Scandinavian Drift at Warren House Gill.

In other parts of the British Isles, and indeed in Europe and North America the trend had been towards the study of total lithologies rather than the selective study of indicator rock types. In the British Isles Simpson I.M. (1960), and Catt J.A. (1963 unpublished Ph.D), Farrington A. 1965 are recent examples, while in the United States and Europe similar work was undertaken by Anderson R.C. (1955), Davis S.N. (1948), Hesse J. (1929, 1930), Kaiser R.F. (1962), MacIntock P. (1933).

The main lithological rock types of North-East England.

Within Eastern Durham three characteristic formations are found. The largest and central part of the area is covered by the dolomitic limestone of the Permian Magnesian Limestone series. To the west and north are the non-calcareous sediments of the Upper and Middle Coal Measures, composed dominantly of sandstones, shales, mudstones, and with smaller amounts of coal and ironstone. Finally in the south, outcropping over only a small area are the Keuper Marls and the bright red Bunter Sandstone.

Encircling Eastern Durham on the landward side are extensive outcrops of the Lower Carboniferous, or Yoredale Series, characterised in the south by widespread outcrops of limestone, but to the

north by more arenaceous and argillaceous deposits.

Rocks of igneous origin are almost completely absent from the solid outcrop of the Eastern Durham area. A few isolated small dykes of basalt do occur in the Coal Measures, but their restricted area of outcrop severely limits the contribution they were able to make to the total lithology of the glacial drifts.

The nearest outcrops of widespread igneous material to Eastern Durham are the basalts and dolerites of the Whin Sill. These rocks stretch as a linear belt south-westwards from the Northumberland coast, and are also found in parts of Weardale and Teesdale.

In contrast the two main sources of igneous rock types are situated almost due north and due west respectively of the Durham area, in the form of the Cheviot and Lake District Massifs. In both a considerable variety of igneous rock types is found, but few types are characteristic of their particular area of origin. In general it can be stated that the Cheviot material tends to be reddish brown in colour, whereas the colours of the Lake District igneous material are more varied. From the Cheviot area the red or chocolate brown porphyritic rhyolites, and the purple or dark brown pyroxene andesitic lavas are generally considered as indicator erratics, whereas from the Lake District the Shap Granite, and the dark green Borrowdale Volcanic Series are the most characteristic.

Other important lithological types are the schists and greywackes of the Southern Uplands. These are resistant rocks and survive glacial transport well.

The importance of these observations is the fact that an ice sheet approaching Eastern Durham from either the north or the west has to travel for the final 30 miles or so over almost identical strata

types in the form of the Lower Carboniferous and Coal Measure Series. This fact alone would lead one to expect that the bulk of the material composing a till sheet within Eastern Durham, whether derived from a northerly or westerly direction would be remarkably similar.

Aim of research.

In the present work the author has employed the technique of stone counting for two main reasons :-

1. To lend supporting evidence to the directions of ice movement as shown by preferred stone orientations.
2. To study in their own right the lithologies of the material present in the stony clays.

Method.

The method of extracting stones from a till used by most workers involves the hand collection of visible stones from a vertical exposure. This method, however objectively it is applied, is still to some extent selective, and possesses the unfortunate tendency for the softer shaly rocks to become broken during collection, and therefore inadequately represented in the ensuing stone count.

It was therefore decided that some volumetric method of sampling the stones should be employed. Experiments showed that between 100 and 1000 rock particles between $\frac{1}{8}$ " and $\frac{3}{4}$ inch in diameter could be obtained from a sample of 2000 grams of stony clay. The method possesses the advantage that all the rock particles present within the clay are obtained and subsequently counted. No human selectivity is involved in the collection.

A sample of c. 5 kilograms of unweathered till was obtained in the field, brought to the laboratory and dried. A representative sample of 2 kilograms was quartered from the larger bulk sample, and divided equally into four large shaking bottles. A solution of distilled water and Calgon was added, and the bottles shaken gently for 4 to 6 hours to aid dispersion of the clay particles. The suspension within the bottles was then wet sieved, so as to avoid damage to the more fragile particles. (British Standard 1377 (1961). The material left on the sieves was used for the stone count. The following British Standard sieve sizes were used :- $\frac{1}{2}$, $\frac{3}{8}$, $\frac{1}{4}$, 3/16th, and $\frac{1}{8}$ inches.

The rock particles were identified into lithological groups with the aid of a binocular microscope of variable magnification, after a rough division has been attempted into calcareous and non calcareous material by the immersion of the particles in dilute hydrochloric acid. Experience showed that some of the more dolomitic Magnesian Limestone did not effervesce in dilute hydrochloric acid. This however presented no problem as such material was subsequently easily distinguished under the microscope.

As the majority of the material being analysed was of a small grain size it was decided that identification should be into a series of major lithological groupings, rather than to attempt to designate the place of origin of the individual particles. Six main groups were distinguished, which were in turn divided to give a total of fourteen categories.

Lithological types.

1.	Calcareous	A Magnesian Limestone
		B Carboniferous Limestone
		C Undifferentiated limestone
		D Clay concretions
		E Sandstone
		F Red sandstone
2.	Arenaceous and argillaceous	G Greywacke
		H Silt and mudstone
3.	Organic	I Coal and black shale
4.	Mineral	J Ironstone
5.	Non-sedimentary	K Quartz and mineral grains
		L Igneous and metamorphic
6.	Unknown	

The Magnesian Limestone is a particularly characteristic rock type on account of its yellow colour and fine texture. It is easily identified under the microscope.

The Carboniferous Limestone is more difficult to identify owing to the fact that it occurs in several colours. Particles were only attributed to this category if they contained visible crinoid ossicles, or were dark grey to black in colour.

All limestone fragments where specific identification could not be made were placed in the category of undifferentiated limestone.

The final calcareous category is used for small concretions of clay and sand which were to be found in some of the clay deposits.

In the argillaceous and arenaceous group, four sub-categories are distinguished. Sandstone is an all embracing term, and included all arenaceous material except red sandstone and greywacke which were given separate categories. Very fine argillaceous and arenaceous material are classified together as siltstone and mudstones.

Two very easily identified types derived solely from the Coal Measures are coal itself and clay ironstone. These were both recorded as separate categories.

The non-sedimentary material is divided into two categories. The quartz and rock mineral category was used to include vein-quartz, together with other mineral fragments, most likely of igneous origin, but which owing to their small size could no longer be identified as being specifically igneous. The igneous and metamorphic category was reserved for rock fragments where positive identification could be made.

Any rock particle which could not be easily placed in any of the above categories was classified as unknown.

Sample variation.

The actual number of pebbles one needs to sample to obtain representative figures for a population has rarely been gone into, and it is generally tacitly assumed by workers that the numbers they included in their results are an adequate representation of the deposit under study.

In an attempt to provide an empirical guide as to how many pebbles are required for sampling purposes, a thousand pebbles were

sampled and studied in groups of 100 from the flood plain gravels of the River Tees. Twelve lithological types were used in the count, and the pebble sizes varied from 1 inch to 3 inches in diameter (Fig. 25). The general similarity of the results indicates that a count of 100 pebbles gives a remarkably good indication of the lithologies present, and that with counts of 200 pebbles or more the similarities are very pronounced.

To evaluate the comparability of the volumetric micro stone count technique employed by the author, a number of samples were examined from the same exposure. The particles for these counts were obtained from a volumetric sample of 1000 grams of till material, half that used for the normal stone count.

The results of two such stone counts for the Upper and Lower Tills of the coastal region are shown in Fig.26.

Fig. 26

Figures in percent	Upper Till		Lower Till	
	a	b	a	b
A. Magnesian Limestone	22.3	23.2	53.4	53.7
B. Carboniferous Limestone	9.6	10.9	8.2	8.7
C. Undifferentiated limestone	-	-	-	-
D. Clay concretions	-	-	-	-
E. Sandstone	41.4	44.2	29.6	26.0
F. Red sandstone	1.9	3.0	-	-
G. Greywacke	1.3	2.2	1.7	2.2
H. Siltstone and mudstone	4.5	3.0	-	0.4
I. Coal and black shale	1.9	0.7	1.7	2.6
J. Ironstone	7.6	4.4	2.1	3.0
K. Quartz	3.8	3.0	2.5	2.2
L. Igneous and Metamorphic	5.7	4.4	0.8	0.9
M. Unknown	-	1.0	-	0.3
Total particles	157	138	243	231

These two samples show typical variations within the sub-samples and indicate the very small variations which are found in the main lithological groups. In all cases lithologies making up more than 20% of the total sub sample show intersample variations of less than 5%. Variations in the lithologies with less than 10% of the total sub-sample are greater. Taking the counts together the similarities between sub-samples are very marked.

A statistical analysis of the two sub-samples of each of the two micro-stone counts from the Upper and Lower Till sheets was made using the Kolmogorov - Smirnov test. (Siegel S. 1965). The data from the sub-samples are assembled into cumulative frequency distributions, and the maximum deviation (D) in any single category is measured. A null hypothesis is set up postulating that the two cumulative frequency curves are drawn from the same populations. A comparison is made between the sample D value, and a calculated D value at the 1% level of significance. If the sample D value is less than the calculated $D_{.01}$ value the null hypothesis must be retained.

The D value at the 1% level of significance is calculated from the formula

$$D_{.01} = 1.63 \sqrt{\frac{\frac{n_1 + n_2}{n_1 \cdot n_2}}$$

1. The Upper Till.

Lithological

categories

(as Fig.26)

	A	B	C	D	E	F	G	H	I	J	K	L	M
a.	.223	.319	.319	.319	.733	.752	.765	.810	.829	.902	.943	1.00	1.00
b.	.232	.341	.341	.341	.783	.813	.835	.865	.872	.916	.946	.990	1.00
D values	.009	.022	.022	.022	.050	.061	.070	.055	.043	.014	.003	.010	0

Max-D value = .070

D value at 1% level of significance = 0.189

Therefore at the 1% level of significance one must conclude that the two samples are drawn from the same population.

2. The Lower Till

Lithological categories	1	2	3	4	5	6	7	8	9	10	11	12	13
a.	.534	.616	.616	.616	.912	.912	.929	.929	.946	.967	.992	1.00	1.00
b.	.537	.624	.624	.624	.884	.884	.906	.910	.936	.966	.988	.997	1.00
D value	.003	.008	.008	.008	.026	.026	.023	.019	.010	.001	.004	.003	.000

Max D value = .028

D value at 1% level of significance = 0.150

Therefore at the 1% level of significance one must conclude that the two samples are drawn from the same population.

These examples therefore show that the micro-stone counts are representative samples from the deposits from which they are obtained.

Results.

Preliminary analysis of the results of the 76 stone counts was attempted to discover the total variations shown by the differing lithologies in the stony clays. For this purpose the individual results are plotted in tabular form Figs. 27, 29, 30.

From this the Magnesian Limestone content is seen to vary absolutely from 0 to 87.7%, but the distribution indicates the tendency for the limestone to be present in quantity (15 to 60%) or else to be completely absent. Values of Magnesian Limestone between 0 to 15% are rare.

The Carboniferous Limestone shows a lower distribution from 0 to 14%, but again shows a similar tendency to the Magnesian Limestone in being completely absent, or present in percentages of 3 to 14.

The most interesting feature of this general distribution is the ubiquity of sandstone. Not a single sample was found in the area in which sandstone is not present. Only one sample was found with less than 20% sandstone, and the vast majority contain between 30 to 80%.

Of all the other lithological types none have concentrations in individual samples of more than 30%. Some lithologies like red sandstone and greywacke are absent from almost half of the samples, while coal, silt and ironstone are present in nearly all. With the exception of red sandstone and greywacke which show a very low percentage occurrence, all the other lithologies show variations of between 0 and 10%. In a few isolated samples figures of between 10 and 30% of the total sample were recorded for both coal and ironstone.

Results for the individual stony clays.

In this section the results for the stone counts of the individual stony clays are recorded. The following categories were employed:-

1. Lower Till
 - a. Lower Till of the Wear Lowlands
 - b. Lower Till of the Magnesian Limestone Plateau
 - c. Lower Till of the coastal region
 2. Upper Till
 3. Upper Tees Clay
 4. Upper Wear Clay
 5. Scandinavian Drift
-

1. Lower Till (Fig 27)

a. Lower Till of the Wear Lowlands

The Lower Till of the Wear Valley is found exclusively on rocks of Coal Measures age.

Magnesian Limestone is absent from all except one sample. In this sample at Houghton-le-Spring (No.9) a small percentage of Magnesian Limestone is noted. The site of this exposure is within 300 yards of the foot of the Magnesian Limestone escarpment, and it is felt that in this case the ice incorporated material which had moved by mass movement down the escarpment.

Key to Fig 27, 29, 30

Lithological types

A.	Magnesian Limestone
B.	Carboniferous Limestone
C.	Undifferentiated limestone
D.	Clay concretions
E.	Sandstone
F.	Red Sandstone
G.	Greywacke
H.	Siltstone and mudstone
I.	Coal and black shale
J.	Ironstone
K.	Quartz and mineral grains
L.	Igneous and metamorphic
M.	Unknown

Fig. 27

LOWER TILL

Lower Till of the Wear Lowlands.

Lithological types	1	2	3	4	5	6	7	8	9
A.	-	-	-	-	-	-	-	-	2.8
B.	3.4	-	-	-	4.1	5.9	2.3	-	4.3
C.	-	-	-	-	1.5	0.4	1.4	-	-
D.	-	-	-	-	-	-	-	-	2.8
E.	65.3	75.6	80.6	48.2	74.7	77.3	53.0	83.9	65.7
F.	-	-	-	-	0.4	0.2	0.9	-	0.6
G.	-	-	-	-	1.7	0.6	0.5	0.3	1.7
H.	1.0	2.2	1.8	13.5	2.8	1.4	9.8	0.3	3.8
I.	22.7	6.3	7.9	29.7	7.6	4.1	22.8	10.0	10.9
J.	5.6	7.1	8.4	8.1	2.0	6.3	5.6	2.8	3.2
K.	1.0	4.6	0.9	-	2.2	2.6	0.9	0.6	3.0
L.	0.5	2.5	0.2	-	1.7	1.2	1.4	1.3	0.6
M.	0.5	1.7	0.2	0.5	1.4	-	1.4	0.8	0.6
Total	740	238	453	677	542	511	215	390	533

Sample Site

1. Finchale Priory	6. Crime Rigg Quarry
2. Windy Nook Quarry	7. Spennymoor Industrial Estate
3. Eighton Bank Quarry	8. Low Grange, Bowburn
4. Brācepeth Beck	9. Building site, Houghton-le-Spring
5. Biddick Burn near Birtley	

Lower Till of the Magnesian Limestone Plateau

Lithological

Lithological types	1	2	3	4	5	6	7	8	9	10
A	16.4	19.0	39.8	-	28.5	12.0	13.3	54.4	87.7	38.6
B	3.4	11.0	9.6	-	3.0	-	0.3	3.6	0.2	1.6
C	0.6	1.6	-	-	1.7	0.4	-	-	-	5.1
D	-	-	-	-	-	-	-	-	-	-
E	69.9	55.5	35.1	71.5	50.9	70.8	68.9	33.2	9.6	42.7
F	-	0.2	-	0.3	0.2	-	-	-	-	1.0
G	-	0.2	-	2.3	2.4	0.4	-	-	-	-
H	1.7	0.9	3.0	2.8	0.6	0.4	2.1	1.2	0.2	1.9
I	0.6	0.9	0.4	2.9	0.9	6.9	-	-	0.6	1.0
J	3.4	3.2	3.6	10.7	5.6	6.9	11.9	2.8	1.3	4.8
K	1.5	2.7	4.7	3.9	2.6	0.4	2.2	1.4	0.2	2.2
L	1.9	2.9	2.1	5.3	2.2	1.3	0.7	3.4	0.2	0.3
M	0.6	1.9	1.7	0.3	1.4	0.5	0.6	0.2	-	0.8
Total	538	443	470	692	536	233	293	501	471	316

Lower Till of the Magnesian Limestone Plateau

Lithological types

	11	12	13	14	15	16	17	18	19	20
A	40.2	-	-	-	21.0	20.1	12.5	0.5	4.1	-
B	2.2	-	-	-	1.5	0.3	11.9	0.5	-	-
C	0.6	-	-	-	-	-	2.1	-	-	-
D	0.3	-	-	-	-	-	1.3	-	-	-
E	39.9	71.8	81.4	79.5	56.3	53.0	53.3	76.4	60.8	79.6
F	0.3	-	-	0.5	-	0.7	3.2	-	-	0.7
G	1.9	0.5	0.4	-	-	1.3	3.7	-	-	-
H	0.6	1.6	2.2	1.9	4.4	2.0	1.2	2.5	2.9	2.6
I	0.6	4.8	1.5	5.0	7.8	4.6	0.8	0.3	18.7	-
J	6.7	19.0	13.8	9.1	2.4	13.8	1.6	7.6	10.5	9.9
K	2.3	1.6	-	2.9	3.4	2.0	3.5	5.3	1.8	4.0
L	3.4	0.4	-	0.7	0.5	1.3	4.1	6.1	-	2.6
M	0.2	0.3	0.7	0.4	2.7	0.9	0.8	0.8	1.2	0.6
Total	316	379	369	419	206	304	377	394	171	152

Sample sites

1. Middridge Quarry	11. Wood Quarry, Wingate.
2. Aycliffe Quarry, (Lower grey clay)	12. Wingate Quarry. D
3. Aycliffe Quarry, (Middle brown clay)	13. Sherburn, Shadforth sand pit.
4. Houghton-le-Spring	14. High Moorsley Quarry.
5. Eppleton	15. South Hetton.
6. Thrislington	16. Wingate Quarry. A.
7. Coxhoe	17. Fulwell.
8. Bishop Middleham	18. Tuthill.
9. Trimdon Colliery	19. Holy Cross.
10. Cope Hill	20. Bradbury.

Lower Till of the Coastal Region

Lithological types	1	2	3	4	5	6	7	8	9	10
A	50.2	61.4	35.2	45.2	31.3	58.6	26.8	47.0	61.2	21.5
B	4.5	4.4	6.3	5.7	5.0	8.1	5.0	6.1	4.8	5.7
C	-	1.7	3.6	3.4	0.5	-	0.3	0.3	-	-
D	-	-	-	-	-	-	-	-	-	-
E	34.5	22.4	34.3	37.3	43.3	23.1	46.4	31.4	25.1	48.5
F	-	0.2	0.3	0.6	1.7	-	0.9	1.7	-	-
G	-	1.8	3.0	0.9	1.4	-	4.1	-	-	-
H	1.4	0.7	2.4	0.3	2.2	1.7	0.8	0.6	2.4	3.1
I	3.2	1.3	2.1	-	1.7	3.9	0.5	6.1	1.0	4.8
J	1.1	0.2	3.6	3.4	5.2	2.1	3.9	3.3	1.0	2.6
K	3.0	2.0	5.4	1.7	3.3	2.5	5.1	2.6	2.6	33.7
L	1.8	1.7	3.6	1.1	3.3	-	5.0	0.9	1.7	9.4
M	0.5	2.1	0.6	0.5	1.4	-	1.2	-	0.2	0.7
Total	401	544	335	354	364	234	765	347	591	456

Lower Till of the Coastal Region.

Lithological types	11	12	13	14	15
A	37.7	25.3	62.1	52.3	47.6
B	1.6	3.2	3.6	9.3	2.8
C	-	-	3.6	-	-
D	-	-	-	-	-
E	40.9	50.7	21.2	29.1	36.5
F	-	0.4	0.5	-	1.2
G	-	1.7	1.9	1.7	1.0
H	2.0	0.7	-	-	0.8
I	2.3	4.8	0.4	0.5	3.1
J	3.6	7.5	3.2	0.8	3.0
K	3.6	3.0	1.4	1.7	2.1
L	8.3	1.6	0.8	4.6	1.5
M	-	1.1	1.3	-	0.4
Total	252	763	773	237	782

Sample Sites

1. Blackhall Colliery	8. South Hylton
2. Salterfen Rocks	9. Chourdon Point
3. Bedlam Gill	10. Castle Eden Dene (A.19. road section).
4. Quarry near Hesleden	11. Shotton Colliery
5. Dalton Piercy	12. Shotton Colliery Brick Pit
6. Castle Eden Dene	13. Hawthorn Quarry
7. Castle Eden Village	14. Dalton-le-Dale
	15. Petrol station, Peterlee

Carboniferous Limestone is present in only half the samples, and shows variations of between 0 and 6%.

Sandstone percentages are high in this clay and vary from 48 to 84%. Five out of the nine samples contain more than 70% sandstone.

In the majority of these samples it is seen that material derived from the Coal Measures (sandstone, siltstone, coal and ironstone) makes up c. 90% of the total sample. Siltstone, coal and ironstone percentages are all particularly high in this clay, and largely reflect local bedrock conditions. In the case of coal this is well seen at sample sites at Finchale Priory (No.1), Brancepeth Beck (No.4), and Spennymoor Industrial Estate (No.7) where the till is resting on or very close to a coal seam.

Quartz shows variations from 0 to 5%, and in these samples the igneous content is particularly low (less than 3%).

b. Lower Till of the Magnesian Limestone Plateau

The Lower Till of the Plateau shows the greatest lithological variations of all the clays in Eastern Durham. This fact is to some extent expected as it is in the area of the plateau that the Lower Till ice sheet encountered a new parent material in the form of the Magnesian Limestone. The result is that in its traverse across the plateau the Lower Till ice sheet incorporated more and more Magnesian Limestone within itself.

Several samples in this area, where the till is relatively thin, were found to contain no Magnesian Limestone, even though the ice which deposited the till must have travelled a number of

miles across Magnesian Limestone parent material. The question arises as to whether this feature is a depositional characteristic, or is due to subsequent leaching of carbonate material. The fact that no Carboniferous Limestone is present in these samples strongly suggests that leaching had taken place.

High Magnesian Limestone contents are noted at Bishop Middleham (No.8) 54.4%, and Trimdon Grange (No.9) 87.7%. At Bishop Middleham the reason appears to be that the Magnesian Limestone at this point is more powdery than usual, and therefore more easily incorporated into the till matrix. The sample at Trimdon Grange is less easily explained. The clay appears superficially typical of the Lower Till, but the stone count indicated that this sample contained the highest Magnesian Limestone content of all the clays examined in Eastern Durham. Because of this and the lack of a pronounced orientation pattern it was concluded that the clay at this site may not be strictly of sub-glacial origin and may possibly represent some form of local periglacial or mass movement type of deposit.

The Carboniferous Limestone percentages show considerable relative variation. Only 3 samples are found where Carboniferous Limestone percentages are more than 5%, and in all three cases these exposures are in the direct line of ice deriving its rock material from the Lower Carboniferous of the Pennines. At Aycliffe (Nos. 2 and 3) the till is derived from the Weardale glacier, and at Fulwell (No.17) from ice moving down the Tyne Valley.

The percentages of sandstone material are high. 15 of the 20 samples have sandstone percentages of more than 50%, and of these 9 recorded figures of more than 65%.

Red sandstone and greywacke material can generally be taken as an indication of sources of ice supply outside the Durham area.

In the Lower Till of the plateau both these lithologies give low figures, and in some samples this material is completely absent. From this it seems that local ice possibly from Weardale played an important part in the glaciation of this area, and greatly diluted in content, rock material derived from elsewhere.

The coal content shows variations from zero to almost 19%. As all samples of the Lower Till of the plateau are situated on Magnesian Limestone, all coal material in the till is erratic, and derived from the Wear Lowlands. The surprising fact is that there appeared to be no correlation between coal content, and the distance from the source of this material. Exposures close to the escarpment gave variable and often low figures (Houghton-le-Spring No.4, 2.9%, Coxhoe (No.7) 0%, High Moorsley (No.14) 5.0%) while 3 to 5 miles further east much higher figures were recorded. (South Hetton (No.15) 7.8%, Holy Cross (No.19) 18.7%). These high figures for coal in the centre of the plateau region are possibly considered to represent coal concentrations due to the leaching of calcareous material.

Ironstone is derived from the same general area as the coal, but no correlation is noted between the coal and ironstone figures. It is seen however that the highest ironstone figures occur in the western and central part of the plateau area.

The igneous content of the Lower Till of the plateau is low and varied from 0 to 6%. No systematic pattern in its distribution can be observed.

c. Lower Till of the coastal area.

The Lower Till of the coastal area rests, with very few exceptions, directly on the Magnesian Limestone. As a result it

possesses high percentages of Magnesian Limestone with variations from 21 to 62%. It is noteworthy that in all the stony clays of Eastern Durham it is only in a very narrow coastal section where the Magnesian Limestone is consistently the dominant lithological type in the till. This suggests that the ice had to traverse on average at least 6 miles of Magnesian Limestone outcrop before it had incorporated an equal amount of material, to that which had been eroded in crossing the Coal Measures and the Lower Carboniferous rocks.

Carboniferous Limestone is always present in concentrations of 1.5 to 10%.

Sandstone percentages are among the lowest found in the Durham clays, with the majority of figures below 40%. An inverse correlation is found between the sandstone and Magnesian Limestone percentages.

Both red sandstone and greywacke are present in small quantities in about half the samples. Greywacke tends to be 2 to 3 times more frequent in occurrence than the red sandstone.

Coal and ironstone are nearly always present with variations from 0.00 to 4.9%, and 0.2 to 7.5% respectively.

Quartz material is always present in concentrations of less than 6%.

Figures for igneous content are low and usually less than 2%. Occasionally however figures of 8 to 9% are noted. From observations of the till it appears that coarse grained igneous material is generally resistant to glacial erosion and breakdown in sizes of more than 4 inches in diameter, but below this size the rock fragments show a tendency to break up into individual mineral grains. This means that locally fairly high concentrations of igneous material can be observed.

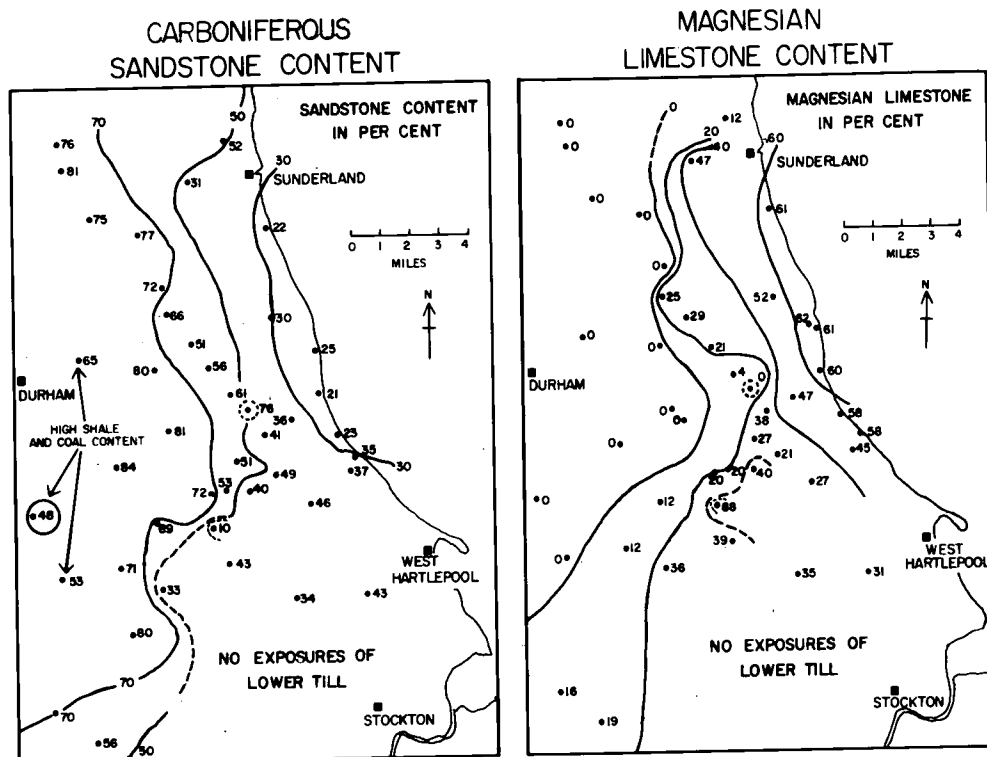
In Chapter 3 it was stated that the Lower Till of the Wear Lowlands, the Magnesian Limestone Plateau area, and the coastal region were considered on stratigraphical evidence to be lateral equivalents. The data from the stone orientations substantiates this conclusion and further evidence is provided for this conclusion by the distribution of the Magnesian Limestone and sandstone components of the till outlined in this Chapter.

Fig. 28 shows the distribution of Magnesian Limestone in the Lower Till sheet plotted as a percentage figure. In the north it is seen that the Magnesian Limestone content of the Lower Till increases towards the east to more than 60% on the coast, in a direction consistent with the results of the stone orientations. A similar distribution is found to the south. In the central part of the plateau it is found that the Magnesian Limestone content of the Lower Till is very low or even non existent. In this area the till is thin and leaching of the carbonates is thought to have caused this anomalous distribution. In the extreme southern part of Eastern Durham the great thicknesses of drift make it impossible to sample the Lower Till. The few samples that were obtained indicated that the Magnesian Limestone content increased slowly towards the south and east.

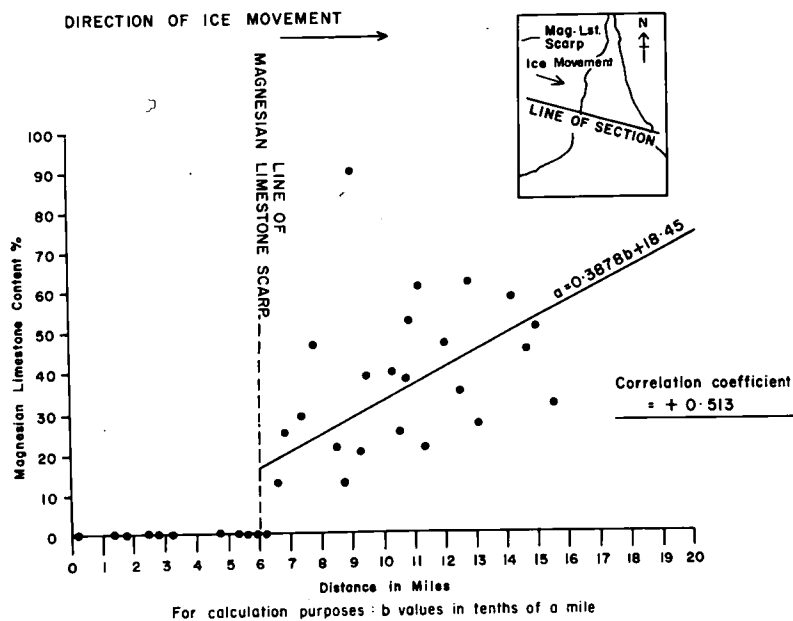
Fig.28 also shows the distribution of sandstone within the Lower Till, and illustrates the fact that the sandstone percentages tend to be inversely proportional to the Magnesian Limestone content. The highest figures for sandstone with values of more than 70%, are found in the Wear Lowlands, and the lowest of less than 30% along the coastal region. Between these extremes a fairly steep gradient exists.

Using the data from Fig.28 certain interesting features can be demonstrated. The stone orientation measurements in Chapter 5 showed that the Lower Till moved in a north-west to south-east direction,

LOWER TILL



MAGNESIAN LIMESTONE CONTENT OF LOWER TILL



and as a consequence crossed the line of the Magnesian Limestone Escarpment almost at right angles. This fact allowed the Magnesian Limestone content of the Lower Till to be plotted graphically along a line at right angles to the Magnesian Limestone escarpment, and at the same time almost exactly parallel to the direction of ice movement as indicated by the stone orientations.

In Fig.28 the changes in the Magnesian Limestone content of the Lower Till in a 16 mile transect of Eastern Durham, parallel to the direction of ice movement are shown. The diagram indicates 6 miles of movement in the Wear Lowlands, where no Magnesian Limestone at all is found in the Lower Till, and 10 miles of movement across the Magnesian Limestone outcrop. In this latter area 26 observations of unweathered till were recorded, and a best fit regression line was constructed through these points. A correlation coefficient of +0.513 (significant at the .01 level) indicated that a correlation is to be noted between the Magnesian Limestone content of the Lower Till, and the amount of movement of this ice sheet over Magnesian Limestone parent material.

The graph gives a quantitative estimate of the amount of incorporation of material within the Lower Till ice sheet once it has begun to move over a new type of parent material. Obviously the results of this graph can not be extended to other areas without some qualification. The two main ones being that in Eastern Durham the Magnesian Limestone outcrops to form a marked escarpment at right angles to the direction of ice movement, and secondly that the Magnesian Limestone is a relatively weak rock, and is easily broken down. These two factors suggest that the rate of erosion and incorporation of material into the Lower Till of Eastern Durham is likely to have been greater than in other areas.

Two important quantitative statements can be made from the information of Fig.28. The positioning of the regression line, by not zeroing at the line of the escarpment, suggests that the Lower Till ice sheet immediately it met the new lithology of the Magnesian Limestone, incorporated a certain proportion of this rock with very little movement over it. The graph shows that a Magnesian Limestone content of c. 18% is to be expected in the Lower Till sheet immediately the line of the escarpment has been crossed. This further emphasises the importance that the form of the outcrop of the Magnesian Limestone, as an escarpment, had on the erosive capacity of the ice sheet. The result is that large quantities of Magnesian Limestone must have been eroded along the very line of the escarpment itself.

The second important point is that the rate of incorporation of Magnesian Limestone within the Lower Till sheet, once the escarpment had been crossed, appears fairly constant. This relationship is expressed by the regression line $a = 0.387b + 18.45$. The regression line shows that Magnesian Limestone becomes the dominant rock type in the Lower Till, (more than 50% of the total rock particles present) after the ice sheet has moved only a distance of c. 8 miles across the outcrop of the Magnesian Limestone. This figure gives a measure of the severity of ice sheet erosion within a lowland area of the British Isles, of an order which has not perhaps been appreciated in the past owing to the scarcity of quantitative information.

The Upper Till of the coastal region. (Fig.29)

The Upper Till generally overlies the Middle Sands of Lower Till, and is only rarely found resting directly on the Magnesian Limestone. At the time of its deposition it is reasonable to suppose

Fig. 29

UPPER TILL

Lithological types	1	2	3	4	5	6	7	8	9	10	11
A	18.6	25.0	55.5	32.2	37.9	-	35.3	26.2	27.0	17.2	63.0
B	11.2	9.7	2.7	6.1	2.1	-	12.0	5.8	12.4	3.2	4.4
C	-	6.7	-	2.7	4.7	-	-	4.0	2.9	3.2	-
D	-	-	3.0	-	-	-	-	11.8	0.7	-	-
E	58.2	42.7	33.8	43.9	37.4	63.5	36.7	38.6	42.3	51.6	21.7
F	-	1.3	-	1.5	0.9	0.7	-	-	-	2.6	2.2
G	-	1.3	-	0.2	1.7	5.4	-	0.3	1.5	2.1	2.2
H	0.8	-	0.4	1.3	1.7	1.4	1.3	1.7	4.4	1.5	0.7
I	3.0	1.3	-	-	-	-	3.3	0.6	0.7	1.5	-
J	-	4.7	2.3	4.6	3.6	19.6	3.3	1.4	2.9	5.3	1.5
K	3.7	3.7	1.5	4.0	4.7	2.7	1.3	3.5	2.3	6.6	2.8
L	2.2	2.0	0.4	2.0	4.3	5.4	6.8	4.3	2.9	4.7	1.5
M	2.3	1.6	0.4	1.5	1.0	1.3	-	1.8	-	0.5	-
Total	134	300	263	918	470	148	150	347	137	471	138

Lithological types.	12	13	14	15	16	17	18
A	32.6	34.0	15.0	40.1	1.1	-	-
B	12.6	4.0	17.5	13.0	-	-	-
C	-	-	1.8	-	-	-	-
D	-	-	-	-	-	-	-
E	34.8	42.0	45.4	37.6	66.3	77.6	68.2
F	2.2	-	1.0	0.8	-	-	0.9
G	3.7	2.0	3.4	2.1	3.4	1.4	2.9
H	-	1.0	2.3	0.7	1.1	-	0.7
I	-	1.0	0.5	0.2	-	0.7	-
J	0.7	2.0	2.8	2.4	5.1	10.5	8.3
K	1.5	5.0	5.4	1.6	6.9	5.6	9.2
L	9.3	6.0	4.9	1.5	13.1	2.8	8.0
M	2.6	3.0	-	-	3.0	1.4	1.8
Total	270	200	388	617	175	143	1040

Sample sites

1. Portrock Brick Pit.	10. Sheraton Hill Farm.
2. Cerebros Salt Works.	11. Seaton Carew.
3. Hawthorn Quarry.	12. Blackhall Rocks.
4. Whelly Hill Quarry.	13. Hart Road.
5. Crimdon Dene.	14. South Hylton.
6. Naisberry Quarry.	15. Hesleden.
7. Castle Eden Dene.	16. Wolviston.
8. Foxholes.	17. Low Burn Toft.
9. Hazel Dene.	18. South of Hart Road.

that most of the Magnesian Limestone was mantled by thick deposits of the Lower Till or Middle Sands. This would mean that the Upper Till ice would have been unable to erode directly the bedrock of the Magnesian Limestone, and that the Magnesian Limestone content of this clay, must have been derived largely from the erosion of the Lower Till or the Middle Sands. In this context it is important to remember that the Magnesian Limestone content of the Lower Till increases eastwards, and that in the offshore area probably reaches figures of more than 70%.

In the majority of cases the Magnesian Limestone content of the Upper Till is less than 40%. Occasionally figures of more than 50% are found, such as at Hawthorn Quarry (No.3), where the Upper Till is resting directly on Magnesian Limestone. Such occurrences are, however, rare and almost solely confined to the reef knolls of the coastal area. With the Upper Till not directly eroding Magnesian Limestone, it is seen that the percentages of Magnesian Limestone within the clay do not show a progressive down-ice increase as is the case with the Lower Till. Instead a rather patchy distribution of Magnesian Limestone content is found.

Three of the samples of the Upper Till show a complete absence of Magnesian and Carboniferous Limestone. These three sites are in the morainic drift material associated with the Upper Till, and it seems that in these cases any limestone which had been originally present within the till, has been removed by post-depositional leaching.

Variations in the Carboniferous Limestone content of the Upper Till from 0-18%, are considerably greater than in the Lower Till.

In three Upper Till samples clay concretions are noted.

With the generally lower figures of Magnesian Limestone content of the Upper Till compared with the Lower Till, sandstone percentages are correspondingly higher with the majority of values more than 40%. Only one sample gave a figure of less than 30%.

Red sandstone, greywacke, and siltstone are present in small and variable amounts.

One of the most interesting features of the Upper Till is to be found in its coal content. Almost half of the samples are completely devoid of coal, and in 5 of the 9 in which it is present, percentages of less than 1% were recorded. This is in marked contrast with the Lower Till where figures of c. 3% coal content are frequently observed. An explanation for this seems to lie in the fact that at the time of the Upper Till ice sheet the coal seams were deeply buried beneath earlier glacial deposits.

The content of igneous material is slightly higher on average than that of the Lower Till. Many of the igneous particles possess a red colouration, suggesting a possible Cheviot origin.

Upper Tees Clay. (Fig. 30)

The Upper Tees Clay is one of the most distinctive deposits of the area on account of its bright red colour, and low stone content. It is found in an area where drift deposits are very thick, and it always overlies other clay deposits or sands and gravels.

The Magnesian Limestone content is low, and nearly always less than 30%. A marked concentration of values in the range 20 to 30% is noted.

In contrast Carboniferous Limestone contents are high, with figures which are consistently higher than for any of the other clays with the exception of the Upper Till of the coast.

UPPER TEES CLAY.

Lithological types	1	2	3	4	5	6	7	8
A	26.0	45.4	30.0	21.0	22.9	20.5	14.9	23.2
B	13.2	8.1	9.3	7.6	10.8	4.6	18.2	7.5
C	-	-	-	-	1.2	1.5	4.1	4.5
D	0.5	-	-	-	15.7	15.9	8.8	6.7
E	45.1	39.3	50.7	46.8	37.4	50.0	37.8	42.0
F	1.0	2.3	-	-	1.2	1.5	1.4	3.4
G	0.5	-	-	-	1.2	1.5	0.7	-
H	1.0	-	-	7.8	0.6	-	0.7	1.5
I	0.5	-	-	-	1.2	-	-	2.3
J	2.5	-	2.9	1.3	4.8	1.3	4.1	3.8
K	3.9	2.3	2.1	10.4	2.4	1.1	6.8	2.3
L	4.3	1.2	2.9	5.1	0.6	2.1	2.5	1.5
M	1.5	1.2	2.1	-	-	-	-	1.3
Total	204	86	140	77	166	88	148	267

Upper Wear Clay.

Sample sites.

1. High Butterby.
2. Railway cutting north of Durham.
3. Sewer trench, Framwellgate.
4. Van Mildert College.
5. Electricity sub station, Ferryhill.

Upper Tees Clay.

Sample sites.

1. Portrack Brick Pit.
2. Wynyard Hall.
3. Stob Cross.
4. Middlefield Farm.
5. Carlton.
6. Gilly Flat.
7. Low Middlefield.
8. Whitehouse Farm.

Fig 30.

Lithological types.	UPPER WEAR CLAY				
	1	2	3	4	5
A	-	-	-	-	-
B	-	-	-	-	-
C	-	-	-	-	-
D	-	-	-	-	-
E	56.0	77.8	79.1	61.5	66.6
F	-	-	-	-	-
G	-	-	-	-	-
H	9.1	4.0	1.4	2.4	0.6
I	19.3	6.4	6.1	9.0	20.2
J	10.1	8.7	6.5	25.9	11.1
K	3.8	1.6	4.7	0.6	1.5
L	-	-	-	-	-
M	1.7	1.5	2.2	0.6	-
Total	109	126	2.5	166	344

Fig. 30 Continued :

SCANDINAVIAN DRIFTLithological types

Shell fragments	7.3
Chalk	7.3
Magnesian Limestone	5.5
Carboniferous Limestone	0.0
Undifferentiated Limestone	9.1
Sandstone	8.2
Red sandstone	3.6
Greywacke	0.0
Siltstone and shale	6.4
Coal and black shale	0.0
Ironstone	0.0
Quartz	21.8
Igneous and metamorphic	30.8
Total particles	110

One of the unusual features of the Upper Tees Clay is the occurrence of small concretions in many of the samples. These are calcareous in nature, and seem from field examination to be a weathering rather than a depositional phenomena.

Sandstone contents are fairly constant and vary between 35 to 50%. Red sandstone occurs in small proportions in nearly all samples, but greywacke concentrations are low.

The most noticeable feature of this clay is the absence of coal in 5 out of 8 samples, and the very low values of siltstone and ironstone.

Quartz and igneous material is noted in all samples and amongst the igneous material, many particles with reddish colours are noted.

In general terms the Upper Tees Clay shows great lithological similarities to that of the Upper Till of the coastal region.

Upper Wear Clay. (Fig. 30)

The Upper Clay of the Wear Lowlands possesses a similar lithology to the Lower Till of the Wear Lowlands, with the major difference being the complete absence of any limestone in the Upper Wear Clay. The bleaching of a number of sandstone fragments in the Upper Clay strongly suggests that leaching has been important, and therefore the possible former presence of limestone.

Sandstone percentages are high, with values between 55 to 80%. One interesting feature observed in the arenaceous group is that neither red sandstone nor greywacke material is present.

Similarly no igneous material is noted in any of the samples of detailed analysis.

All this evidence suggests that the Upper Wear Clay is dominantly of local (i.e. Coal Measures) origin. What seems remarkable is the fact that this clay does not in the samples examined contain any far-travelled material, when a nearby source exists in the form of the Lower Till.

Scandinavian Drift. (Fig. 30)

A sample of the Scandinavian Drift from the only available present-day exposure at Warren House Gill was subjected to stone count analysis. It was found however that the lithologies present within this clay can not be adequately classified under the lithological groupings used for the other Durham stony clays. Therefore a number of new categories were added to those already employed.

In the calcareous section two main differences from the other Durham stony clays are noted. The first is the presence of well preserved shell fragments (7.3%), and the second the occurrence of undoubted Chalk particles (7.3%). The closest landward exposure of Chalk at the present day is the Yorkshire Wolds some 60 miles to the south. The chalk in the Scandinavian Drift is therefore thought to have been derived from exposures somewhere in the bed of the North Sea, possibly close to Scandinavia.

Only 5.5% of the rock particles can be identified as Magnesian Limestone; the local parent material, and no Carboniferous Limestone at all is found. There are however many limestone particles present which the author found it impossible to identify, and which showed a variety of colours from white to bluey grey. No fossils were noted in these rocks. The origin of this material is probably Scandinavia.

The arenaceous component is very small and no yellow or yellow brown Carboniferous sandstone nor greywackes are found. Small pieces of red Triassic sandstone are however noted.

Some siltstone material is found, mostly tinged red, green or grey. None of this material is typical of the Coal Measures, and it was considered that it had been derived from a Triassic outcrop.

Coal and ironstone, both particularly characteristic of Coal Measures strata, are completely absent.

Quartz material, mostly vein quartz with pinkish hues is found in considerable quantity, and flint particles are also present.

Igneous material is very common and makes up c. 30% of the total sample. The majority of this material is coarse grained, but more specific identification proved impossible.

This stone count undoubtably suggests that the Scandinavian Drift is considerably different in lithology from the other stony clays which have been studied in detail. It also seems undisputed from the above evidence that the Scandinavian Drift is the product of the first ice sheet to enter the area, before any Coal Measures material had been brought into the coastal zone. Nearly all the lithologies in the Scandinavian Drift suggests derivation from exposures to the east of the present coastline.

When the data for all the stone counts are bulked together into 6 groups corresponding to the 6 main clay types of Eastern Durham, certain interesting relationships are found :-

Lithological Groups	<u>Lower Till</u> <u>Wear</u> Lowlands	Magnesian Limestone Plateau.	Coastal Region.	<u>Upper</u> <u>Till</u>	<u>Upper Tees</u> <u>Clay</u>	<u>Upper Wear</u> <u>Clay</u>
A	0.31	20.41	44.23	25.59	25.48	0.00
B	2.22	2.46	5.07	6.48	9.91	0.00
C	0.37	0.61	0.89	1.44	1.41	0.00
D	0.31	0.08	0.00	0.86	5.95	0.00
E	69.37	58.01	34.98	46.79	43.66	68.20
F	0.23	0.36	0.50	0.78	1.35	0.00
G	0.53	0.66	1.17	1.87	0.49	0.00
H	4.11	1.80	1.31	1.17	1.45	3.50
I	13.56	2.92	2.40	0.71	0.50	12.24
J	5.46	7.40	3.02	4.39	2.61	12.46
K	1.81	2.45	2.95	4.01	4.06	2.44
L	1.08	2.00	3.05	4.57	2.60	0.00
M	0.61	0.82	0.43	1.34	0.51	1.20
Total particles 4299		7480	7198	6309	1176	960

It is seen for example that the lithological differences between the Lower Till in its three divisions are quite considerable. On the other hand very marked similarities are seen between the Upper Till and the Upper Tees Clay, and the Lower Till of the Wear Lowlands and the Upper Wear Clay. When the results are compared statistically using the Kolmogorov - Smirnov test it is found that there are differences at the 1% level of significance between any two of the groups. The following results were obtained. A null hypothesis was postulated that any two of the distributions were obtained from the same population.

1. Comparison of the Lower Till of the Wear Lowlands with the Lower Till of the Magnesian Limestone Plateau.

Maximum sample D value = .206

calculated D value at 1% level of significance = .031

Therefore the null hypothesis is rejected and the two distributions must be regarded as being drawn from different populations.

2. Comparison of the Lower Till of the Magnesian Limestone Plateau and the Lower Till of the Coastal Region.

Maximum sample D value = .265

Calculated D value at 1% level of significance = .029

Therefore the null hypothesis is rejected and the two distributions must be regarded as being drawn from different populations.

3. Comparison of the Lower Till of the coastal region with the Upper Till.

Maximum sample D value = .184

Calculated D value at 1% level of significance = .026

Therefore the null hypothesis is rejected and the two distributions must be regarded as being drawn from different populations.

4. Comparison of the Upper Till and the Upper Tees Clay

Maximum sample D value = .081

Calculated D value at the 1% level of significance = .052

Therefore the null hypothesis is rejected and the two distributions must be regarded as being drawn from different populations.

5. Comparison of the Lower Till of the Wear Lowlands and the Upper Wear Clay.

Maximum sample D value = .071

Calculated D value at the 1% level of significance = .058

Therefore the null hypothesis is rejected and the two distributions must be regarded as being drawn from different populations.

These results indicate some of the difficulties experienced in the interpretation of statistical analysis. In the case of the Lower Till it is seen that a laterally continuous deposit shows very marked statistical differences in terms of the lithologies which compose it. This is due to the evolutionary mature of the till sheet, and the increase in the Magnesian Limestone content in a down ice direction. The result is that the division of the Lower Till into three groups corresponding to the main topographical regions of Eastern Durham is somewhat meaningless for the purposes of comparison. This fact gives further evidence for the necessity of studying evolutionary changes in a till sheet rather than mere differences between arbitrary divisions.

Even though there are statistical differences at the 1% level of significance between the Upper Till and the Upper Tees Clay, and the Lower Till of the Wear Lowlands and the Upper Wear Clay, it seems reasonable to postulate that these slight lithological differences may also be due to evolutionary differences in the material, and to sampling errors, rather than to any intrinsic differences between the deposits.

It is interesting to note that the two most comparable deposits in terms of their location, namely the Upper Till and the Lower Till of the coastal region, show a marked statistical difference which cannot be satisfactorily explained by evolutionary differences. In this case it seems reasonable to conclude that different clay types are present in the same area.

Conclusions.

The most important single conclusion to emerge from this study is the fact that a single till sheet, even over a small area does not possess a uniform lithology in areas of different parent material. Evidence from the Lower Till of Eastern Durham proves conclusively that till sheets evolve in a downstream direction of movement, in response to changes in bedrock material. This work also shows that such changes are extremely rapid, with a change in the dominant lithological group taking place over distances of less than 10 miles.

These facts suggest therefore that it is not possible to talk in terms of a diagnostic lithological composition for a particular till sheet, unless the parent material over which the ice is moving is of a very uniform nature over great distances. Certainly if three samples are obtained from the Lower Till of Eastern Durham, one each from the Wear Lowlands, the Magnesian Limestone Plateau, and the coastal area, and are subjected to lithological analysis, the results suggest that three separate till sheets are present. Such an example does emphasise the necessity of using more than a single technique of analysis if the distribution and evolution of glacial deposits is to be fully understood.

The stone counts from the Upper Till suggest that this clay is lithologically distinct from the Lower Till, and is characterised by much lower percentages of Coal Measures material, and the presence of igneous particles possessing a strong red colouration.

The great lithological similarities between the Upper Till and the Upper Tees Clay suggest that these two deposits are closely related, and derived from a similar source, even though their modes of origin may have been different.

The Upper Clay of the Wear Lowlands however bears no resemblance at all to either the Upper Till of the coast or the Upper Tees Clay. The most characteristic feature of the Upper Wear Clay is the apparently complete absence of far-travelled lithologies. This suggests that this clay is basically of local origin, and was formed within the Wear Valley area. Whether any Carboniferous Limestone was originally present is purely conjectural, but the bleaching of many of the sandstone particles shows that leaching has been severe.

The micro-stone counts described in this Chapter are seen therefore as a useful correlative tool over short distance, and of great value for studying lateral variations in till lithology. The great disadvantage is that stone counting is a slow and laborious technique, and in the course of the present work more than 34,000 rock particles had to be collected and identified individually.

Comparisons with the stone counts of other workers.

As most of the previous analyses of stone counts in Northern England were made on large sized pebbles (actual sizes have rarely been specified) it was decided necessary to make some evaluation between the micro-stone count employed by the author, and the more usual

large stone counts. This seemed particularly necessary as Davis S.N. (1958) has proved that in some glacial deposits there could be considerable variation in lithological percentages depending on the grain size being studied.

Three samples for comparative purposes are shown of macro and micro-stone counts made on the Lower Till of the coastal area. (Fig. 31) These three samples give representative variations similar to those found in the other stony clays. Variations between the two types of stone counts in some cases are fairly considerable, but in general a similar relative distribution is noted. These variations do stress the point emphasised by Davis S.N. (1958) that one should only compare samples with similar grade sizes. Although this was rigidly adhered to for the micro-stone counts, no such sampling was employed for the macro-counts of the present author.

From a comparison of the sets of data it is difficult to point out any features which are particularly characteristic of either type of stone count. There is a general tendency for sandstone percentages to be greater in the micro-stone counts than in the macro-stone counts. Similarly the siltstone, coal and ironstone percentages show a tendency to be higher in the micro-stone counts, owing possibly to their relative structural weakness in large pieces. However the only really consistent feature shown by all the samples examined is the considerably higher percentages of igneous material found in the macro-sized samples compared with the micro-counts. This gives a measure of objectivity to the already noted observation that below a certain diameter coarse grained igneous rocks show a marked tendency to be rapidly broken down into individual mineral grains.

Fig. 31

Comparison of macro-and micro-stone counts in Lower Till of coastal area.

	A		B		C	
	Macro	Micro	Macro	Micro	Macro	Micro
Magnesian Limestone	31.7	25.3	68.3	58.6	58.3	61.2
Carboniferous Limestone	6.8	3.1	3.3	8.1	6.8	4.8
Undifferentiated Limestone	0	0	1.2	0	0	0
Clay concretions	0	0	0	0	0	0
Sandstone	41.4	50.7	16.8	23.1	19.3	25.1
Red sandstone	0	0.4	0.7	0	1.0	0
Greywackes	0	1.7	1.4	0	0	0
Siltstone and shale	0.3	0.7	2.1	1.7	2.1	2.4
Coal and black shale	1.0	4.8	0	3.9	0	1.0
Ironstone	3.0	7.5	0	2.1	1.0	1.0
Quartz etc.	1.2	3.0	0.2	2.5	1.6	2.6
Igneous and metamorphic	11.1	1.6	3.6	0	9.4	1.7
Unknown	3.5	1.0	2.4	0	0.5	0.2
Total particles	297	763	419	234	194	591

A = Lower Till Shotton Brick Pit.

B = Lower Till Castle Eden Dene mouth.

C = Lower Till Chourdon Point.

Macro-stone counts - particles with diameters of $\frac{3}{4}$ inch to 6 inches.

Micro-stone counts on particles with diameter of $\frac{1}{8}$ inch to $\frac{3}{4}$ inch.

In order to test the statistical similarity between the large stones and the micro-stone counts, the data of Fig 31 were subjected to the Kolmogorov - Smirnov test. A null hypothesis was postulated that the large and micro-stone counts were drawn from the same population at each of the sample sites.

A. Lower Till Shotton Colliery Brick Pit.

Maximum sample D = .101

Calculated D at 1% level of significance = .112

Therefore the null hypothesis must be retained, and it is concluded that the two samples are drawn from the same population.

B. Lower Till Castle Eden Dene

Maximum sample D = .097

Calculated D at 1% level of significance = .113

Therefore the null hypothesis must be retained and it is concluded that the two samples are drawn from the same population.

C. Lower Till Chourdon Point.

Maximum sample D = .078

Calculated D at 1% level of significance = .134

Therefore the null hypothesis must be retained and it is concluded that the two samples are drawn from the same population.

The statistical analysis shows that in the Eastern Durham area samples of large stone counts are comparable with micro-stone counts, and both results are obtained from the same population.

Earlier stone counts

Only two quantitative records of the stone lithologies of glacial till are to be found in the literature of north-east England. These are the results of Herdman T. (1909) for tills in the River Derwent Valley, and Trechmann C.T. (1915) with a single stone count from the Scandinavian Drift at Warren House Gill.

Herdman made his stone counts of 200 stones per exposure from a till of the Derwent region which he described as "frequently reddish brown or bluish grey in colour" (p. 110). From his description it seems obvious that he considered the colour variations to be of little significance, whereas the present author would have thought it possible that this colour difference may represent differing origins for the two clays, with the bluish grey clay being derived chiefly from the Pennine Valleys, and the reddish clay derived from the Lake District area. (Dwerryhouse A.R. 1902). Unfortunately Herdman does not distinguish from which clay his stone counts were obtained.

The lithological groups used by Herdman are very similar to those used by the present author, and so allow a direct comparison to be made between the two areas, (Fig. 32). A number of interesting points emerge. The first is the high proportion of erratic rocks c. 40%, which Herdman found in the till. This is in sharp contrast to the Eastern Durham area, where even in the macro-stone counts erratic material in the sense of non-Coal Measures or non-Magnesian Limestone material makes up less than 20% of the sample in all cases, and frequently less than 10%.

Detailed generalisations are difficult to make with Herdman only publishing the results of two stone counts, but it is at least possible to point out the main lithological differences between the

from the Magnesian Limestone area, or Coal Measures strata make up 83 of the 90 stones present. Only one angular pebble of igneous origin was found and this was a piece of basalt.

Rounded

Magnesian Limestone	0
Ironstone	3
Coal	0
Red sandstone	8
Quartz	1
Igneous	39
Greywacke	29
Unknown	3

Total 83

In the rounded category an entirely different distribution of material is found, with the dominance of far travelled rocks from the Lake District and Southern Upland area. Igneous material is the largest single lithology with 39 out of the 83 pebbles. Of these 36 are fine grained, indicating the very low proportions of coarse grained igneous material in this shape category. Greywackes are the second most abundant lithology, and make up 29 of the 83 stones counted. Together igneous and greywacke material, both erratic in Eastern Durham, make up 68 of the 83 pebbles. In the rounded category only 8 pebbles are of Carboniferous sandstone.

In the intermediate category all lithological types were present. Sandstone was by far the dominant lithology with 326 out of 438 particles.

A second sample was obtained from the Lower Till at Tuthill quarry (No.18). In this just over 300 pebbles were counted and a similar distribution noted. In this sample it was noted that angular

material is almost twice as common as rounded material, but within each group the relative proportions are similar to the earlier sample

	Angular	Rounded
Magnesian Limestone	1	0
Carboniferous Limestone	2	0
Ironstone	4	0
Red sandstone	7	1
Sandstone	76	5
Siltstone	1	0
Greywacke	1	12
Igneous	6	28
Quartz	0	2
Total	98	48

In the angular category there is once more the complete dominance of Carboniferous sandstone, and the very small amounts of igneous and greywacke material. In the rounded categories the converse is true with the dominance of igneous and greywacke lithologies.

Conclusion

The analysis shows that there is a good correlation between shape and lithology, with the more resistant rocks being better rounded. Equally however there is a correlation between degree of rounding and distance of glacial transport. The fact however that in Eastern Durham the far travelled rocks are also the hardest means that it is impossible to separate the effects of lithological hardness and distance of transport as far as these influenced stone shape.

generally represents the interaction of a whole series of environmental factors such as drainage, aspect, vegetation, slope and parent material.

The pH of a soil or clay therefore tends to express the environmental conditions which persist at the present day, and only to a lesser extent the history of the soil. As a general rule the lower the pH, the faster is the rate of leaching within a deposit. Although a pH of 7.0 represents neutrality it should be remembered that the dissolution of calcium carbonate can occur up to a pH of 8.4 if the acidifying substance is carbon dioxide (Cornwall *I.W.*, 1958). In nature the highest normally found pH s are close to 8.4, and are reached when free calcium carbonate is in equilibrium with atmospheric carbon dioxide. However if magnesian carbonate is present in excess in a deposit the pH values can be raised to a theoretical pH 9.5 (Cornwall 1958). In Eastern Durham the presence of large quantities of magnesian carbonate in the Magnesian Limestone suggested that the pH values of the stony clays would be high.

While pH values tend to reflect present environmental conditions, calcium carbonate figures in contrast may reflect both the original amount of carbonate present in a sample, and any weathering it may subsequently have undergone. When pH values of different samples are similar at the present day it can be assumed that any carbonate differences may possibly represent initial depositional differences. (Although this does depend on what else is present or has been present in the soil). On the other hand when there are large variations in pH between two samples this would suggest differing rates of leaching, at least in the present environment, and also that absolute carbonate differences may be explicable by differing environmental conditions, from original samples with similar carbonate contents.

Method of analysis.

pH readings were obtained from measurement of a soil solution using 1 part soil, (less than 2 mm fraction,) to 2.5 parts distilled water. The pH of the solution was read with an electrometric pH meter.

Results.

The pH values for the Eastern Durham stony clays vary from 5.2 to 8.9. The distribution of these values is not uniform throughout this range and it is seen (Figs. 34 and 35) that there is a very marked concentration of values between pH 8.0 and 9.0 , with a modal value of pH 8.5.

As regards the pH values of the individual clays it is obvious that the technique is of little value for differentiation purposes between the deposits. (Fig. 34). Certain interesting features are however noted.

1. Lower Till

a. Lower Till of the Wear Lowlands.

The Lower Till of the Wear Lowlands shows two pH groupings; a higher one with the majority of pH values between 7.8 to 8.6 , and a lower one with pH values of 5.3 and 6.2. The surprising fact about this clay is the high pH values recorded by so many of the samples, even though the clay is nowhere found resting on limestone parent material, and nowhere has a carbonate content of more than 3%. The reason for these high pH values is not understood.

Fig. 34

pH and Calcium Carbonate Content

Lower till of the Wear Lowlands.

	pH	Calcium carbonate content percent.
Finchale Priory	8.4	1.8
Windy Nook Quarry	6.2	1.3
Eighton Banks Quarry	5.3	0.3
Brancepeth Beck	8.0	1.0
Biddick Burn, near Birtley	8.3	2.5
Crime Rigg Quarry	8.6 =	1.0
Spennymoor Industrial Estate	8.1	1.8
Low Grange, Bowburn	7.8	1.5
Building site, Houghton-le-Spring	8.3	1.5

Lower Till of Magnesian Limestone Plateau

Middridge Quarry	8.5	6.0
Aycliffe Quarry	8.7	9.3
Houghton-le-Spring	7.9	1.8
Eppleton	8.6	7.8
Thrislington	7.6	3.0
Coxhoe	8.3	2.5
Bishop Middleham	8.4	33.8
Trimdon Colliery	8.2	44.3
Cope Hill	8.5	27.5
Wood Quarry Wingate	8.4	14.8
Wingate Quarry D.	7.5	0.3
Westmoor Farm	8.3	11.7
Sherburn Sand Pit	7.1	2.3
West Cornforth Quarry	7.5	1.5
Pit Fall Warden Law.	7.6	1.8
High Moorsley	7.4	2.5
South Hetton	8.2	12.0
Wingate Quarry A.	8.0	8.2
Fulwell	8.5	6.3
Tuthill	7.4	2.5
Holy Cross	7.6	1.0
Sand Pit north of Bradbury	7.1	1.0

Calcium carbonate
content
percent

Lower Till of Coastal Area

	pH	
Blackhall Colliery	8.1	23.8
Salterfen Rocks	8.3	40.5
Bedlam Gill	8.4	18.0
Warren House Gill	8.4	26.0
Quarry near Hesleden	8.6	17.0
Dalton Piercy	8.7	13.5
Castle Eden Dene	8.2	25.5
Peterlee	8.3	18.5
Castle Eden Village	8.6	11.0
South Hylton	8.5	13.0
Chourdon Point	8.6	26.8
A.19 section Castle Eden Dene	8.2	16.9
Shotton Colliery	8.5	15.0
Shotton Colliery Brick Pit	8.1	10.5
Hawthorn Quarry	8.5	31.3
Seaham Harbour	8.5	9.3
Dalton-le-Dale	8.5	25.3
Peterlee Petrol Station	8.4	21.0
Peterlee Acre Rigg	8.3	18.0
Blackhall Rocks	8.8	25.5
Cliff south of Castle Eden Dene	8.6	34.0
Green Steps Crimdon	8.8	36.3

Upper Till

Portrack Brick Pit	8.5	12.3
Cerebros Salt Works	8.6	12.8
Hawthorn Quarry	8.4	16.8
Whelly Hill Quarry	8.6	12.3
Crimdon Dene	8.4	15.3
Naisberry Quarry	7.9	1.5
North of Castle Eden Dene	8.3	8.6
Peterlee Main Drain	8.6	10.3
Blackhall Rocks	8.6	11.0
Foxholes	8.5	8.1
Hazel Dene	8.4	10.4
Sheraton Hill Farm	8.5	13.1
Seaton Carew	8.9	14.5
Hart	8.8	19.9
South Hylton Quarry	8.5	8.8

Calcium carbonate
content
percent

Upper Till continued :

	pH	
Low Stotfield Farm	8.5	16.8
Hilltop east of Sheraton Hill Farm	8.5	8.6
Hesleden Dene	8.6	13.5
Wolviston	8.3	2.5
Low Burn Toft	6.8	0.0
South of Hart Road	6.6	0.0
Elwick	8.3	12.5
High Stotfield Farm	8.4	20.5
Benknowle	8.6	16.0

Upper Wear Clay

Usworth Hall	6.4	0.8
High Butterby Farm	8.4	0.5
Railway Cutting north of Durham	5.2	1.5
Sewer Trench Framwellgate	5.5	1.3
Van Mildert College	7.4	0.3
Electricity sub-station Ferryhill	5.4	0.3
Bowburn	6.6	1.0
Belmont	5.4	0.8

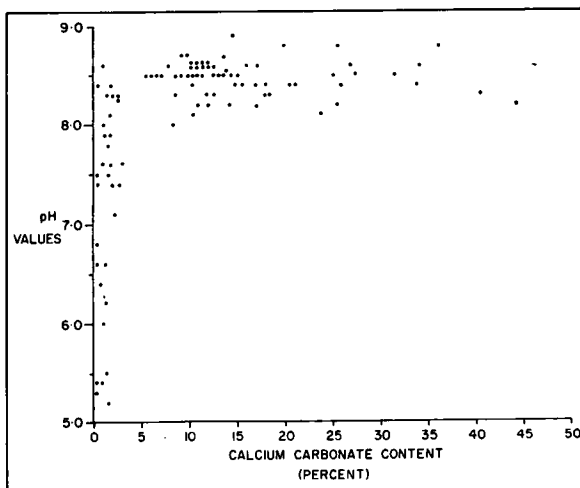
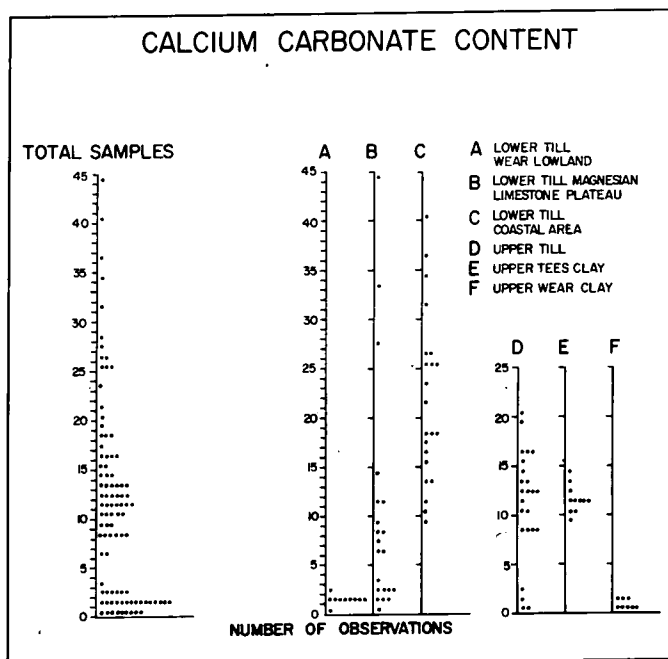
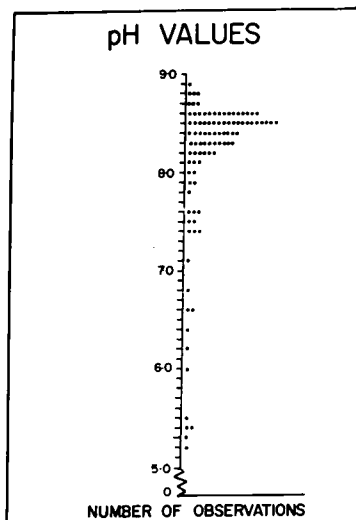
Upper Tees Clay

Portrack Brick Pit	8.5	13.8
Wynyard Hall	8.2	14.3
Brierton Sand Pit	8.5	11.3
Stob Cross	8.6	10.5
Middlefield Farm	8.5	11.0
Carlton	8.7	9.5
Gilly Flat	8.6	11.0
Low Middlefield	8.5	11.0
Whitehouse Farm	8.5	10.5
Sedgefield Road Wolviston	8.2	11.0
Redmarshall	8.6	12.0

Scandinavian Drift

Stony Clay	8.3	9.5
"Loess"	8.5	5.9

Figure 35.



b. Lower Till of the Magnesian Limestone Plateau.

The Lower Till plateau shows pH variations from 7.1 to 8.7, with a reasonably even distribution throughout this range. In general there is a tendency for low pH values to be associated with low carbonate contents in proximity to the escarpment edge, but this is by no means invariable.

c. Lower Till of the coastal area.

The Lower Till of the coastal area has without exception pH values between 8.1 and 8.8. The majority of values are concentrated between pH 8.4 to 8.6.

2. Upper Till.

The Upper Till of the coastal area shows a marked concentration of pH values between 8.3 to 8.6, but does at the same time show a scatter of values. The three lowest values below pH 8.0 represent coarse morainic deposits, which possess only small amounts, or a complete absence of calcium carbonate. The highest pH value for the Upper Till is a pH of 8.9 found in an exposure on the foreshore at Seaton Carew. In this case the high pH value is probably the result of sodium chloride contamination from sea water.

3. Upper Tees Clay.

The Upper Tees Clay always shows pH values of more than 8.0, with the majority of the results concentrated around pH 8.5.

4. Upper Wear Clay.

The Upper Wear Clay shows considerable variation in pH values from 5.4 to 8.4. In this clay a concentration of values is found in the lower part of the range between pH 5.2 to 6.6.

5. Scandinavian Drift.

Samples from the Scandinavian Drift show a pH value of 8.5 for the loess deposit, and pH 8.3 for the stony clay.

b. Calcium carbonate content.

The calcium carbonate content of glacial deposits has been used as a method for the differentiation of glacial deposits on a number of occasions in the past. (Andrews J.T. and Sim V.W. 1964; Catt J.A. 1963; Dreimanis A. and Reavely G.H. 1953; Dreimanis A. 1962). More often however studies of carbonate content have been concentrated on profile studies and the formation of leached or weathering zones. (Leighton M.M. and MacIntock P. 1930; White G.W. 1951). In north-eastern England neither technique has been used in the study of glacial deposits.

Method of analysis.

Calcium carbonate determinations were carried out using a rapid titration method outlined by Piper C.S. (1942) (Appendix 5).

Results.

The calcium carbonate content of the matrix of the stony clays of Eastern Durham shows a considerable absolute variation from 0 to 45%. (Fig. 34). Sample results are spread fairly evenly throughout this range, but there is a tendency for a bi-modal distribution to appear in the lower percentages. The upper peak is centred on 12% and the lower one on 1%. A relative absence of values around 5% is noted. (Figs 34 and 35). When the results are plotted for the individual clays certain interesting patterns were to be seen.

1. Lower Till

a. Lower Till of the Wear Lowlands.

The Lower Till of the Wear Lowlands shows very low carbonate contents. All samples give recorded values of less than 5%, and the majority of values are grouped around 1%. The carbonate content of this clay is considered to have been solely derived from Carboniferous limestone sources in the Pennine Uplands.

b. Lower Till of the Magnesian Limestone Plateau.

The Lower Till of the Magnesian Limestone Plateau exhibits considerable variation in carbonate content from 0 to 44%. The two highest values are thought to be due to anomalous local conditions. On the whole it can be seen that the carbonate contents of the Lower Till of the plateau fall considerably below those of the Lower Till of the coastal area.

c. Lower Till of the coastal area.

The Lower Till of the coastal area shows absolute carbonate variations from 9 to 40%. When one distinguishes further between the Lower Till at its most easterly exposures in the cliffs, and in inland exposures, a marked difference between the two is seen, with the cliff samples consistently giving the higher values.

2. Upper Till

The carbonate content of the Upper Till shows a marked concentration of values between 8 to 16%, and only one value of more than 20 is observed. In the area of the coastal exposures there is no overlap of carbonate content between the Upper and the Lower Till, and in this region carbonate contents provide a definite way of distinguishing between

the two deposits. Inland however the carbonate content of the Lower Till drops and becomes similar to that of the Upper Till. The coarser material of the Upper Till consistently has negligible amounts of calcium carbonate present.

3. Upper Tees Clay.

The Upper Tees Clay shows a consistent and limited distribution of carbonate values between 9 to 14%. The similarity of these values to those of the Upper Till is noted.

4. Upper Wear Clay.

The carbonate contents of the Upper Wear Clay are always less than 1% , and generally similar to those of the Lower Till of the Wear Lowlands.

5. Scandinavian Drift.

Analysis of the loess deposit reveals a carbonate content of 5.5% , and a value of 9.5% for the stony clay. The low carbonate figure for this clay is unusual, as it rests directly on the Magnesian Limestone and the ice which deposited it must have moved a considerable distance over Magnesian Limestone in its westward passage from the North Sea. In contrast the Lower Till of the coastal region, also resting on Magnesian Limestone has carbonate figures of more than 25% in the cliff exposures.

The calcium carbonate values for the six main clay types were subjected to statistical analysis of variance (Huntsberger D.V. 1961) to determine the likelihood of whether the individual sample values have been drawn from the same population or from different ones. In all cases a null hypothesis was postulated that the samples groups being analysed were drawn from the same population.

A. Comparison of sample values of the six main clay groups.

(data from Fig. 34)

The following results were obtained.

$$\begin{aligned}\text{Sample F value} &= 14.69 \\ \text{Table F value, } F_{5 \ 90(.01)} &= 3.17\end{aligned}$$

Therefore the null hypothesis is rejected and the sample values are regarded as having been obtained from more than 1 population.

B. Comparison of sample values of the three divisions of the Lower Till (data from Fig. 34) The following results were obtained.

$$\begin{aligned}\text{Sample F value} &= 15.39 \\ \text{Table F value, } F_{2 \ 48(.01)} &= 4.98\end{aligned}$$

Therefore the null hypothesis is rejected and the sample values are regarded as having been obtained from more than 1 population.

C. Comparison of sample values of the Upper Till and the Upper Tees Clay. (data from Fig. 34) The following results were obtained.

$$\begin{aligned}\text{Sample F value} &= 0.039 \\ \text{Table F value, } F_{1 \ 33(.01)} &= 7.31\end{aligned}$$

Therefore the null hypothesis is retained and the sample values are regarded as having been obtained from the same population.

D. Comparison of samples values of the Lower Till of the Wear Lowlands and the Upper Wear Clay. (data from Fig. 34) The following results were obtained.

$$\begin{aligned}\text{Sample F value} &= 5.25 \\ \text{Table F value, } F_{1 \ 15(.01)} &= 8.68\end{aligned}$$

Therefore the null hypothesis is retained and the sample values are regarded as having been drawn from the same population.

E. Comparison of sample values of the Lower Till of the Coastal Region and the Upper Till. (data from Fig. 34) The following results were obtained.

$$\begin{array}{lcl} \text{Sample F value} & = & 24.42 \\ \text{Table F value, } F_{1, 44(0.01)} & = & 7.10 \end{array}$$

Therefore the null hypothesis is rejected and the sample values are regarded as having been obtained from more than 1 population.

These results reveal certain interesting points. In the case of the Lower Till sheet the difficulty of comparing the same deposit in different areas when rapid lateral evolution in lithological content is taking place is clearly seen. The analysis emphasises the basic similarities between the Upper Till and the Upper Tees Clay, and between the Lower Till of the Wear Lowlands and the Upper Wear Clay. At the same time a very marked statistical difference is seen between the Lower Till of the Coastal Region and the Upper Till in the same area. From this it is concluded that a calcium carbonate analysis of the matrix of the stony clay deposits gives very similar correlation results to those obtained from stone count analysis. (Chapter 6).

The relationship between pH values and calcium carbonate contents is shown in Fig. 35. No direct correlation is obvious. There is however a general tendency for low pH values to be associated with low calcium carbonate contents, but at the same time high pH values do not necessarily mean high calcium carbonate contents. High calcium carbonate contents are always associated with high pH values of more than pH 8.0. Low calcium carbonate contents are associated with all pH values.

A marked change in the distribution appears to occur close to pH 8.0 , and below this value no calcium carbonate content of more than 5% is seen. The significance of this apparent break in the distribution, if it indeed has any significance, is unknown. In such a case it is impossible to state whether the present pH values have been caused by the calcium carbonate contents observed at the present day, or vice versa. Such a feature merits further study.

C. Coal content.

From an examination of the tills of Eastern Durham it quickly became obvious that coal is to be found in nearly all the deposits. It was therefore decided to employ an analytical technique to estimate the coal content within the matrix of the stony clays, and to see if this would prove useful for correlation purposes.

A study of the literature of pedology and sedimentary petrology indicated that details of a suitable technique did not exist. In pedology there are several techniques for estimating the organic carbon content of soils, but when these are applied to artificially created mix^xtures of coal and clay the results obtained by both the Walkley Black method and the Schollenberger method (Jackson M.L. (1958), gave unsatisfactorily results with figures well below the known amounts of coal present.

Consideration was given to a technique for the combustion of coal at c. 500 degrees centigrade, and the construction of a standard curve to determine the relative proportions of coal present within the stony clays. This method, a modification of the loss on ignition method of pedology works well on controlled mixtures of quartz and coal. However in a soil mixture in which both calcium carbonate and clay minerals are present, the combustion of coal is masked by the breakdown of calcium carbonate and the dehydration of the free and the interlayer water of the

clay minerals. In such a case it proved impossible to separate the relative proportions of the different constituents and the technique was therefore discarded.

Method of analysis.

It was decided because of these complications that what was wanted was a method which involved the physical separation of the coal from the bulk of the sample. This could then be weighed and expressed as a percentage of the total weight.

The low specific gravity of bituminous coal (1.4 to 1.6) suggested the possibility of some flotation process for separating a sample into coal and heavier fractions. What was needed was a liquid with a specific gravity of c. 1.7 which would allow the coal to float to the surface. A number of liquids with this property were investigated, but all proved very difficult to handle. These were ortho-phosphoric acid, concentrated hydrochloric acid, chloroform, and carbon tetra-chloride. The first two were discarded immediately after trials because of the very great danger of burns when large quantities were being used. Chloroform was tried but rejected because of high cost, danger of explosion, and the rather toxic nature of the vapour. Carbon tetra-chloride was therefore, by elimination, considered the most suitable liquid. This too proved difficult to handle owing to the highly toxic nature of the fumes.

A microscopic examination of the stony clays indicated that most of the coal present was in the size range of more than 30 microns. This fact allowed an initial wet sieving of the sample through a 300 mesh British Standard sieve to remove the fine clay and silt material, and at the same time to ensure that the coal fragments were clean.

After washing and the initial sieve separation, the sample was centrifuged in a suspension of carbon tetrachloride. The coal floated to the top of the centrifuge tubes, and was then filtered and

weighed and expressed as a percentage of the sieved sample. With each sample a microscopic examination of the recovered coal was made to determine if any other material besides coal was present. In the majority of cases no other material was found. Analysis of controlled made up mixture of coal and sand sized material indicated a recovery rate for the coal of between 85 to 100%. (Appendix 6).

Results.

The results show variations in coal contents for the stony clays of between 0.5 to 3.0%. Coal was in fact extracted from all the stony clays with the exception of the Scandinavian Drift. The modal value for the coal contents is between 0.3 to 0.5%. Only a very few samples have coal contents of more than 1%. (Fig. 36)

1. Lower Till

a. Lower Till of the Wear Lowlands.

The Lower Till of the Wear Lowlands possesses high coal contents with no sample having less than 0.71% coal. The two extremely high values for the Lower Till at Finchale Priory and Brancepeth Beck are from clays which are within c. 100 yards of a coal seam outcrop.

b. Lower Till of the Magnesian Limestone Plateau.

The Lower Till of the Plateau shows considerable coal content variation with values from 0.1 to 2.5%. No apparent correlation is noted between distance from coal seam outcrops and coal contents of the tills.

c. Lower Till of the coastal area.

The Lower Till of the coastal area shows a marked concentration of coal contents between 0.3 to 0.5%. A single coal content of more than 1% is noted.

Fig. 36.Coal Content

Lower Till of the Wear Lowlands	Coal content percent
Finchale Priory	2.95
Windy Nook Quarry	0.71
Eighton Banks Quarry	0.94
Brancepeth Beck	2.52
Biddick Burn, near Birtley	0.95
Crime Rigg Quarry	0.88
Spennymoor Industrial Estate	0.90
Low Grange Bowburn	0.81
Building site Houghton-le-Spring	0.74
Lower Till of the Magnesian Limestone Plateau	
Middridge Quarry	0.43
Aycliffe Quarry	0.25
Houghton-le-Spring	0.31
Eppleton	0.79
Thrislington	0.91
Coxhoe	1.50
Bishop Middleham	0.48
Trimdon Colliery	0.31
Cope Hill	0.09
Wood Quarry Wingate	0.42
Wingate Quarry D.	2.38
Westmoor Farm	0.84
Sherburn Sand Pit	0.77
West Cornforth Quarry	0.66
Pit Fall Warden Law	0.70
High Moorsley	0.73
South Hetton	0.93
Wingate Quarry A.	0.95
Fulwell	0.56
Tuthill	0.58
Holy Cross	1.58

Lower Till of the Coastal area.

Coal content
percent

Blackhall Colliery	0.33
Salterfen Rocks	0.34
Bedlam Gill	0.43
Warren House Gill	0.38
Quarry near Hesleden	0.42
Dalton Piercy	0.49
Castle Eden Dene	0.43
Peterlee	0.50
Castle Eden Village	0.32
South Hylton	0.76
Chourdon Point	0.48
A.19 section Castle Eden Dene	0.55
Shotton Colliery	0.53
Shotton Colliery Brick Pit	0.45
Hawthorn Quarry	0.35
Seaham Harbour	0.49
Dalton-le-Dale	0.30
Peterlee Petrol Station	0.43
Peterlee Acre Rigg	1.20
Blackhall Rocks	0.35
Cliffs south of Castle Eden Dene	0.40
Crimdon Green Steps	0.38

Upper Till

Portrack Brick Pit	0.25
Cerebros Salt Works	0.69
Hawthorn Quarry	0.10
Whelly Hill Quarry	0.17
Crimdon Dene	0.27
Naisberry Quarry	0.21
North of Castle Eden Dene	0.56
Peterlee Main Drain	0.47
Blackhall Rocks	0.42
Foxholes	0.38
Hazel Dene	0.59
Sheraton Hill Farm	0.62
Seaton Carew	0.20
Hart	0.26
South Hylton Quarry	0.64

Upper Till (cont):

Low Stotfield Farm	0.47
Hilltop east of Sheraton Hill Farm	0.33
Hesleden Dene	0.40
Wolviston	0.18
Low Burn Toft	0.10
South of Hart Road	0.56
Elwick	0.41
High Stotfield Farm	0.39
Benknowle	0.37

Upper Wear Clay

Usworth Hall	1.1
High Butterby Farm	0.83
Railway cutting north of Durham	1.10
Sewer Trench, Framwellgate	1.10
Van Mildert College	1.01
Electricity sub-station Ferryhill	1.02
Bowburn	0.98
Belmont	1.14

Upper Tees Clay

Portrack Brick Pit	0.40
Wynyard Hall	0.15
Brierton Sand Pit	0.28
Stob Cross	0.23
Middlefield Farm	0.31
Carlton	0.41
Gilly Flat	0.13
Low Middlefield	0.17
Whitehouse Farm	0.28
Sedgefield Road Wolviston	0.30
Redmarshall	0.30

Scandinavian Drift

0.05

2. Upper Till.

The Upper Till possesses a scatter of coal content values from 0.1 to 0.7% , although a marked concentration of values in the lower ranges is noted.

3. Upper Tees Clay.

The coal content of the samples of the Upper Tees Clay is always below 0.5% , and as a group forms the lowest results found in Eastern Durham.

4. Upper Wear Clay.

Very high coal contents are noted in the Upper Wear Clay, and are the highest values for a single group in the area. These high values pose something of a problem as throughout its outcrop the Upper Wear Clay is separated from Coal Measures parent material by thicknesses of other glacial deposits. Two possibilities seem to explain these high coal contents. The first is that the Upper Wear Clay was derived from sand deposits in which the coal had already been concentrated by the action of running water. Secondly that the environment of deposition of the Upper Wear Clay concentrated coal by a process of the differential sorting of material. The fact that many of the exposures of the Upper Wear Clay often contained quantities of large sized coal material strongly suggested the latter assumption.

5. Scandinavian Drift.

A coal content of 0.05% is recorded for the analysis of the Scandinavian Drift. However microscopic analysis of the recovered material revealed that no coal is present, and that only peat fragments and ostracods are to be found.

Statistical analysis of the coal contents (data from Fig. 36) by analysis of variance indicated similar results to those obtained from calcium carbonate analysis. In all cases a null hypothesis was postulated that in the groups under examination all sample values were drawn from a single population.

A. Comparison of the sample values of the six main clay types. (data from Fig. 36) The following results were obtained.

$$\text{Sample F value} = 12.45$$

$$\text{Table F value, } F_{5 \ 89(.01)} = 3.20$$

Therefore the null hypothesis is rejected and the sample values are regarded as having been obtained from more than 1 population.

B. Comparison of the sample values of the three divisions of the Lower Till. (data from Fig. 36) The following results were obtained.

$$\text{Sample F value} = 8.53$$

$$\text{Table F value, } F_{2 \ 49(.01)} = 5.00$$

Therefore the null hypothesis is rejected and the sample values are regarded as having been obtained from more than 1 population.

C. Comparison of sample values of the Upper Till and the Upper Tees Clay. (data from Fig. 36) The following results were obtained.

$$\text{Sample F value} = 4.04$$

$$\text{Table F value, } F_{1 \ 33(.01)} = 7.30$$

Therefore the null hypothesis is retained and the sample values are regarded as having been obtained from the same population.

D. Comparison of sample values of the Lower Till of the Wear Lowlands and the Upper Wear Clay. (data from Fig. 36) The following results were obtained.

$$\text{Sample F value} = 0.605$$

$$\text{Table F value, } F_{1 \ 13(.01)} = 8.68$$

Therefore the null hypothesis is retained and the sample values are regarded as having been obtained from the same population.

E. Comparison of sample values of the Lower Till of the Coastal Region and the Upper Till. (data from Fig. 36) The following results were obtained.

$$\text{Sample F value} = 3.058$$

$$\text{Table F value, } F_{1 \ 44(.01)} = 7.09$$

Therefore the null hypothesis is retained and the sample values are regarded as having been obtained from the same population.

The analysis of the coal contents of the different clays shows a similar general pattern to the results of calcium carbonate analysis. In both cases significant differences are noted between the three divisions of the Lower Till, and in both cases similarities are noted between the Upper Till and the Upper Tees Clay, and between the Lower Till of the Wear Lowlands and the Upper Wear Clay. However with the coal content analysis, in contrast to the calcium carbonate analysis no difference is noted at the 1% level of significance between the sample values of the Upper Till and the Lower Till of the Coastal Region.

Therefore using different laboratory techniques, to measure different properties of the clays of Eastern Durham, it is found that statistical analysis of the sample values provides extremely similar results.

d. Comparison with other areas.

The comparison of the pH values, calcium carbonate contents, and coal contents of the Durham stony clays with comparable deposits elsewhere proved difficult owing to the lack of available published information. Holderness is obviously the area where comparison with the Durham clays would yield the most interesting results. Fortunately in this area the till deposits have been the subject of a PhD thesis by Catt. J.A. (1963), and in the course of his work calcium carbonate contents of the four tills of the area were obtained.

After Catt J.A.

<u>Till sheet</u>	<u>Calcium carbonate content</u>
Hessle	10% (4 unweathered values)
Purple	15 to 20% (7 values)
Drab	20 to 25% (13 values)
Basement	up to 10% (8 values)

As these carbonate contents were obtained by a differing method from that of the present author, it was decided to collect 6 samples from each of the till sheets of Holderness and subject them to the type of analysis used on the Eastern Durham Clays.

The results are as follows :-

<u>Till sheet</u>	<u>pH values</u>	<u>Calcium carbonate content</u>
Hessle	8.2 to 8.5	9 to 13%
Purple	8.0 to 8.3	12 to 16%
Drab	8.0 to 8.4	17 to 22%
Basement	8.0 to 8.3	6 to 9%

The pH values are high and extremely similar to those found in the Durham stony clays.

The carbonate contents determined by the present author give slightly lower results than those obtained by Catt J.A., but the relative amounts found in the till sheets remain the same.

The detailed results obtained by Catt are as follows. Calcium carbonate figures in percent.

Till sheet

Hessle	10.95,	7.71,	8.75,	7.22.			
Purple	16.71,	21.97,	15.15,	16.80,	19.11,	18.23,	15.39.
Drab	13.69,	23.09,	21.40,	21.22,	23.22,	23.63,	20.02,
	21.13,	24.80,	22.33,	23.74,	18.30.		
Basement	9.30,	10.20,	8.11,	8.17,	5.12,	4.62,	2.38,
	1.17.						

The detailed results of pH analysis and calcium carbonate analysis by the present author are as follows.

pH values

Till sheet

Hessle	8.2,	8.4,	8.4,	8.5,	8.2,	8.4.
Purple	8.0,	8.1,	8.0,	8.0,	8.3,	8.3.
Drab	8.4,	8.4,	8.2,	8.0,	8.1,	8.1.
Basement	8.0,	8.0,	8.3,	8.3,	8.2,	8.1.

Calcium carbonate contents in percent.

Till sheet

Hessle	9.1,	11.6,	11.8,	9.5,	10.2,	12.7.
Purple	12.4,	14.8,	16.1,	15.8,	14.6,	13.2.
Drab	23.2,	18.6,	17.2,	20.1,	22.1,	19.9.
Basement	6.3,	7.1,	7.5,	8.8,	6.2,	6.5.

The comparison of absolute values of carbonate content can be a difficult task, because as the author has already shown (Chapter 6 and this Chapter) such characteristics change fairly rapidly in short distances as new lithological boundaries are crossed. As a result of this it becomes meaningless to give an average figure for a single clay sheet over a large area. It is however feasible to split an area into provinces where carbonate contents are reasonably uniform, although of course changes are still occurring. For example in Durham the Lower Till can be divided into three main zones, although it has already been shown that because of lithological evolution these values are statistically drawn from different populations. Calcium carbonate content

Lower Till of the Wear Lowlands	0 to 3%
Lower Till of the Magnesian Limestone Plateau	1 to 15%
Lower Till of the coastal area (coastal exposures)	10 to 40%

Because of such facts it is impossible to compare any values obtained in County Durham with those from Holderness on anything but a qualitative basis. However certain interesting relationships can be seen between the two areas in terms of average values for the individual deposits.

Figures indicate calcium carbonate content (approximate ranges).

<u>Eastern Durham</u>		<u>Holderness</u>	
Upper Till	8 to 16%	Hessle Till	9 to 13%
		Purple Till	12 to 16%
Lower Till	10 to 40% (coastal exposures)	Drab Till	17 to 22%
		Basement Till	6 to 9%
Scandinavian Drift	c. 9%		

The basal clay in both areas, although resting on highly calcareous formations (Magnesian Limestone in Durham, Chalk in Holderness) possesses calcium carbonate contents of less than 10%.

Overlying this and representing the basal English drift in both areas is a clay with the highest calcium carbonate content found in the succession. (The Lower Till of Durham, and the Drab Till of Holderness).

Forming the topmost member of the succession is a clay with a moderately high carbonate content, but one which appears to show very little change in a southerly journey of more than 50 miles.

The Purple Till of Holderness does not appear to be present in the Eastern Durham area.

A comparison of coal contents between the Durham and Holderness samples also shows a similar general pattern.

Figures indicated coal contents in percent.

<u>Eastern Durham</u>		<u>Holderness</u>	
Upper Till	0.1 to 0.6	Hessle Till	0.1 to 0.2
		Purple Till	0.06 to 0.1
Lower Till		Drab Till	0.2 to 0.4
(Coastal)	0.3 to 1.2	Basement Till	0.04 to 0.08
Scandinavian			
Drift	0.05		

In both cases the basal clays of Scandinavian origin give the lowest values. It has already been mentioned that the Scandinavian Drift of the Durham coast contains no coal when viewed under a microscope, and that the material recovered by the carbon tetrachloride flotation process consists of peat remains and ostracods. The same is generally true for the material recovered from the Basement Till of Holderness, although in some cases true coal does appear to be present.

Of all the Holderness clays the Drab Till gives the highest coal content with values more than double those of the other clays. Similarly in Durham it is the Lower Till which possesses the highest coal contents.

The Hessle Till has a low coal content of between 0.1 to 0.2%. This is lower than the Upper Till of Durham, but well within the range one would expect allowing for dilution by newly eroded material.

The Purple Till possesses a very low coal content of less than 0.1% in all cases.

These results give further evidence for the view that the Upper Till of the Durham coast is the lateral equivalent of the Hessle Till; the Lower Till of the Drab Till; and the Scandinavian Drift of the Basement Till. (Catt J.A. and Penny L.F. 1966)

Conclusions

These studies of pH values, calcium carbonate contents, and coal contents indicate that such data can be of use for correlation purposes between till sheets. At the same time the study emphasises that the relationships which exist between different criteria, such as pH and calcium carbonate contents are still not fully understood.

Chapter 8

PARTICLE SIZE ANALYSISIntroduction.

The mechanical analysis, or particle size analysis of deposits is playing an increasing role in glaciological studies, and has been widely employed by American workers for correlation and weathering studies. For correlation and analytical purposes it has been successfully used by Udden J.A. (1914); Krumbein W.C. (1933); and Shepps V.C. (1953, 1958), who laid the groundwork for such studies. (Also Dreimanis A. and Reavely G.H. (1953); Kaiser R.F. (1962); Knox K.S. (1953); Kruger F.C. (1937); MacIntock P (1937); Murray B.C. (1953); White G.W. and Shepps V.C. (1952).) Other workers have used grain size analysis to study weathering characteristics on the assumption that weathering results in grain size reduction and clay enrichment in the lower parts of the profile. (Gravenor C.P. 1954; Goldthwaite R.P. 1959; Gooding A.M., Thorp J. and Gamble E. 1959; Gooding A.M. and Gamble E. 1960). Still others have dealt with the interpretation of particle size analysis results. (Doeglas D.J. 1946; Freidman G.M. 1962; Masom C.C. and Folk R.L. 1958; Spencer D.W. 1963).

In the British Isles the mechanical analysis of glacial deposits has lagged well behind comparable studies in North America, with the result that the majority of data which exists in Great Britain on the particle size distributions of glacial deposits, has been collected almost incidentally by the Soil Surveys of Great Britain, and by various civil engineering concerns.

Certain exceptions do however stand out. As early as 1916 Boswell P.G.H. attempted particle size analysis of the tills of East Anglia, but no research following this early work was carried out. In 1948 Bisat W.S. calculated the percentages of sand residues in the tills of Holderness, and indicated the possibilities that this type of work might have. Work by Catt J.H. (1963) extended Bisat's work by studying the sand and fine gravel residues of the Holderness deposits, but no study was made of the clay and silt contents. In Ireland Farrington A. (1944) has used the gravel content of till sheets as a method of differentiation between deposits.

METHODS AND PROBLEMS OF ANALYSIS.

To partially overcome the lack of knowledge on particle size distribution within glacial deposits the author undertook detailed analysis of the stony clays of Eastern Durham.

The greatest problem in dealing with glacial deposits is the actual sampling technique and procedure. It is essential to obtain a sample large enough to be representative of the deposit as a whole, and yet at the same time to be of manageable proportions. A glacial till presents a sampling problem of the greatest magnitude, owing to the immense diversity of particle sizes found within it, from clay minerals less than 1 micron to boulders more than 5 feet in diameter. The accuracy of sampling techniques depends on each grade size under consideration being adequately represented within the sample analysed. It is therefore the sample size which becomes the key single factor. The British Standard Institution has calculated the size of sample required to express the true particle size character of any deposit being studied (B.S. 1377). It is concluded that where stones of up to 1' in diameter are a common constituent of a deposit, a sample size of

approximately 1 ton would be required. Such quantities are beyond the capabilities of most laboratories, and it is obvious therefore that only a portion of the till deposit can be adequately studied at a large number of sites. Where stones of more than $2\frac{1}{2}$ inches make up a sizeable proportion of the deposit, a sample of at least 1 cwt is required for analysis. For material of $\frac{3}{4}$ " and less a sample of only 2 kilograms is required. Bearing this in mind it was finally decided to study only the particle size distribution up to the size of medium gravel (20 mm) as facilities were not available for collecting samples of up to 1 cwt in weight.

The field sampling consisted of obtaining a composite sample of 10 kilograms, made up by combining 4 discrete samples of c. $2\frac{1}{2}$ kilograms each from a single lithological horizon. (Zones 4 or 5 of a weathering profile Leighton M.M. and MacIntock P. 1930 or from the C. horizon of soil science nomenclature). Such samples were carefully obtained to avoid crushing of the smaller and more delicate particles.

In the laboratory the material was broken down by hand, and passed through a $\frac{3}{4}$ " British Standard sieve and dried. From this material, a representative sample of 2000 grams was obtained by quartering and this was used for the coarse particle size analysis. A further 1000 grams of material was gently broken up in a mortar with a rubber tipped pestle and passed through a No. 8 B.S. sieve. This material was used for silt and clay, and chemical analysis.

The coarse particle size analysis was carried out using wet sieving methods and the finer analysis using hydrometer analysis (Appendix 7). Both these methods of analysis were extremely time consuming.

In all, a size range from 20 mm to .001 mm was covered, with the result that only the extremes of the particle size distribution were not adequately represented.

RESULTS :

Because so little published work exists concerning the mechanical analysis of glacial tills, there is as yet no generally accepted method of presentation and analysis, nor indeed any agreement as to the particle size categories for gravel, sand, silt and clay. In this work the present author has used categories as recommended by the British Standard association. (B.S. 1377, 1961).

They are :-

Medium Gravel	20mm - 6mm
Fine Gravel	6mm - 2.0mm
Coarse Sand	2.0mm - 0.6mm
Medium Sand	0.6mm - 0.2mm
Fine Sand	0.2mm - 0.06mm
Coarse Silt	0.06mm - 0.02mm
Medium Silt	0.02mm - 0.006mm
Fine Silt	0.006mm - 0.002mm
Clay	less than .002mm

SAND, SILT AND CLAY PERCENTAGES.

In the literature glacial till is generally described as an unsorted deposit formed by glacial action. While agreeing with the fact that till material shows a great variation in grain size, the author has always been impressed by the marked visual similarities over long distances shown by the till deposits of Northern England, and also by the basic similarities of tills considered to be the products of different glaciations.

The first task of the author therefore was to assess the similarity or otherwise between the six main stony clays which have at some time or another been considered to represent glacial tills in Eastern Durham.

The results of 90 analyses of these clays (Fig.37) were plotted in the form of three histograms showing percentages of sand, silt and clay respectively. (Fig.38). Each distribution shows a marked approximation to a normal distribution, suggesting that at least in Eastern Durham the clays do show a noticeable similarity, and a tendency for the ingredients of the till material, sand, silt, and clay, to be found in characteristic proportions and not be purely randomly distributed. In East Durham at least "stony clays" appear to be a characteristic deposit in their own right, with the sand, silt and clay proportions being a diagnostic property determined by the processes of deposition and/or the character of the parent material, from which the stony clays are derived.

The sand sized material shows the greatest variation with individual figures ranging from 5 to 55%. There is however a marked concentration of values between 20 and 40%, with more than 50% of the total number of observations.

The distribution of the silt sized fraction shows the most marked concentration of all these groups. Absolute values vary from 28 to 70%, but within the single modal category of 40 to 45%, 33% of the observations are found, while between 35 and 55%, 75% of the observations are noted.

In the clay size fraction variations between 10 and 55% are seen, with a modal category of between 25 and 30%. Between 20 and 30% clay content, more than 40% of the observations are found.

Fig. 37

Particle size Analysis

Sand, silt and clay contents.

	Percentages		
	Sand	Silt	Clay
Lower Till of the Wear Lowlands			
Finchale Priory	38.8	42.2	19.0
Windy Nook Quarry	26.7	40.8	32.5
Eighton Banks Quarry	40.7	36.8	22.5
Brancepeth Beck	22.7	49.3	28.0
Biddick Burn near Birtley	45.8	33.3	21.0
Crime Rigg Quarry	35.2	40.8	24.0
Spennymoor Industrial Estate	24.7	48.3	27.0
Low Grange Bowburn	34.4	46.6	18.0
Building site Houghton-le-Spring	38.0	39.5	22.5
Lower Till of the Magnesian Limestone Plateau			
Middridge Quarry	34.4	37.6	28.0
Aycliffe Quarry (lower Grey Clay)	38.3	35.2	26.5
(Middle Brown Clay)	38.7	40.8	20.5
Houghton-le-Spring	37.1	37.4	25.5
Eppleton	30.5	49.5	20.0
Thrislington	25.8	40.2	25.0
Coxhoe	27.2	42.3	30.5
Bishop Middleham	22.0	55.5	22.5
Trimdon Colliery	11.7	65.8	22.5
Cope Hill	23.0	51.0	26.0
Wood Quarry Wingate	27.9	44.6	27.5
Wingate Quarry D	30.5	42.0	27.5
Westmoor Farm	35.4	43.4	21.2
Sherburn Sand Pit	33.7	40.3	26.0
West Cornforth Quarry	40.6	38.2	21.2
Pit Fall Warden Law	30.8	44.1	25.1
High Moorsley	45.6	41.4	13.0
South Hetton	33.0	46.0	21.0
Wingate Quarry A	25.5	42.0	32.5
Fulwell	32.6	39.4	28.0
Tuthill	28.8	48.2	23.0
Holy Cross	31.5	43.0	25.5

Lower Till of the Coastal Area

Blackhall Colliery	27.5	50.5	22.0
Salterfen Rocks	29.9	51.2	19.0
Bedlam Gill	29.2	41.0	24.0
Warren House Gill	36.1	41.4	22.2
Quarry near Hesleden	28.0	44.5	27.5
Dalton Piercy	36.7	42.3	20.0
Castle Eden Dene	30.8	49.2	20.0
Peterlee	42.4	39.1	19.5
Castle Eden Village	37.7	38.8	23.5
South Hylton	35.3	39.1	19.5
Chourdon Point	32.0	50.0	18.0
A 19 section Castle Eden Dene	44.1	40.4	14.5
Shotton Colliery	42.3	40.2	17.5
Shotton Colliery Brick Pit	44.1	41.9	14.0
Hawthorn Quarry	43.8	43.7	12.5
Seaham Harbour	33.1	46.4	30.5
Dalton-le-Dale	35.1	41.9	23.0
Peterlee Petrol Station	48.3	37.5	14.0
Peterlee Acre Rigg	32.2	50.1	17.7

Upper Till

Portrack Brick Pit	25.9	44.1	30.0
Cerebros Salt Works	37.1	41.9	21.0
Hawthorn Quarry	20.1	45.4	34.5
Whelly Hill Quarry	43.3	37.7	19.0
Crimdon Dene	39.7	42.8	17.5
Naisberry Quarry	26.4	33.2	40.2
North of Castle Eden Dene	29.1	45.4	25.5
Peterlee Main Drain	29.0	47.4	23.6
Blackhall Rocks	31.6	43.9	24.5
Foxholes	27.6	39.9	32.5
Hazel Dene	27.5	42.5	30.0
Sheraton Hill Farm	35.4	45.6	19.0
Seaton Carew	22.7	52.3	25.0
Hart	29.6	51.4	19.0
South Hylton Quarry	34.5	33.5	32.0
Low Stotfield Farm	28.0	42.7	29.3
Hilltop east of Sheraton Hill Farm	28.5	43.5	28.0
Hesleden Dene	43.1	39.9	17.0

Upper Till (continued) :

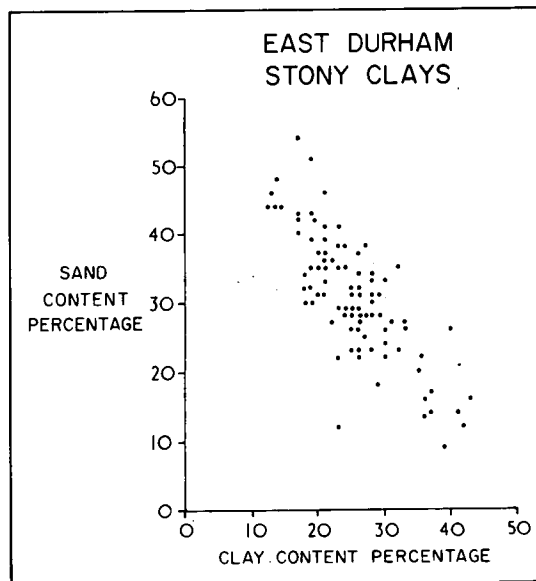
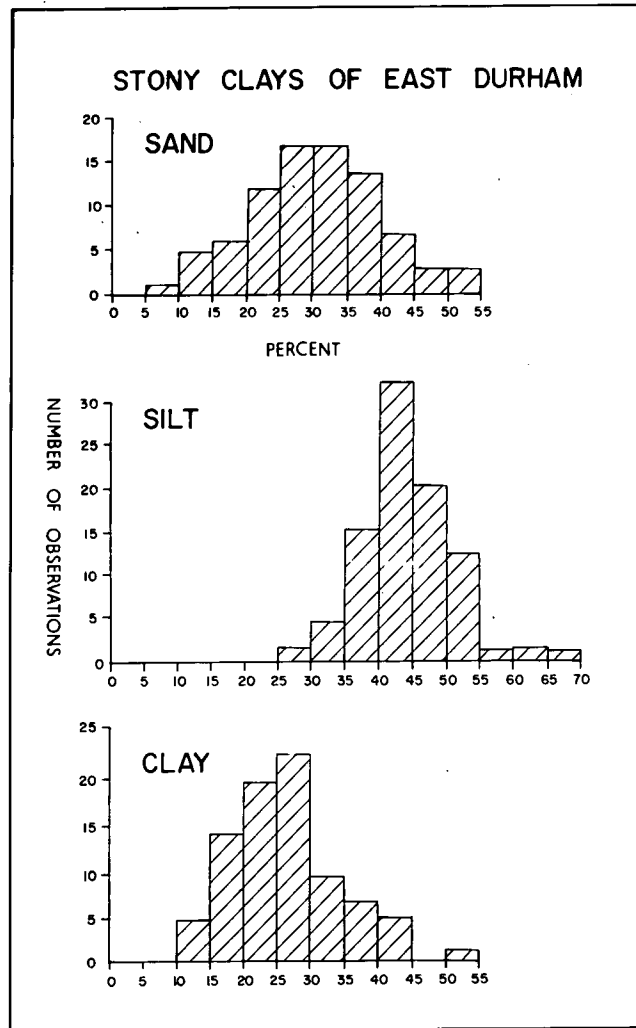
Wolviston	51.0	30.0	19.0
Low Burn Toft	31.2	40.3	28.5
South of Hart Road	54.1	28.9	17.0

Upper Wear Clay

Usworth Hall	24.0	46.3	29.7
High Butterby Farm	22.2	47.8	30.0
Railway Cutting north of Durham	23.2	44.5	32.3
Sewer Trench Framwellgate	26.2	46.9	26.5
Van Mildert College	22.5	51.0	26.5
Electricity sub station Ferryhill	27.6	24 (35.9)	26.5
Belmont	36.2	43.7	21.1
Bowburn	30.5	41.6	27.9

Upper Tees Clay

Portrack Brick Pit	14.5	48.5	37.0
Wynyard Hall	17.7	50.0	29.0
Brierton Sand Pit	16.4	48.2	35.8
Stob Cross	12.2	45.8	42.0
Middlefield Farm	17.6	45.9	36.5
Carlton	31.5	42.5	26.0
Gilly Flat	8.6	52.4	39.0
Low Middlefield	15.7	39.8	42.5
Whitehouse Farm	22.5	42.0	35.5
Redmarshall	13.6	49.9	36.5
Sedgefield Road Wolviston	14.8	44.2	41.0



From the above it can be deduced that there is a "typical" stony clay for Eastern Durham with a sand content between 30-35%, silt content, 40-45%, and clay content 25-30%.

For comparative purposes four other tills, from parts of northern England, three from Holderness, (the Drab, Purple, and Hessle tills) and a till from the West Riding of Yorkshire were subjected to analysis. These samples give figures very similar to the results obtained from the Eastern Durham area, and indicate the basic similarities between tills in northern England.

<u>Till</u>	<u>Sand</u>	<u>Silt</u>	<u>Clay</u>
Leeds Till (West Riding)	33	46	21
Hessle Till	23	51	26
Purple Till	20	50	30
Drab Till	35	40	25

The marked concentration of the silt values into a single 5% category as seen in Fig.38 suggested the possibility that there might exist some kind of linear relationship between the sand and clay values for the deposits under consideration. When the sand content is plotted against the clay content it is found that an inverse linear relationship between the two constituents is to be seen for the Eastern Durham samples. (Fig.38).

The strength of the relationship shown in Fig.38 was assessed statistically and it was found that the correlation coefficient for the sand and clay values was -0.787 (For the 90 samples examined this correlation coefficient is significant at the 0.001 level). However the data was derived from a closed number system. Under such conditions

correlations among closed data have some restraints upon them, which are properties of the closed number system itself and not of the objects being measured. (Krumbein W.C. and Graybill F.A. 1965). For such reasons this correlation value must be viewed with caution.

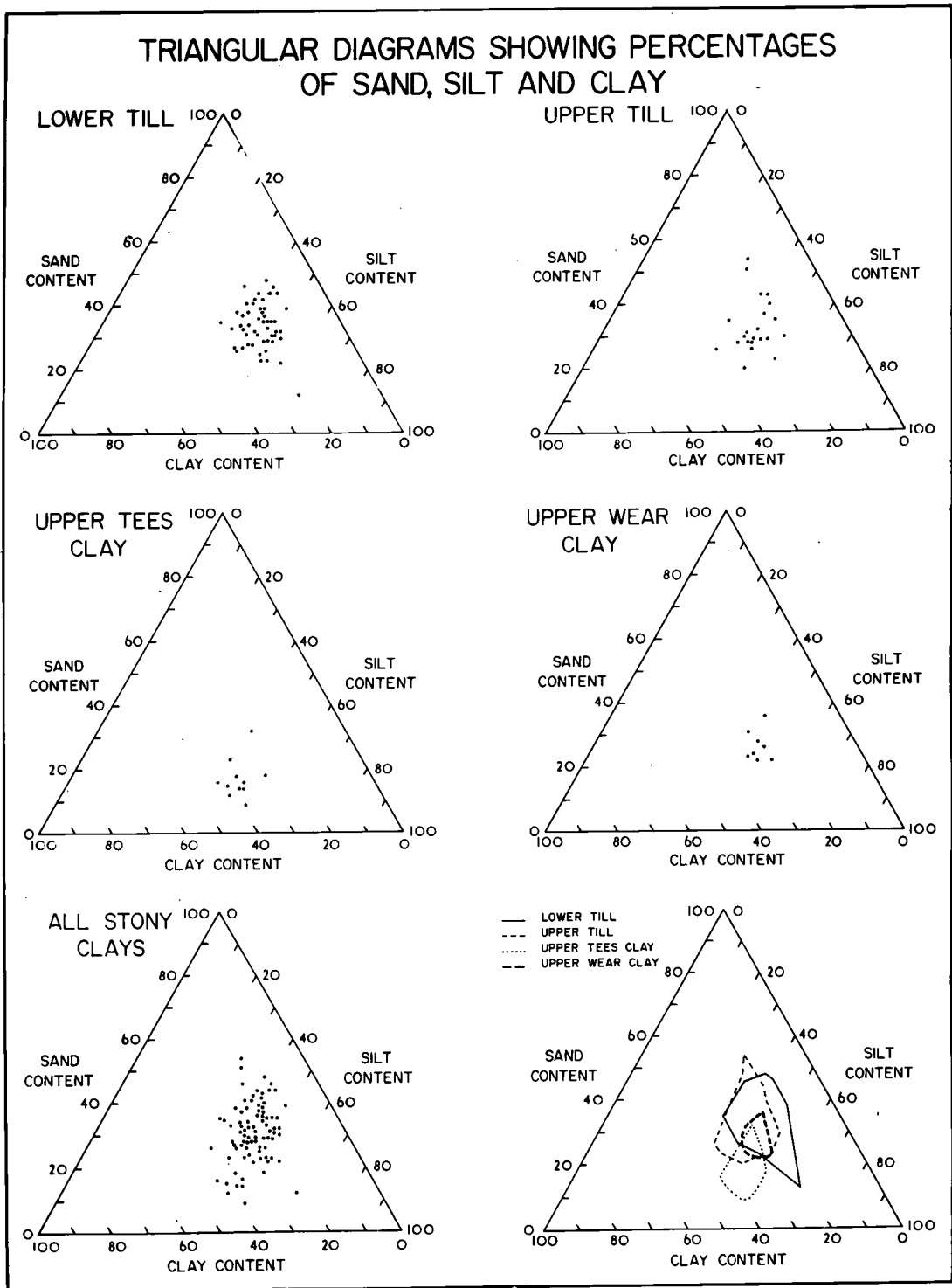
Of the two values of sand and clay content it is far easier in the laboratory to determine the sand value than the clay value. Therefore it was decided to calculate a regression equation which would allow the clay content to be estimated for a given sand content, for the Eastern Durham stony clays. Confidence limits were also calculated so that predictions could be made with a 95% certainty. The following results were obtained. Figures in percent.

Clay content = $43.43 - (0.589 \times \text{sand content})$ plus or minus 5.18 with a 95% probability.

Using this formula it is found that clay values of the tills from Holderness and the West Riding fall within the prescribed values. Lack of comparable published data makes it impossible to assess the value of this formula for till deposits elsewhere in the British Isles.

V.C. Shepps (1953) demonstrated that tills of differing ages could be distinguished in north-east U.S.A. by the plotting of sand, silt and clay contents on a triangular diagram. Working on the Tazewell, Early and Late Cary deposits he was able to show that the results from these three till sheets fall into 3 distinct and separate groups. His conclusion was that from a single particle size determination one could predict with complete certainty from which till sheet the sample had been obtained.

A similar attempt was made to distinguish between the clay deposits of Durham by this method, and to see if it was possible to separate the Upper Clays of the Wear, and Tees from the Upper Till and the Lower Till. (Fig.39)



Only clays which were considered unweathered and unaffected by solifluction and periglacial activity are included, as it was felt that either of these processes might have effected the sorting of material. 50 samples are used for the Lower Till and 21 samples for the Upper Till of the coast. The results indicate that these two clays have a virtually identical particle size distribution and so cannot be distinguished using this method. (Fig.39) Stratigraphically however they can clearly be seen to be distinct in the coastal area, and stone orientation and carbonate analysis indicate considerable differences between the two clays.

There seems to be 3 possible reasons to account for the similarity between these clays. Firstly that they have been formed by similar processes, namely as a glacial till; secondly that they are the same clay in differing stratigraphical positions; and thirdly that they are derived dominantly from the same parent material.

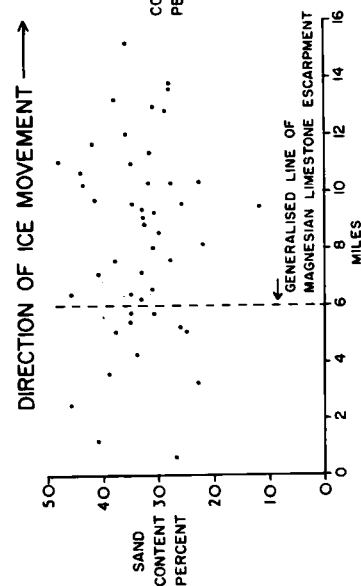
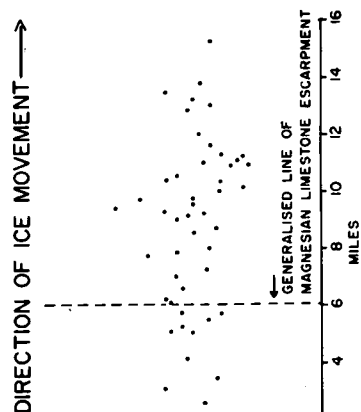
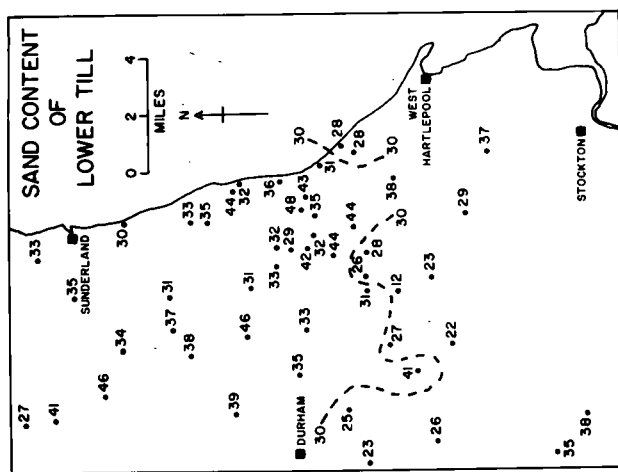
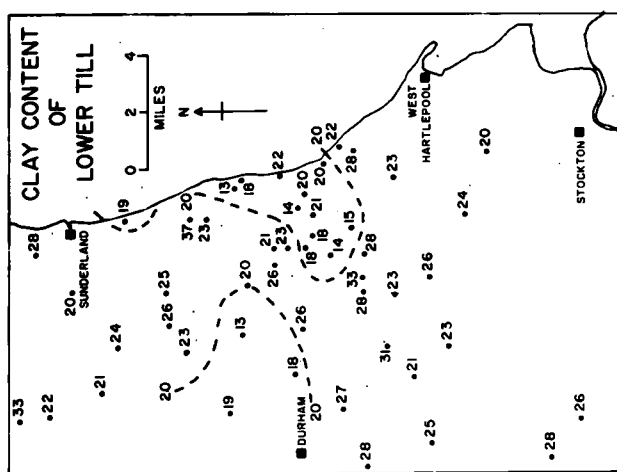
Two of these conditions seem to have been met. Firstly both the Upper and the Lower Till are considered to be undoubted glacial tills, and therefore the product of a sub-glacial environment. Secondly both clays over a major portion of their travel have been moving over Carboniferous rocks of Coal Measure age. The marked differences in orientation patterns between the two deposits would suggest that the clays were not the product of the same ice movement. Which of these criteria has had a dominant effect on the composition^{sl} of the clays is unknown.

As with the Upper Till of the coast, the Upper Clay of the Wear lowlands shows a complete overlap in terms of sand, silt and clay contents, with the Lower Till (Fig.39). In this case the parent material is similar; the processes of deposition are probably similar and the possibility even exists that the material is identical.

In the case of the Upper Tees clay a marked distinction is to be seen between this deposit and all the other clays of Eastern Durham, in terms of particle size distribution. The close similarity in stone lithology and carbonate content between the Upper Tees Clay and the Upper Till of the coastal area has already been demonstrated, and used to suggest that the Tees clay has been largely derived from the Upper Till of the coast. If this is the case it suggests that any particle size differences between the two deposits might well be due to differences in processes of deposition. The possibility does seem to exist that the Upper Tees Clay although considered in the original mapping of the Geological Survey as a glacial till, might not in fact be so, and may represent some kind of mass movement deposit. As a deposit the Upper Tees Clay possesses lower sand percentages (i.e. less than 20%) and higher clay contents (i.e. more than 30%) than the other Durham stony clays. This fact may possibly be due to the sorting action of running water during the process of deposition.

Using data obtained from the Lower Till of Eastern Durham (data from Fig.37) an attempt was made to discover if it were possible to detect changes in the sand and clay content of the till sheet over large areas governed perhaps by lithological differences within the parent material over which the ice sheet was moving. The results of this study are shown in Fig.40, and indicate that in Eastern Durham, despite considerable changes in the lithological make up of this till sheet (see Chapter 6); only very minor changes are noted in the particle size distribution, of the till matrix. From this the sand and clay contents are seen to vary in an apparently random spatial nature.

Figure 40.



This data was projected onto a single plane parallel to the direction of ice movement (Fig.40) to discover if it were possible to discern changes in the sand and clay content of the Lower Till in a down ice direction. The diagram reveals that no such changes take place in a down ice direction in terms of sand and clay content, even though a marked lithological change was noted in the included pebble types after the crossing of the Magnesian Limestone escarpment (see Fig.28 Chapter 6). One is therefore led to conclude that a lithological change in the parent material over which the ice sheet is moving has little immediate effect in this specific case on the particle size composition of the till sheet deposited by the ice. It is however worth pointing out that the Magnesian Limestone is a sedimentary rock type of chemical origin, and that other rock types such as sandstone or shales may give rise to different results under similar conditions.

2. TOTAL PARTICLE SIZE ANALYSIS

Introduction.

The detailed sieving and hydrometer analysis allowed a total of 30 points to be plotted on a particle size distribution curve for each sample, between the grain sizes of 20mm - 0.001mm.

The values of the individual point determinations are set out below. (In millimetres) 20.0, 13.0, 9.7, 6.0, 4.7, 3.2, 2.0, 1.2, 0.6, 0.4, 0.3, 0.2, 0.15, 0.10, 0.075, 0.062, 0.046, 0.038, 0.034, 0.027, 0.021, 0.016, 0.013, 0.0090, 0.0066, 0.0048, 0.0033, 0.0022, 0.0014, 0.0010. The British Standards method of using cumulative frequency curves plotted on semi-logarithmic paper was employed for plotting the data. For detailed statistical examination instead of the millimetre scale a more comprehensive system based on phi units was used.

The phi units are found by conversion from the millimetre scale where phi is $-\log_2$ of the diameter in millimetres. This conversion means that one division of the commonly used Wentworth scale, is the equivalent of one unit on the phi scale. With the phi scale, the negative values of the phi units are the values coarser than 1 millimetre. As the phi unit increases the size of the particle decreases. The method has the advantage that small fractions are not required for the smaller particles and that for many of the common sediment sizes the results in terms of phi units are positive. (Fig.43). The use of the logarithmic scale also has the advantage pointed out by Inman D.L. 1952 that the size frequency curve of most sediments becomes more symmetrical when the diameter of the grains is plotted as a logarithm of the real value.

To comply with the already used British Standard presentation of particle size data the abscissa of the graph is used for the cumulative frequency with percentage finer decreasing downwards. Using arithmetic divisions for the abscissa a normal sediment is shown as an S shaped curve starting in the top right and trending to the bottom left of the graph.

Many workers have claimed that using this method the curve at the top and bottom of the graph becomes difficult to interpret. As the tails of the curve are of considerable importance in analysing the characteristics of the sediment it is important that percentage values at the extremes of the curve are plotted accurately. To this end it has been suggested that the data should be plotted on arithmetic probability paper, with the probability scale being used on the abscissa for plotting the percentage coarser values. This type of paper has the advantage that a normal distribution curve is a straight line when plotted on it. (King C.A.M. 1966).

Fig. 43

Conversion of millimetre scale to phi units

<u>millimetres</u>	<u>phi units</u>
256	- 8.0
128	- 7.0
64	- 6.0
32	- 5.0
16	- 4.0
8	- 3.0
4	- 2.0
2	- 1.0
1	0.0
0.5	1.0
0.25	2.0
0.125	3.0
0.063	4.0
0.031	5.0
0.016	6.0
0.0078	7.0
0.0039	8.0
0.0020	9.0
0.0010	10.0

It is however when one applies these techniques to a study of glacial tills that difficulties arise owing to the very great diversity in grain size shown by such deposits. In the first place one can never adequately sample a till deposit owing to the large volume and weight required, and secondly it is exceedingly difficult to study the finer particle size range within the deposit, and so determine the smallest size particle present.

The first problem is solved arbitrarily by studying and sampling only material of medium gravel size and below. This limits the size of the field sample required to 10 kilograms, which is manageable in most circumstances.

The second problem is more difficult to solve. Most fine analysis of sediments is carried out using sedimentary techniques based on Stoke's Law. The two main methods being hydrometer and pipette analysis. Both methods have disadvantages, but when used within the limitations set by the technique itself, provide satisfactory and reasonably comparable results when used in concentration of 6-24 grams/litre in the size range of 5-9 ϕ (Sternberg R.W. and Craiger J.S. 1961). The author throughout this work used the hydrometer method of analysis.

Sedimentation techniques are suitable for analysing material with a grain size variation of between 60 microns to 1 micron. Below 1 micron however Brownian motion develops in liquids, and the results obtained for material below this equivalent diameter size bear no relation to the percentages of material actually present.

All the cumulative frequency curves in this work are therefore terminated at an equivalent particle size diameter of one micron. Below one micron diameter centrifugal techniques of analysis have to be employed. The laboratory used by the author did not possess the necessary type of equipment for this type of analysis.

It was found however that in many of the tills more than 20 per cent of the sample lies below one micron in size. As within this size range the shape of the cumulative frequency curve was unknown it became impossible to utilise statistical techniques of analysis which require that the less than 5% finer fraction be known. This unfortunately eliminates a number of the proposed measures introduced by Macmammon R.B. 1962, which place importance on the extreme values of the cumulative frequency curve for estimating mean size and sorting. On the same grounds the use of the kurtosis measure, a measure of peakedness as defined by Inman D.L. 1952, and the use of probability paper is also eliminated.

The analysis and interpretation of cumulative frequency curves has always posed considerable problems. Since each curve is made up of so many observations (30 in each case) a visual comparison of the shapes of curves can only give subjective impressions of comparability. Nevertheless such visual comparison have been the basis of most of such work in the past (Catt J.A. 1963),

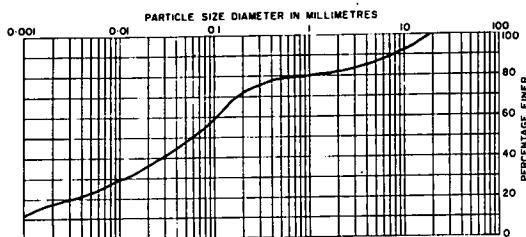
The only way this problem can be overcome is by the utilization of statistical techniques which allow the curves, or particle size distributions for each sample to be compared in terms of numerical values. By the use of standardised techniques this allows the comparison of deposits in different areas, collected and analysed by different workers.

The cumulative frequency curves for the six main clays of Eastern Durham are plotted in Fig.41 (For data see Fig.42). Some visual differences i.e. between the Upper Clay of the Tees, and the Lower Till of the coast are immediately apparent, but no quantitative, and what is perhaps more important no reproducible estimate of this difference can be attempted.

Figure 41.

LOWER TILL OF THE WEAR
LOWLANDS

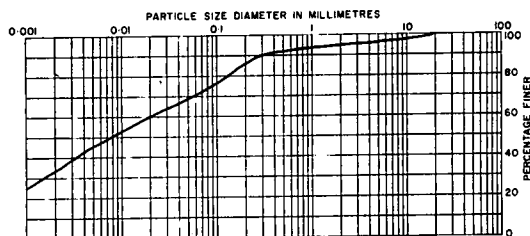
218



Finchale Priory

Mean = 3.83 phi

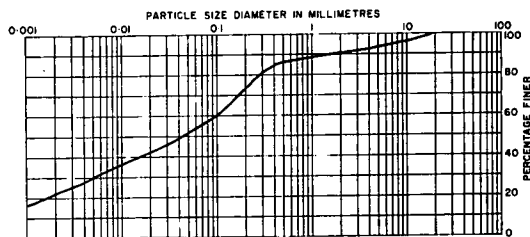
Sorting = 5.35 phi



Windy Nook Quarry

Mean = 7.13 phi

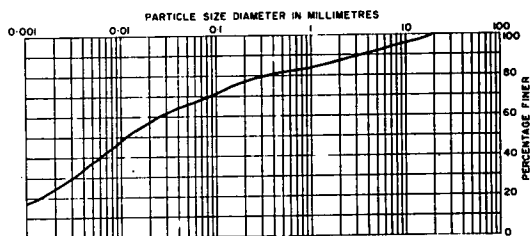
Sorting = 4.75 phi



Eighton Banks Quarry

Mean = 5.27 phi

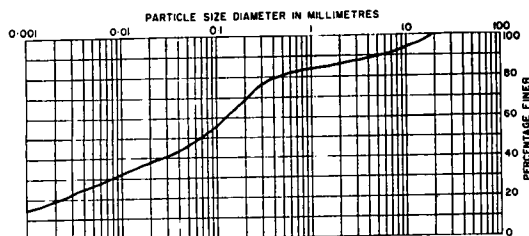
Sorting = 4.30 phi



Brancepeth Beck

Mean = 5.37 phi

Sorting = 4.90 phi

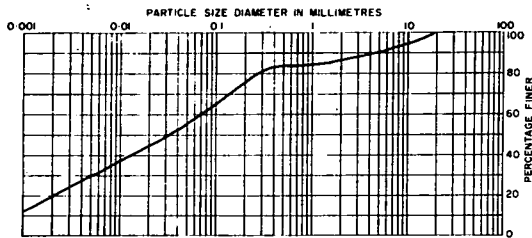


Biddick Burn

Mean = 4.47 phi

Sorting = 4.85 phi

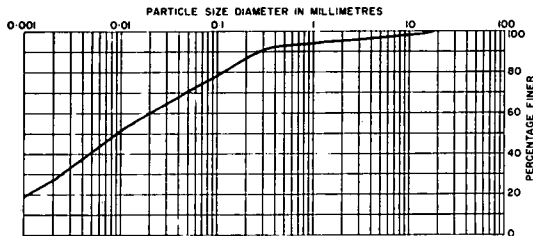
Figure 41.



Crime Rigg Quarry

Mean = 5.13 phi

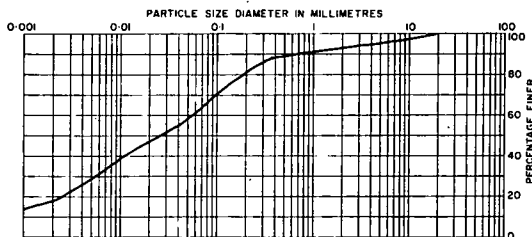
Sorting = 4.20 phi



Spennymoor Ind. Estate

Mean = 6.53 phi

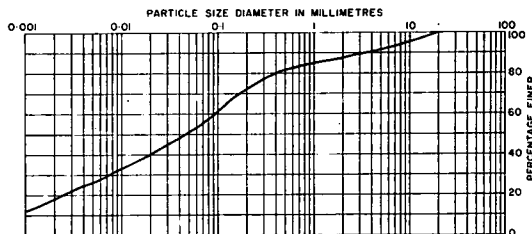
Sorting = 3.90 phi



Low Grange Bowburn

Mean = 5.53 phi

Sorting = 3.65 phi



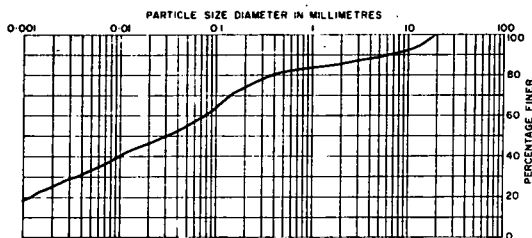
Building site Houghton-le-S.

Mean = 4.66 phi

Sorting = 4.75 phi

Figure 41.

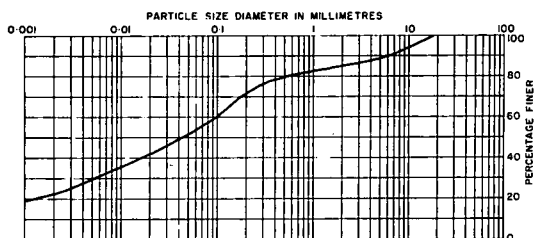
LOWER TILL OF THE MAGNESIAN LIME-
STONE PLATEAU 22



Middridge Quarry

Mean = 4.77 phi

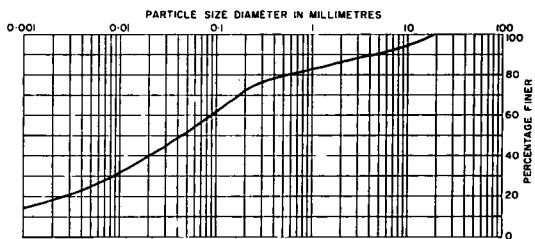
Sorting = 5.50 phi



Aycliffe Lower Grey Clay

Mean = 4.67 phi

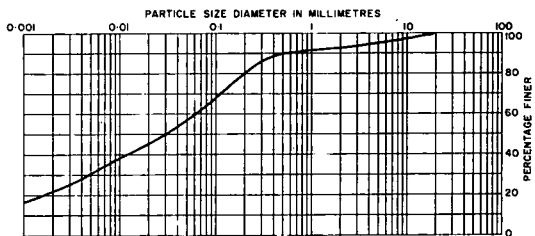
Sorting = 5.35 phi



Aycliffe Middle Brown Clay

Mean = 4.70 phi

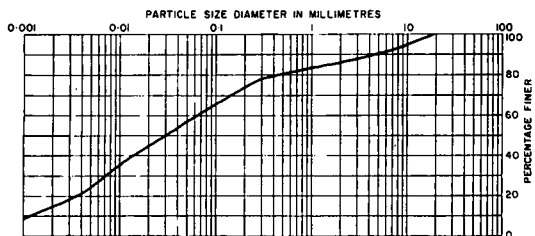
Sorting = 4.75 phi



Houghton-le-Spring

Mean = 5.57 phi

Sorting = 3.95 phi



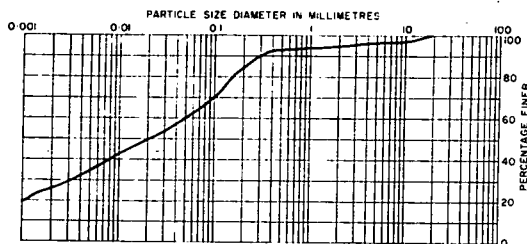
Eppleton

Mean = 4.36 phi

Sorting = 4.60 phi

Figure 41.

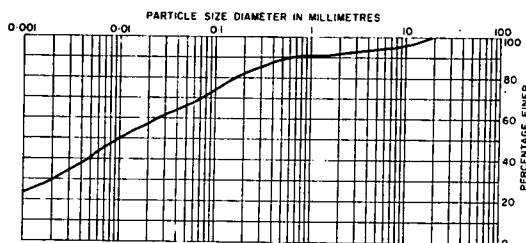
LOWER TILL OF THE MAGNESIAN
LIMESTONE PLATEAU



Thrislington

Mean = 6.20 phi

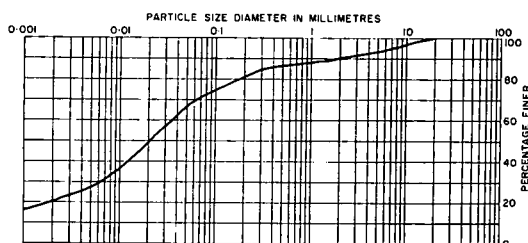
Sorting = 4.20 phi



Coxhoe

Mean = 6.50 phi

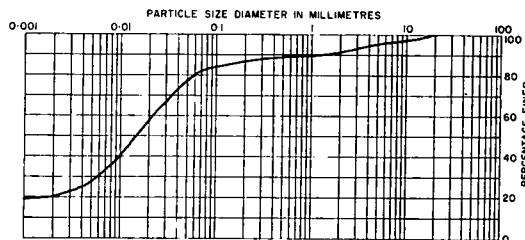
Sorting = 4.55 phi



Bishop Middleham

Mean = 5.70 phi

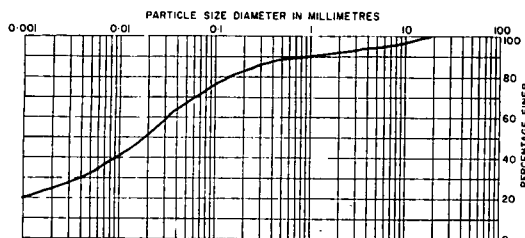
Sorting = 4.10 phi



Trimdon Grange

Mean = 6.73 phi

Sorting = 4.00 phi



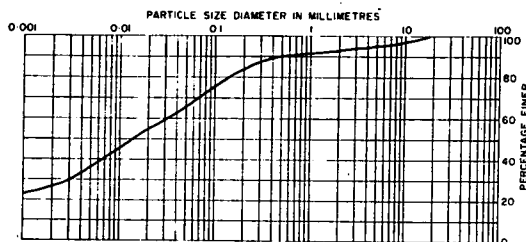
Cope Hill

Mean = 6.40 phi

Sorting = 4.55 phi

Figure 41.

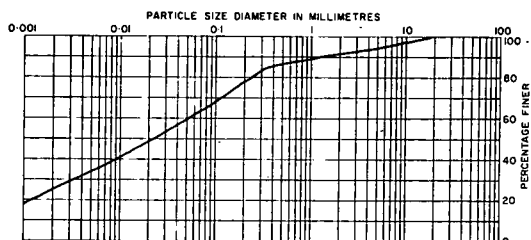
LOWER TILL OF THE MAGNESIAN
LIMESTONE PLATEAU



Wood Quarry Wingate

Mean = 6.73 phi

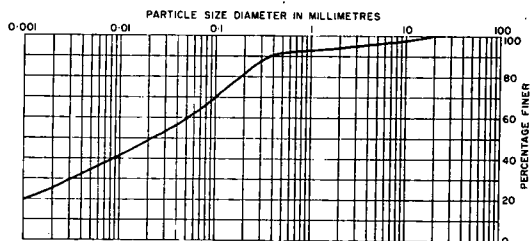
Sorting = 5.00 phi



Wingate Quarry D.

Mean = 5.83 phi

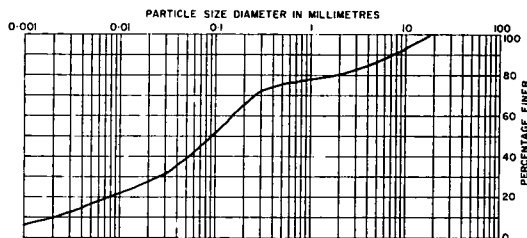
Sorting = 4.40 phi



Sherburn Sand Pit

Mean = 6.20 phi

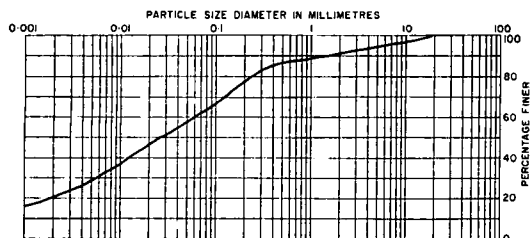
Sorting = 4.45 phi



High Moorsley

Mean = 3.10 phi

Sorting = 4.65 phi

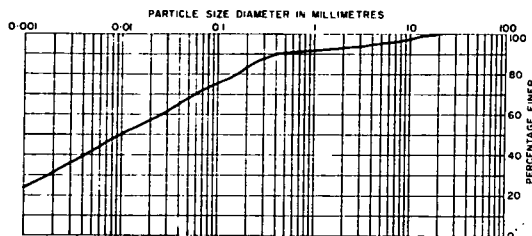


South Hetton

Mean = 5.53 phi

Sorting = 4.15 phi

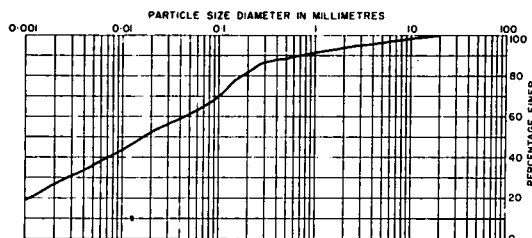
Figure 41.



Wingate Quarry A

Mean = 6.53 phi

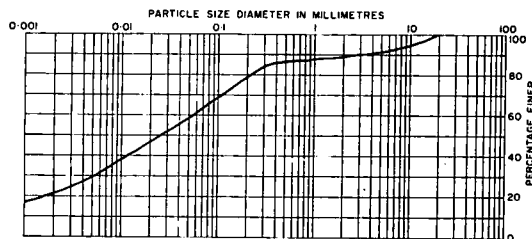
Sorting = 4.66 phi



Fulwell Quarry

Mean = 6.13 phi

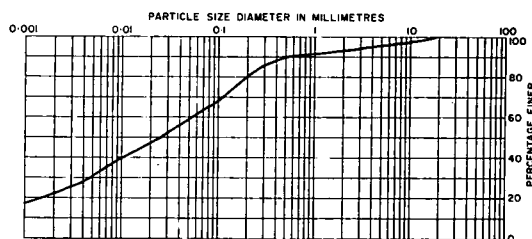
Sorting = 4.66 phi



Tuthill Quarry

Mean = 5.80 phi

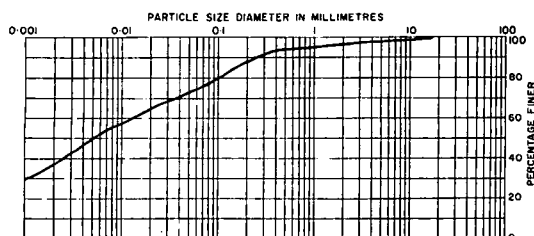
Sorting = 4.22 phi



Holy Cross

Mean = 5.70 phi

Sorting = 4.22 phi

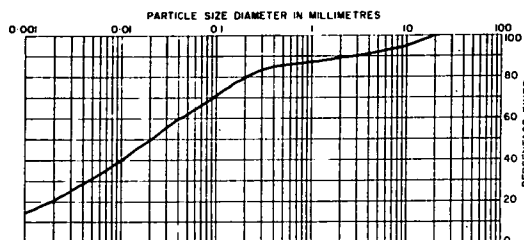


Bradbury

Mean = 7.47 phi

Sorting = 4.55 phi

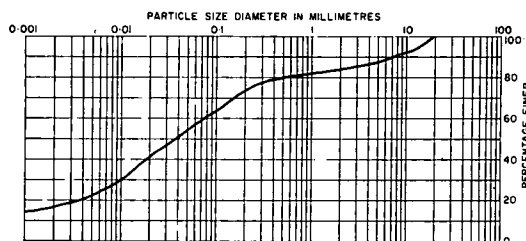
Figure 41.



Blackhall Colliery

Mean = 5.70 phi

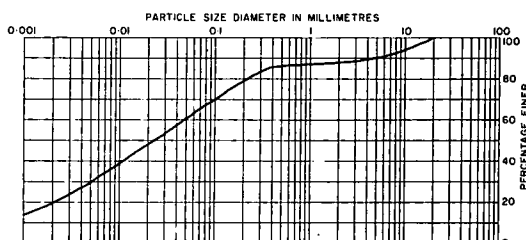
Sorting = 3.95 phi



Salterfen Rocks

Mean = 4.27 phi

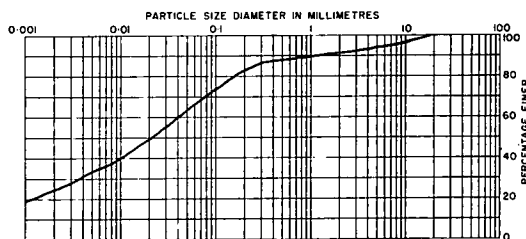
Sorting = 5.15 phi



Bedlam Gill

Mean = 5.60 phi

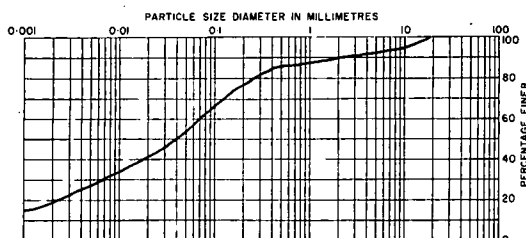
Sorting = 4.00 phi



Hesleden Village

Mean = 6.20 phi

Sorting = 4.30 phi

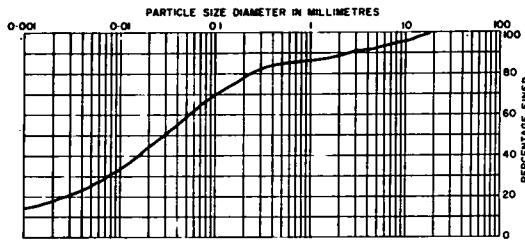


Dalton Riercy

Mean = 5.30 phi

Sorting = 4.10 phi

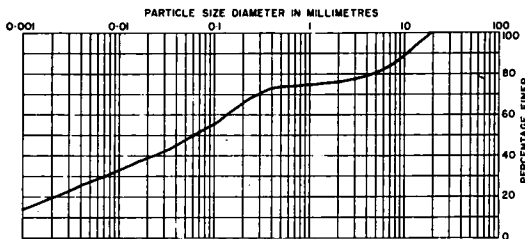
Figure 41.



Castle Eden Dene

Mean = 5.50 phi

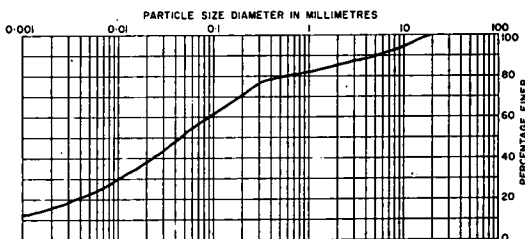
Sorting = 4.15 phi



Castle Eden Village

Mean = 3.57 phi

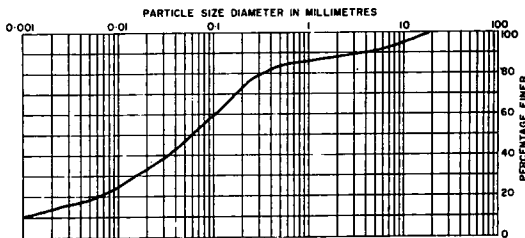
Sorting = 6.55 phi



Chourdon Point

Mean = 4.27 phi

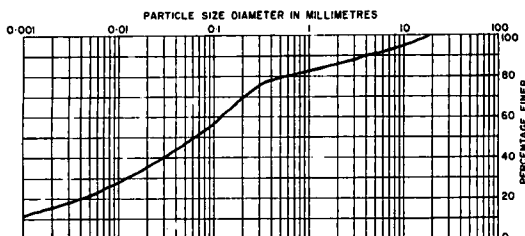
Sorting = 4.60 phi



A. 19 Castle Eden Dene

Mean = 4.40 phi

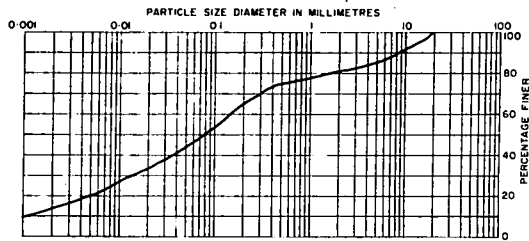
Sorting = 3.80 phi



Shotton Colliery

Mean = 4.03 phi

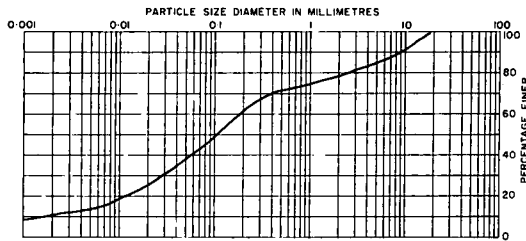
Sorting = 4.65 phi



Shotton Colliery Brick Pit

Mean = 3.33 phi

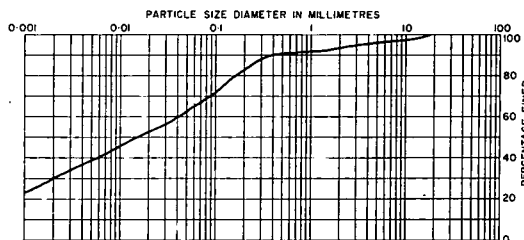
Sorting = 5.10 phi



Hawthorn Quarry

Mean = 2.58 phi

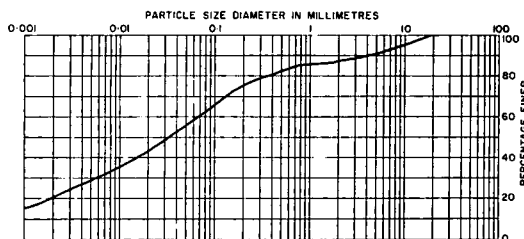
Sorting = 4.15 phi



Seaham Harbour Brick Pit

Mean = 6.53 phi

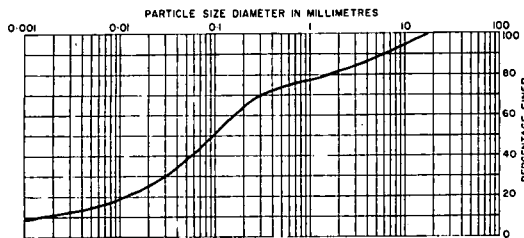
Sorting = 4.55 phi



Dalton-le-Dale

Mean = 5.00 phi

Sorting = 4.65 phi



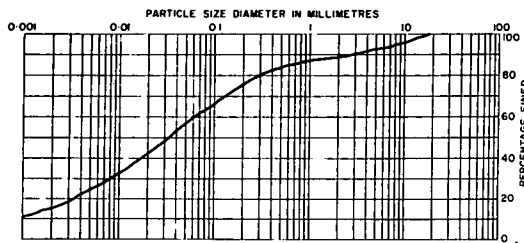
Peterlee Petrol Station

Mean = 3.07 phi

Sorting = 4.50 phi

Figure 41.

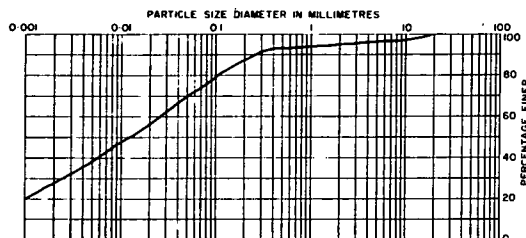
LOWER TILL OF THE COASTAL 227
REGION.



Peterlee Acre Rigg

Mean = 4.88 phi

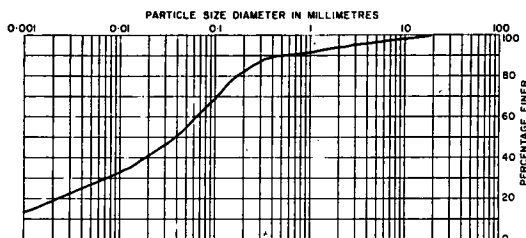
Sorting = 3.99 phi



Portrack Brick Pit

Mean = 6.57 phi

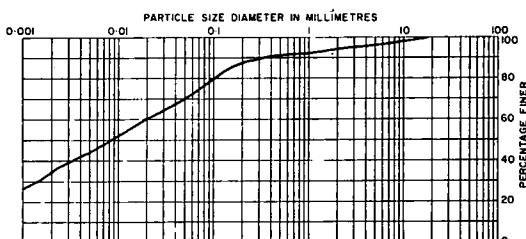
Sorting = 3.85 phi



Cerebros Works

Mean = 5.50 phi

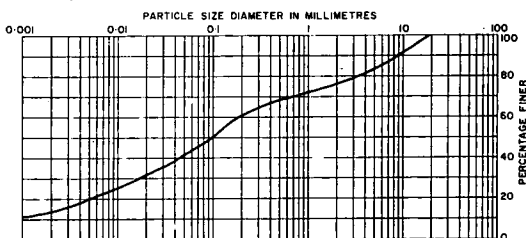
Sorting = 3.70 phi



Hawthorn Quarry

Mean = 7.00 phi

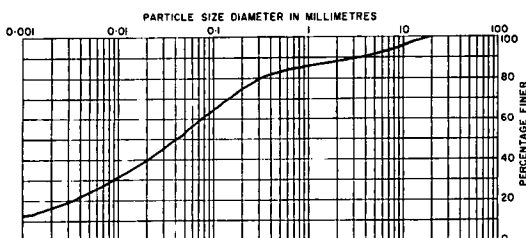
Sorting = 4.20 phi



Whelly Hill

Mean = 3.23 phi

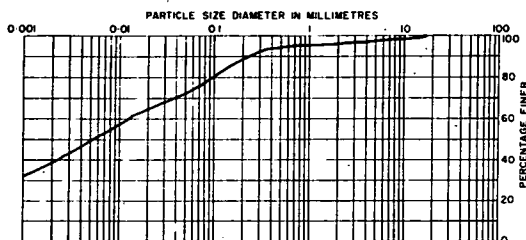
Sorting = 5.45 phi



Crimdon Dene

Mean = 4.90 phi

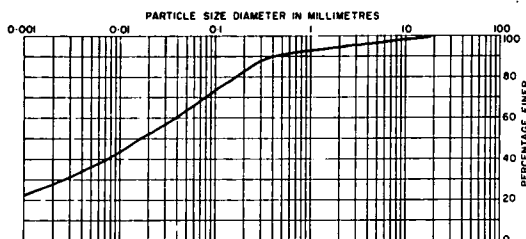
Sorting = 4.25 phi



Naisberry

Mean = 7.53 phi

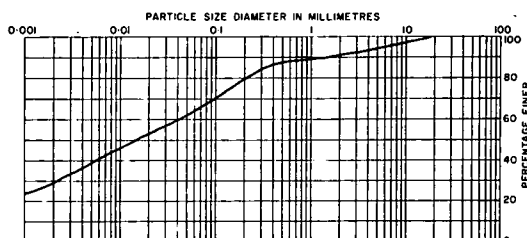
Sorting = 4.60 phi



Castle Eden Dene

Mean = 6.17 phi

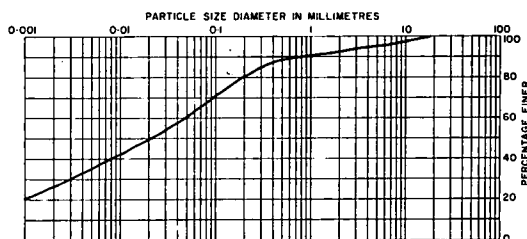
Sorting = 4.10 phi



Foxholes

Mean = 6.37 phi

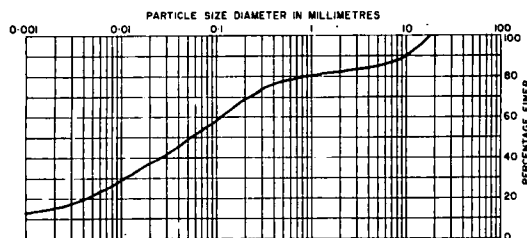
Sorting = 4.70 phi



Hazel Dene

Mean = 6.03 phi

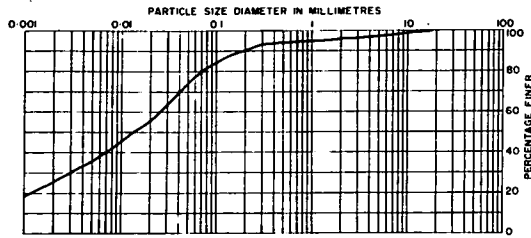
Sorting = 4.30 phi



Sheraton Hill Farm

Mean = 3.77 phi

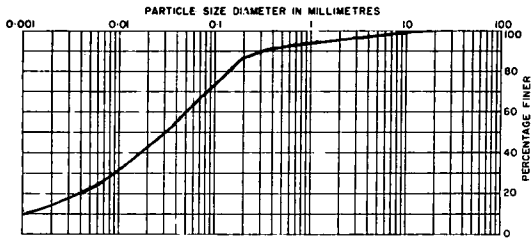
Sorting = 5.25 phi



Seaton Carew

Mean = 6.66 phi

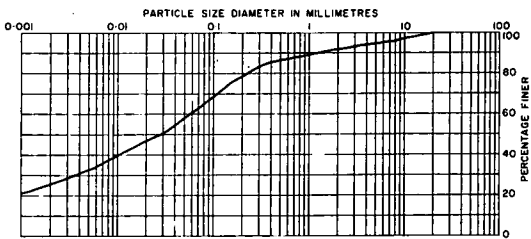
Sorting = 3.55 phi



Hart

Mean = 6.06 phi

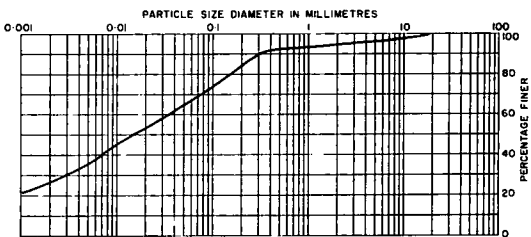
Sorting = 3.55 phi



South Hylton

Mean = 5.83 phi

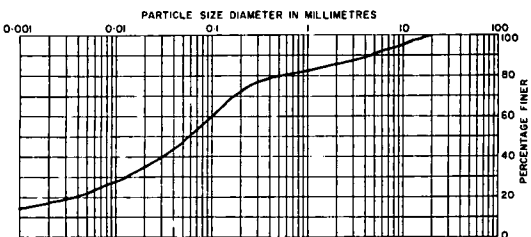
Sorting = 4.55 phi



Sheraton Hill Farm, hilltop

Mean = 6.25 phi

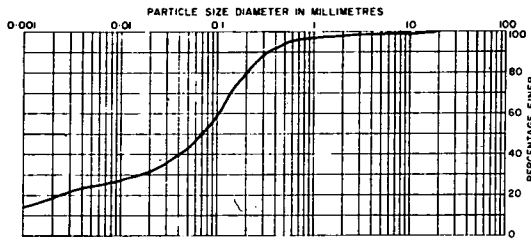
Sorting = 4.25 phi



Hesleden Dene

Mean = 4.50 phi

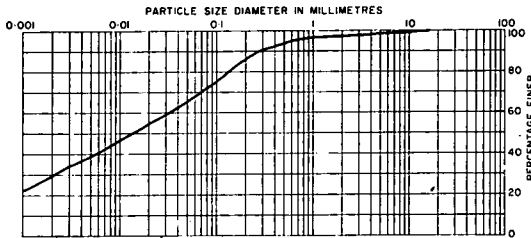
Sorting = 5.00 phi



Wolviston

Mean = 4.75 phi

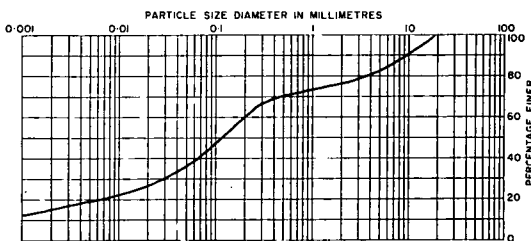
Sorting = 3.10 phi



Low Burn Toft

Mean = 6.50 phi

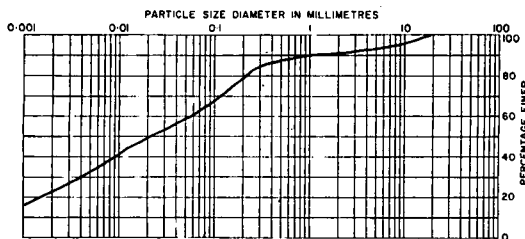
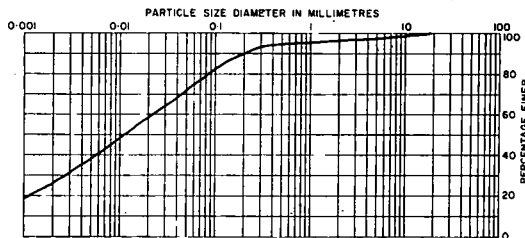
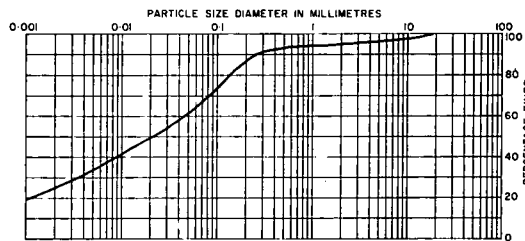
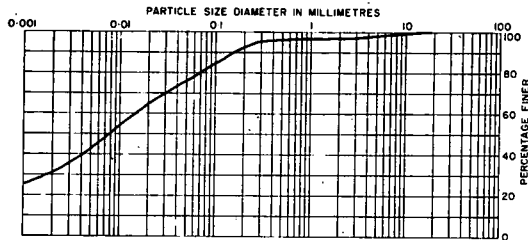
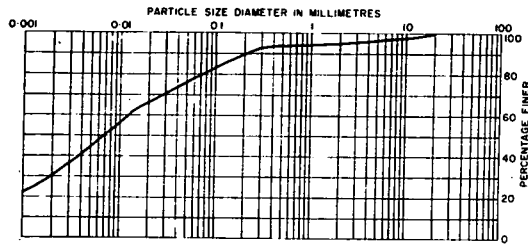
Sorting = 4.35 phi

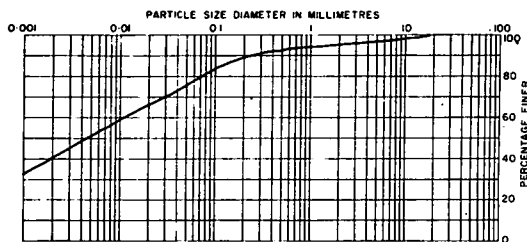


South of Hart road

Mean = 3.07 phi

Sorting = 5.56 phi

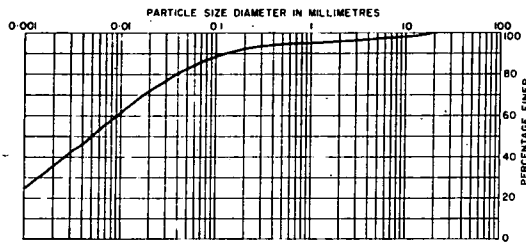




Crime Rigg

Mean = 8.13 phi

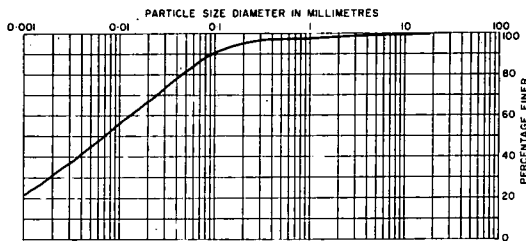
Sorting = 4.74 phi



Portrack Gravel Pit

Mean = 7.57 phi

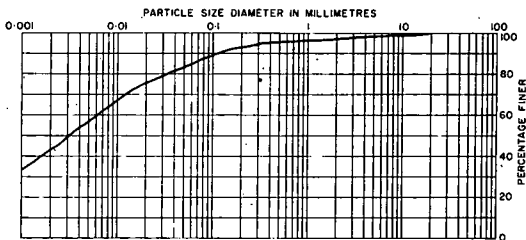
Sorting = 3.50 phi



Wynyard Hall Gravel Pit

Mean = 7.23 phi

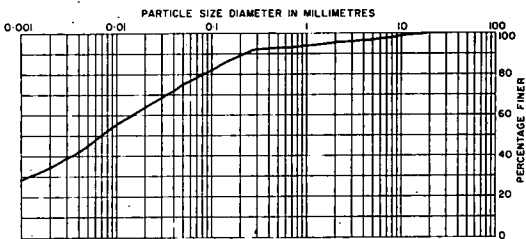
Sorting = 3.30 phi



Stob Cross

Mean = 8.07 phi

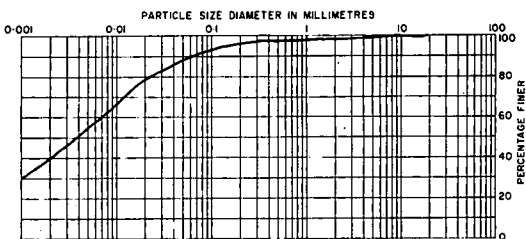
Sorting = 3.75 phi



Middlefield Farm

Mean = 7.30 phi

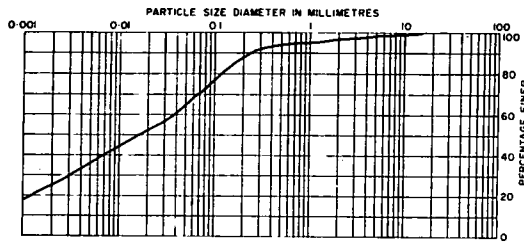
Sorting = 4.35 phi



Gilly Flat

Mean = 8.13 phi

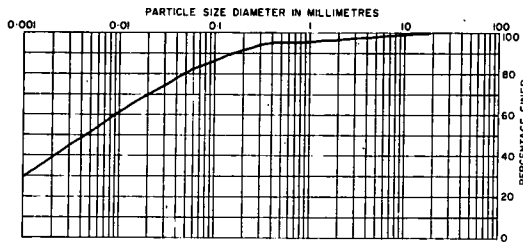
Sorting = 3.20 phi



Carlton

Mean = 6.27 phi

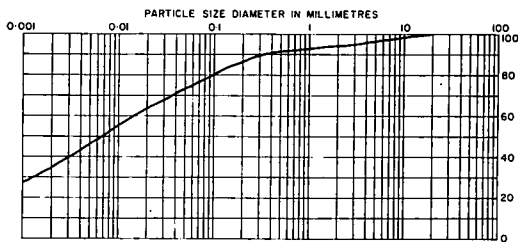
Sorting = 3.95 phi



Low Middlefield

Mean = 7.63 phi

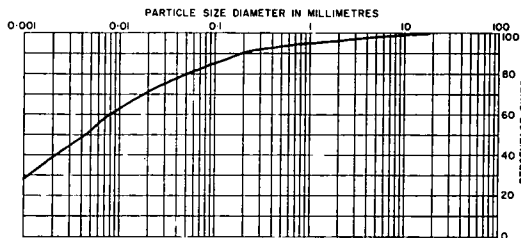
Sorting = 3.90 phi



Whitehouse Farm

Mean = 7.07 phi

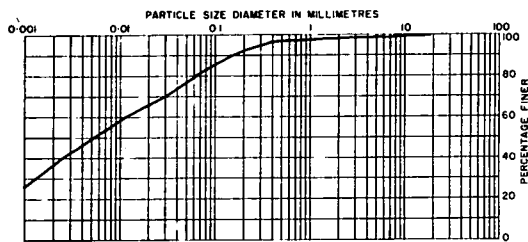
Sorting = 4.10 phi



Sedgefield Road Wolviston

Mean = 7.87 phi

Sorting = 4.15 phi



Warren House Gill

Mean = 7.63 phi

Sorting = 4.00 phi

Figure 42.

Key to figure 42. Particle size analysis of stony clays.

LOWER TILL OF THE WEAR LOWLANDS.

1. Finchale Priory
2. Windy Nook Quarry
3. Eighton Banks Quarry
4. Brancepeth Beck
5. Biddick Burn
6. Crime Rigg Quarry
7. Spennymoor Industrial Estate
8. Low Grange Bowburn
9. Building site Houghton-le-Spring

LOWER TILL OF THE MAGNESIAN LIMESTONE PLATEAU.

1. Middridge Quarry
2. Aycliffe Lower grey clay
3. Aycliffe Middle brown clay
4. Houghton le Spring
5. Eppleton
6. Thrislington
7. Coxhoe
8. Bishop Middleham
9. Trimdon Colliery
10. Cope Hill
11. Wood Quarry Wingate
12. Wingate Quarry D
13. Sherburn Sand Pit
14. High Moorsley
15. South Hetton
16. Wingate Quarry A

17. Fulwell Quarry
18. Tuthill Quarry
19. Holy Cross
20. Bradbury

LOWER TILL OF THE COASTAL REGION

1. Blackhall Colliery
2. Salterfen Rocks
3. Bedlam Gill
4. Hesleden Village
5. Dalton Piercy
6. Castle Eden Dene
7. Castle Eden Village
8. Chourdon Point
9. A.19 Castle Eden Dene
10. Shotton Colliery
11. Shotton Colliery Brick Pit
12. Hawthorn Quarry
13. Seaham Harbour Brick Pit
14. Dalton le Dale
15. Peterlee Petrol Station
16. Peterlee Acre Rigg

UPPER TILL

1. Portrack Brick Pit
2. Cerebros Works
3. Hawthorn
4. Whelly Hill
5. Crimdon Dene
6. Naisberry

7. Castle Eden Dene
8. Foxholes
9. Hazel Dene
10. Sheraton Hill Farm
11. Seaton Carew
12. Hart
13. South Hylton
14. Hilltop east of Sheraton Hill Farm
15. Hesleden Dene
16. Wolviston
17. Low Burn Toft
18. South of Hart Road

UPPER TEES CLAY

1. Portrack Brick Pit
2. Wynyard Hall Gravel Pit
3. Stob Cross
4. Middlefield Farm
5. Gilly Flat
6. Carlton
7. Low Middlefield
8. Whitehouse Farm
9. Wolviston Sedgefield Road

UPPER WEAR CLAY

1. High Butterby
2. Railway cutting north of Durham
3. Sewer Trench Framwellgate
4. Van Mildert
5. Ferryhill Electricity Station
6. Crime Rigg Quarry red clay.

SCANDINAVIAN DRIFT.

1. Warren House Gill.

Figure 42.

LOWER TILL OF THE WEAR LOWLANDS

Particle size diameter in millimetres.	1	2	3	4	5	6	7	8	9
20.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
13.0	95.11	99.35	98.39	97.59	97.20	97.00	99.85	98.52	97.14
9.7	92.52	98.37	97.11	96.04	93.48	95.29	99.09	97.78	95.53
6.0	88.87	97.44	94.80	93.37	91.31	92.25	98.20	96.64	93.33
4.7	86.63	96.76	93.23	91.77	88.28	90.85	97.54	95.73	91.70
3.2	84.85	96.09	92.16	89.96	86.67	89.51	96.97	94.59	90.22
2.0	82.70	95.29	90.79	87.24	85.25	87.63	96.15	92.61	88.10
1.2	81.29	94.61	89.96	85.14	83.36	86.45	95.48	91.94	86.33
0.6	79.53	93.28	87.70	82.40	81.85	84.61	94.20	89.91	82.53
0.4	78.26	92.18	85.36	81.06	79.56	83.24	93.19	88.63	80.22
0.3	76.01	90.26	80.93	79.38	75.57	80.93	91.23	86.20	76.77
0.2	72.10	86.86	75.09	77.22	69.77	76.65	87.80	81.79	72.10
0.15	66.78	82.44	68.86	74.68	63.25	71.92	83.67	76.64	67.02
0.10	59.10	76.75	61.62	71.36	55.54	64.71	78.84	70.10	60.34
0.075	54.18	73.20	57.15	69.08	51.05	60.20	75.57	65.46	56.10
0.062	50.55	70.77	53.99	67.30	48.11	56.98	72.96	61.74	53.28
0.046	46.87	68.07	50.81	64.74	45.67	53.57	69.29	57.25	50.43
0.038	44.20	65.97	49.10	63.01	44.03	51.67	66.93	54.39	47.85
0.034	42.70	64.57	47.38	61.85	42.40	49.79	65.28	52.49	46.24
0.027	40.02	62.46	45.67	59.52	40.76	47.28	63.63	50.59	43.98
0.021	38.24	61.07	43.62	57.48	40.11	45.70	61.32	49.33	42.37

Figure 42 - Continued:
LOWER TILL OF THE WEAR LOWLANDS.

Particle size diameter in millimetres	1	2	3	4	5	6	7	8	9
0.016	34.67	58.62	40.88	54.29	38.47	42.88	58.35	45.21	38.50
0.013	32.29	55.82	39.86	50.79	37.15	41.00	55.71	42.36	36.25
0.0090	29.02	51.97	37.12	46.42	33.55	36.90	50.75	38.87	33.02
0.0066	26.34	48.82	32.67	40.89	30.28	33.46	45.80	32.85	28.20
0.0048	23.06	45.32	29.60	35.36	25.70	29.69	39.53	28.10	24.97
0.0033	20.08	40.42	27.20	30.70	23.41	26.54	31.93	24.30	23.68
0.0022	19.26	36.23	23.77	26.63	23.00	23.08	29.95	19.55	20.14
0.0014	14.44	29.22	18.99	20.52	17.52	16.49	24.99	16.54	14.98
0.0010	12.06	25.02	16.25	-	15.22	-	-	13.53	12.73

Figure 42

LOWER TILL OF THE MEGNESIAN LIMESTONE PLATEAU

Particle size diameter in millimetres	1	2	3	4	5	6	7	8	9	10
20.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
13.0	95.15	97.37	97.03	98.76	96.63	98.80	97.97	98.25	98.94	98.21
9.7	93.69	93.71	95.18	97.98	94.69	97.83	96.26	96.50	97.61	96.71
6.0	91.24	90.47	92.04	96.69	91.73	96.78	95.29	94.17	96.23	95.11
4.7	89.64	88.88	90.33	95.75	89.92	96.12	94.41	92.75	94.98	94.34
3.2	88.18	87.78	88.66	94.85	88.56	95.51	93.48	91.47	93.63	93.57
2.0	86.32	85.71	86.33	93.64	86.51	94.54	92.43	90.06	91.81	92.36
1.2	84.82	83.87	84.33	92.61	84.72	93.97	91.45	88.72	90.69	91.13
0.6	82.33	80.81	81.17	90.58	81.75	93.03	89.82	86.73	89.18	89.19
0.4	80.59	78.63	79.01	88.88	79.86	92.08	88.59	85.60	88.54	87.93
0.3	78.01	75.57	76.05	85.61	77.03	89.79	86.52	83.99	87.78	86.21
0.2	74.71	71.69	72.45	80.89	73.54	84.96	83.18	81.87	86.89	83.83
0.15	70.70	66.95	67.91	74.44	69.55	79.30	79.22	79.22	85.71	80.62
0.10	64.70	60.23	61.85	67.08	65.21	70.93	73.81	75.32	83.88	76.52
0.075	59.62	56.13	57.99	62.92	61.26	65.56	70.56	72.81	82.34	73.64
0.062	56.58	53.47	54.99	60.08	58.86	62.56	67.87	70.30	80.52	71.08
0.046	34.32	51.53	52.01	55.74	56.36	59.04	65.80	64.75	74.69	66.64
0.038	53.37	49.03	49.40	53.27	54.39	56.59	64.15	61.05	71.08	62.37
0.034	52.09	47.48	47.45	51.87	52.09	54.84	62.50	57.97	68.37	59.92
0.027	49.85	45.61	45.16	49.75	49.79	53.09	60.85	53.97	64.77	56.25
0.021	48.24	43.43	41.93	48.00	47.49	50.98	59.20	49.96	59.06	52.27
0.016	45.68	40.63	37.66	44.48	42.88	47.13	56.56	44.41	51.56	47.39
0.013	43.43	38.14	34.73	42.37	39.93	45.38	54.25	41.02	47.06	44.34
0.0090	39.91	35.34	30.82	39.10	34.67	42.23	49.96	35.78	38.65	39.14

Figure 42.

LOWER TILL OF THE MAGNESIAN LIMESTONE PLATEAU

Particle size diameter in millimetres.	1	2	3	4	5	6	7	8	9	10
0.0060	36.03	31.92	27.56	33.58	29.74	36.97	45.35	30.85	33.85	34.56
0.0048	32.53	30.36	22.99	30.76	24.48	34.52	40.07	26.53	28.13	31.50
0.0033	30.61	28.18	21.04	27.25	19.88	30.66	36.11	24.69	25.44	39.05
0.0022	27.52	26.31	16.47	24.44	17.58	27.86	33.14	22.52	22.14	26.92
0.0014	22.60	20.40	13.86	19.16	12.32	23.30	27.21	18.83	19.43	22.95
0.0010	19.72	-	-	16.35	9.36	19.90	23.91	-	18.23	20.80

Particle size diameter in millimetres.	11	12	13	14	15	16	17	18	19	20
20.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
13.0	98.84	98.29	98.85	95.81	98.12	98.62	99.67	96.06	99.05	99.75
9.7	97.85	97.45	98.05	93.01	97.24	97.47	99.20	94.92	97.92	99.31
6.0	96.24	95.67	96.57	88.70	95.62	96.13	97.54	92.84	96.80	98.54
4.7	95.40	94.62	95.83	85.64	94.46	95.11	96.46	91.57	95.90	98.10
3.2	94.66	93.60	95.13	83.41	93.38	94.31	95.31	90.60	95.04	97.19
2.0	93.71	91.96	94.05	80.70	91.60	93.25	93.47	89.45	93.80	96.54
1.2	92.70	90.57	93.42	79.00	90.12	92.46	91.91	88.65	92.75	95.94
0.6	90.84	87.78	91.91	76.54	87.42	91.09	89.43	87.06	90.57	94.42
0.4	89.44	86.05	90.50	74.65	85.57	89.84	87.84	85.91	88.64	93.18
0.3	87.14	83.41	87.71	71.20	82.53	87.78	85.23	83.77	85.35	91.20
0.2	83.65	79.79	83.01	66.44	78.67	84.82	80.97	80.20	80.92	88.42

Figure 42.

Particle size
diameter in
millimetres.

	11	12	13	14	15	16	17	18	19	20
0.15	79.88	75.36	76.38	58.09	72.97	-	76.17	75.96	74.79	84.65
0.10	74.64	69.29	68.63	50.53	66.67	75.85	69.75	69.49	68.65	79.94
0.075	71.52	-	64.33	45.93	63.07	-	65.88	-	64.99	76.73
0.062	68.90	62.42	61.40	43.27	60.75	70.21	62.98	62.06	62.21	74.28
0.046	63.50	57.59	58.01	36.79	57.20	66.16	60.68	56.84	57.98	71.63
0.038	61.09	55.61	56.15	34.64	54.73	64.19	58.87	54.57	56.00	70.02
0.034	59.59	53.87	53.99	32.92	52.86	62.60	-	52.81	53.74	68.73
0.027	57.78	51.63	52.14	30.98	50.40	60.73	55.24	50.54	51.48	67.73
0.021	56.28	49.89	50.90	29.68	48.23	58.57	53.44	48.01	48.95	65.18
0.016	51.77	46.15	46.89	26.45	43.89	55.29	49.81	44.24	45.00	61.30
0.013	49.66	43.91	45.35	24.08	41.72	52.36	46.92	42.22	42.88	59.36
0.0090	44.25	40.18	40.71	21.93	37.09	49.09	42.93	37.68	39.35	56.13
0.0060	40.01	36.70	37.31	18.49	32.13	43.64	37.86	32.89	34.84	51.93
0.0048	35.52	33.22	34.22	16.11	28.42	40.54	34.23	29.36	30.61	47.40
0.0033	31.31	29.98	29.84	13.42	25.63	36.50	32.43	24.83	27.37	43.52
0.0022	28.61	26.49	26.97	10.95	22.54	32.77	29.52	23.07	24.41	-
0.0014	25.90	21.77	21.87	8.57	18.51	26.72	22.28	18.78	-	32.21
0.0010	22.59	19.03	19.70	-	16.34	25.32	-	16.76	16.51	29.96

Figure 42.
LOWER TILL OF THE COASTAL REGION

Particle size diameter in millimetres	1	2	3	4	5	6	7	8
20.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
13.0	96.13	94.04	96.19	98.61	97.04	97.73	93.37	97.95
9.7	95.21	92.55	93.98	97.35	95.87	96.44	88.70	94.91
6.0	92.92	89.49	91.67	95.16	94.14	93.83	83.36	92.05
4.7	91.84	87.86	90.60	94.03	93.12	92.63	81.11	90.10
3.2	90.65	86.28	89.73	93.10	92.09	91.23	79.29	88.38
2.0	89.02	84.14	88.63	91.73	90.50	89.26	77.23	86.31
1.2	87.76	82.65	87.76	90.62	89.10	87.64	76.00	84.22
0.6	86.08	80.61	86.32	89.00	86.75	85.33	74.74	80.77
0.4	84.96	79.17	85.17	87.93	85.03	83.81	73.40	78.82
0.3	83.26	77.02	83.23	86.33	81.96	81.64	70.62	75.99
0.2	80.46	73.65	80.05	83.59	77.68	78.65	67.05	71.90
0.15	76.72	69.33	75.59	79.64	72.69	74.17	62.04	67.06
0.10	71.52	63.78	69.48	74.25	65.78	68.74	56.11	61.23
0.075	68.06	60.31	65.37	70.48	61.47	65.39	-	57.98
0.062	65.46	57.78	62.17	67.48	57.78	62.75	50.56	55.16
0.046	61.60	54.11	60.46	61.49	53.12	58.49	46.68	50.90
0.038	58.67	51.35	57.37	59.35	50.15	54.90	44.51	48.03
0.034	56.78	49.20	54.98	57.20	48.37	53.80	43.30	46.31
0.027	53.82	46.13	52.24	54.44	45.70	50.86	41.86	43.45
0.021	50.59	43.38	50.18	51.69	42.74	46.66	40.17	40.01
0.016	46.07	36.94	46.07	47.07	38.89	41.36	37.27	35.71
0.013	42.83	33.57	42.99	44.33	37.11	38.24	34.86	33.13
0.0090	38.63	28.97	38.87	39.74	33.25	32.33	32.21	29.13

Figure 42.

Particle size diameter in millimetres.	1	2	3	4	5	6	7	8
0.0060	34.43	23.76	33.65	36.67	30.00	28.89	28.82	25.97
0.0048	30.88	22.22	29.29	32.40	26.73	26.10	26.41	23.11
0.0033	26.67	19.78	26.89	30.85	24.65	23.30	23.76	20.53
0.0022	23.12	17.32	22.09	26.35	21.38	20.33	21.11	17.38
0.0014	16.97	17.00	18.33	23.19	17.82	17.37	16.76	14.52
0.0010	-	14.87	16.27	21.57	14.56	15.19	-	12.51
20.0	9	10	11	12	13	14	15	16
13.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
9.7	96.84	97.38	94.82	94.68	99.25	97.50	97.12	98.38
6.0	95.50	95.88	92.11	90.81	98.41	95.37	94.17	96.33
4.7	92.67	92.67	87.93	87.47	97.32	92.55	89.93	94.19
3.2	91.38	91.12	85.38	84.87	96.49	90.90	87.27	93.01
2.0	90.13	89.47	83.49	82.64	95.69	89.38	85.08	91.77
1.2	88.33	85.53	80.98	79.54	94.35	87.34	81.89	89.91
0.6	86.93	84.25	79.04	76.97	93.32	85.66	79.36	88.41
0.4	84.40	81.15	76.01	73.02	91.47	83.28	75.43	85.61
0.3	82.46	79.16	74.05	70.66	90.19	81.81	72.90	82.83
0.2	79.07	75.92	70.93	67.25	87.93	79.53	68.95	79.99
0.15	74.37	70.20	66.19	62.44	83.66	75.89	63.93	76.90
0.10	66.86	64.11	60.73	56.27	78.55	71.37	57.66	72.63
0.075	59.22	56.76	53.82	48.82	71.62	65.17	50.06	67.31
0.062	54.80	-	49.58	44.40	67.82	61.14	45.40	63.91
0.046	52.16	49.60	46.58	41.27	64.45	58.31	41.90	60.76
	46.35	44.85	44.06	37.77	61.25	54.20	38.00	55.92

Figure 42.

Particle size diameter in millimetres.	9	10	11	12	13	14	15	16
0.038	43.08	42.56	41.40	34.86	58.89	51.46	34.74	52.58
0.034	41.32	40.95	39.33	33.28	57.21	49.63	32.73	49.81
0.027	38.02	38.65	37.26	30.80	55.52	47.19	30.21	47.58
0.021	35.58	36.13	34.31	27.74	53.83	44.14	27.69	44.25
0.016	30.85	31.77	31.65	24.04	51.14	40.48	24.17	39.26
0.013	28.27	29.71	28.99	21.66	48.78	38.34	22.41	35.93
0.0090	24.25	26.27	25.15	19.55	46.08	34.69	19.39	31.77
0.0060	21.38	23.52	21.90	16.13	42.04	32.54	16.37	27.61
0.0048	18.23	20.99	18.94	14.28	39.34	27.97	14.61	24.55
0.0033	16.79	19.16	16.58	-	35.29	26.14	-	20.67
0.0022	15.07	16.86	14.51	12.70	32.92	-	12.85	17.34
0.0014	12.47	12.04	11.56	-	26.19	18.21	10.34	12.63
0.0010	-	11.35	-	9.26	23.50	16.99	8.07	11.24

Figure 42.

UPPER TILL.

Particle size diameter in millimetres.	1	2	3	4	5	6	7	8	9
20.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
13.0	98.22	98.87	99.17	94.97	97.88	98.95	99.45	98.06	99.24
9.7	97.90	98.18	98.71	91.20	95.70	98.52	99.11	97.41	97.65
6.0	97.08	97.18	96.87	86.77	93.23	97.89	97.54	95.04	96.55
4.7	96.29	96.30	96.01	82.81	91.76	97.27	96.77	-	-
3.2	95.78	95.38	95.17	80.35	90.43	96.89	95.88	93.06	94.47
2.0	95.01	93.87	93.98	77.13	88.71	95.96	94.45	91.55	92.88
1.2	94.36	92.65	92.85	74.31	87.32	95.41	93.24	-	-
0.6	93.35	90.57	91.28	69.80	84.75	94.46	91.36	88.09	89.03
0.4	92.60	89.17	90.34	67.53	82.87	93.67	89.94	-	-
0.3	91.21	86.65	89.06	64.72	79.75	92.20	87.68	-	-
0.2	88.60	82.35	87.05	61.57	75.27	89.65	84.30	80.21	81.65
0.15	84.63	76.70	83.92	57.82	70.45	85.73	78.94	-	-
0.10	78.74	68.74	79.36	51.61	64.35	80.72	72.86	-	-
0.075	74.90	63.46	75.18	47.40	60.13	77.27	69.35	-	-
0.062	72.12	59.51	72.76	44.41	56.76	74.73	67.19	63.82	63.67
0.046	68.78	55.72	68.57	41.61	52.22	71.37	62.32	61.43	57.82
0.038	65.50	52.44	66.03	39.20	49.43	70.36	59.41	59.62	55.85
0.034	63.67	49.87	64.76	38.13	47.56	69.01	57.79	58.41	54.30
0.027	61.48	47.32	62.54	35.46	44.76	68.00	55.52	56.60	52.18
0.021	58.93	44.76	60.95	34.39	42.29	65.32	53.91	55.70	51.33
0.016	54.19	40.01	56.19	31.98	37.62	62.62	50.98	52.07	47.66
0.013	52.00	36.72	54.29	29.31	34.52	60.94	47.75	51.17	44.83

Figure 42.

Particle size
diameter in
millimetres.

	1	2	3	4	5	6	7	8	9
0.0090	46.89	33.07	50.16	26.64	31.72	56.57	43.54	46.95	41.73
0.0060	41.78	30.87	46.68	23.44	27.99	52.86	39.98	43.02	37.78
0.0048	37.04	25.39	43.18	22.64	23.02	47.81	35.45	37.88	34.67
0.0033	34.48	24.30	40.01	18.36	20.85	43.10	32.38	34.56	31.57
0.0022	30.47	21.74	37.15	16.22	17.74	41.42	30.27	32.30	28.18
0.0014	24.63	16.62	28.91	14.35	15.56	34.35	24.12	26.11	23.38
0.0010	-	13.70	-	13.28	13.70	-	21.54	24.60	21.12

	10	11	12	13	14	15	16	17	18
20.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
13.0	92.50	99.04	99.30	98.82	98.85	96.61	99.68	99.62	93.79
9.7	89.59	98.53	99.11	97.53	98.38	94.43	-	99.52	90.64
6.0	86.49	97.81	98.10	95.93	97.09	92.03	98.95	98.64	85.10
4.7	85.22	97.46	96.95	94.75	96.59	89.87	98.68	98.16	81.79
3.2	84.10	97.03	-	93.62	96.03	88.14	98.31	97.86	79.46
2.0	82.52	96.29	96.03	91.84	95.15	85.16	97.73	97.36	76.70
1.2	81.26	95.60	-	90.27	94.41	83.20	97.17	96.83	74.89
0.6	78.58	94.45	93.22	87.88	93.05	80.52	95.54	95.13	71.59
0.4	76.51	93.66	-	86.25	91.87	79.02	92.01	93.57	69.25
0.3	73.34	92.47	-	83.61	89.77	76.68	87.85	90.97	66.46
0.2	69.23	90.49	85.71	79.40	86.28	71.93	80.98	86.60	61.00
0.15	63.59	87.83	-	74.13	81.35	67.09	71.54	82.12	54.38
0.10	57.40	83.41	-	67.74	74.95	59.37	60.22	75.58	46.06
0.075	53.75	80.03	-	64.01	-	54.60	51.80	71.31	-
0.062	51.00	77.38	61.42	61.32	68.25	50.95	46.97	68.03	38.66
0.046	47.29	70.79	56.78	56.98	63.83	47.10	43.08	65.04	35.92

Figure 42.

Particle size
diameter in
millimetres.

	10	11	12	13	14	15	16	17	18
0.038	44.94	67.09	53.05	53.67	61.44	43.71	40.54	62.07	33.39
0.034	43.12	64.62	50.50	52.49	59.65	41.86	38.73	60.09	31.77
0.027	40.78	61.52	50.44	57.56	39.39	36.18	57.77	29.92	47.11
0.021	38.17	55.96	43.79	48.71	55.47	37.54	33.99	56.44	28.08
0.016	34.78	52.51	38.29	45.26	50.68	33.87	30.36	52.48	25.77
0.013	32.18	50.09	35.39	43.55	48.27	31.37	29.27	49.84	24.15
0.0090	28.53	45.14	76.42	39.76	44.70	28.29	27.81	46.53	22.30
0.0060	24.36	38.96	22.80	37.01	39.02	25.20	25.63	41.56	20.44
0.0048	21.75	34.95	20.49	32.53	35.13	22.74	22.73	38.27	18.83
0.0033	19.67	32.17	18.73	32.18	32.44	20.26	22.73	35.61	18.13
0.0022	17.33	27.53	18.73	30.47	28.85	18.11	20.18	31.97	16.75
0.0014	13.94	21.97	15.57	21.52	24.67	15.64	15.09	25.03	13.05
0.0010	12.63	-	13.25	-	22.58	14.71	14.37	21.73	11.44

Figure 42.
UPPER TEES CLAY

Particle size diameter in millimetres.	1	2	3	4	5	6	7	8	9
20.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
13.0	98.59	99.85	99.63	99.27	100.00	99.49	99.63	99.58	99.70
9.7	98.29	99.85	99.24	98.40	99.65	99.20	99.05	99.24	98.13
6.0	97.55	99.72	98.44	97.11	99.16	98.17	98.15	97.67	98.48
4.7	97.19	99.67	98.00	96.48	98.92	97.63	97.69	96.92	97.93
3.2	96.79	99.41	97.60	95.97	98.69	97.15	97.28	96.12	97.38
2.0	96.18	99.20	97.04	95.13	98.33	96.47	96.53	94.97	96.53
1.2	95.41	99.00	96.55	94.40	98.05	95.78	95.86	94.00	95.42
0.6	94.24	98.43	95.62	93.32	97.62	94.47	94.89	92.38	94.76
0.4	93.65	98.20	95.16	92.62	97.33	93.36	94.26	91.37	93.75
0.3	92.80	97.71	94.40	91.39	96.88	91.29	93.25	89.73	93.10
0.2	91.51	96.69	93.14	89.21	96.14	88.09	91.63	87.12	91.30
0.15	89.75	94.87	91.36	86.37	94.93	83.24	89.46	84.11	88.91
0.10	87.12	91.67	88.78	82.33	93.08	76.51	86.47	80.08	85.85
0.075	85.29	88.45	86.89	79.62	91.73	72.07	84.59	77.86	83.61
0.062	83.83	85.23	85.45	77.76	90.42	68.83	82.97	75.76	81.82
0.046	82.56	79.01	82.35	75.60	86.61	63.10	82.24	72.25	79.16
0.038	81.04	75.67	80.91	72.27	85.57	60.16	77.16	70.32	76.66
0.034	79.27	73.44	79.46	69.21	83.51	57.95	75.19	68.72	74.91
0.027	76.79	70.09	78.38	67.92	81.43	56.26	73.78	66.79	73.67
0.021	75.03	67.48	76.58	65.37	78.67	53.98	72.39	64.85	72.41
0.016	72.56	61.91	71.90	64.09	74.19	50.72	68.98	60.99	70.66
0.013	67.96	58.56	69.74	59.23	70.74	47.46	65.03	57.78	65.91
0.0090	64.79	53.72	66.14	54.44	63.50	44.53	58.55	53.91	63.66
0.0060	59.14	47.78	60.01	53.35	57.98	40.30	52.90	49.73	59.41
0.0048	53.84	42.94	56.04	48.23	53.14	36.06	48.67	45.54	54.40

Figure 42.

UPPER TEES CLAY (Continued):

Particle size diameter in millimetres.	1	2	3	4	5	6	7	8	9
0.0033	48.19	38.11	51.00	43.62	47.63	30.20	46.42	40.72	49.90
0.0022	44.31	34.02	45.95	39.79	42.46	28.34	41.61	37.17	45.40
0.0014	37.96	27.33	38.02	35.69	34.52	22.05	33.43	31.70	40.90
0.0010	31.25	23.61	34.06	30.83	30.39	18.79	29.20	26.52	32.89

Figure 42.

Particle size diameter in millimetres.	UPPER WEAR CLAY.						SCANDINAVIAN DRIFT.	
	1	2	3	4	5	6		
0.0090	54.24	53.35	41.08	46.97	41.46	58.50		57.76
0.0066	47.82	47.66	37.81	41.92	36.97	54.80		54.43
0.0048	41.76	41.99	32.90	37.21	32.80	51.79		47.45
0.0033	37.48	38.32	29.95	32.83	28.61	47.77		44.12
0.0022	34.63	33.97	27.01	29.12	25.62	42.74		38.47
0.0014	29.64	29.63	23.17	23.06	20.53	35.70		32.32
0.0010	22.50	25.95	19.80	-	16.95	-		26.50

To overcome this problem statistical techniques for the description of particle size distributions are used.

STATISTICAL MEASURES USED FOR ANALYSIS.

1. CENTRAL TENDENCY

Certain statistical measures were found to be of value in describing the Durham stony clays.

a. MEDIAN

The median, or 50% value on the cumulative frequency curve, has been widely used in early work on sediment analysis to represent the size grade which separates the sample into 2 equal halves by weight. The median has the disadvantage that it takes no account of the grain size distribution on either side of the 50% value.

b. MEAN

The mean is a second measure of central tendency. The methods for determining it, used in this work follow. Folk R.L. and Ward W.C. 1957.

$$\text{Mean} = (\phi 16\% + \phi 50\% + \phi 84\%) / 3. \quad (\phi = \text{phi})$$

The advantage of the arithmetic mean over the median is that it is more suitable for mathematical analysis, being the average of a series of readings. The mean gives the diameter value of the centre of gravity of the frequency distribution curve.

Folk and Ward recommend that the mean value is a better measure of the sediment size than the median.

2. SORTING

The degree of sorting is one of the most important measures in sediment analysis. By using the phi value for the 16 and 84th percentiles the standard deviation of the distribution can be obtained directly from the cumulative frequency curve, and this value can be used as a measure of dispersion. On a normal curve about two thirds of the sample lies within + or - 1 standard deviation from the mean value. To utilise this Inman 1952 suggested the ϕ deviation measure :-

$$\text{Sorting on } \phi \text{ deviation measure} = \frac{1}{2} (\phi 84 - \phi 16).$$

This was found to give good results for a sediment of nearly normal distribution, but has the disadvantage of ignoring a third of the sample at either end of the size ranges. To overcome this difficulty Folk and Ward suggested a sorting measure called the Inclusive Graphic Standard Deviation.

$$= \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

The present author found it impossible to apply this measure because of the inability to obtain accurate phi 95 and $\phi 5$ readings. Therefore Inman's phi deviation measure was used.

3. SKEWNESS.

The skewness of a sediment is indicated by the difference between the mean and median values. In a normal distribution the mean and median coincide, and there is no skewness. Where skewness does exist the amount and direction can be obtained using Inman's formula comparing the mean and median values.

$$\text{Skewness} = \frac{\text{Mean} - \text{Median}}{\text{Standard deviation}}$$

If the skewness is negative the mean is less than the median, and the distribution is skewed towards the ~~coarser~~ particles. If the skewness is positive the distribution is skewed towards the finer particles. The skewness measure gives some indication of the amount by which the curve departs from the normal distribution.

STATISTICAL RESULTS OF EASTERN DURHAM STONY CLAYS.

79 samples representative of the differing conditions within the stony clay deposits of Eastern Durham were subjected to detailed statistical analysis. (Fig. 44 and 45).

1. CENTRAL TENDENCY

a. Median

The median values show an absolute variation from 3.1 ϕ to 8.3 ϕ for all the samples. The median variation within each of the sample clay-types is considerable, and there is considerable overlap between the different clays. More than 60% of the total observations fall between 4 ϕ and 6.5 ϕ . The only group which tend to stand apart from the others is the Upper Tees Clay, which shows in almost every case median values of more than 7 ϕ . The Upper Till, the Lower Till of the coastal region and Upper Wear Clay do however show some overlap with the Upper Tees clay.

b. Mean

The mean values indicate almost identical results to those of the median and no important differences are noted between them. (Figs. 44 and 45).

Figure 44.

Statistical analysis of particle size distribution curves.

	MEDIAN (50%)	MEAN	SORTING	SKEWNESS
	(phi units)	$\frac{(\phi_{16} + \phi_{50} + \phi_{84})}{3}$ (phi units)	$\frac{(\phi_{84} - \phi_{16})}{2}$ (phi units)	$\frac{(\text{Mean } \phi - \text{Median } \phi)}{\text{Sorting } \phi}$ (phi units)
<u>Lower Till of Wear Lowlands</u>				
Finchale Priory	4.0	3.83	5.35	+0.0318
Windy Nook Quarry	7.0	7.13	4.75	+0.0273
Eighton Banks Quarry	4.4	5.27	4.30	+0.2023
Brancepeth Beck	6.3	5.37	4.90	-0.1890
Biddick Burn near Birtley	3.7	4.47	4.85	+0.1587
Crime Rigg Quarry	5.0	5.13	4.20	+0.0309
Spennymoor Industrial Estate	6.6	6.53	3.90	-0.0179
Low Grange Bowburn	5.3	5.53	3.65	+0.0630
Building Site, Houghton-le-Spring	4.5	4.66	4.75	+0.0358
<u>Lower Till of Magnesian Limestone Plateau.</u>				
Middridge Quarry	5.0	4.77	5.50	-0.0420
Aycliffe Quarry	4.5	4.67	5.35	+0.0317
Middle Brown Clay	4.6	4.70	4.75	+0.0211
Houghton-le-Spring	5.0	5.57	3.95	+0.1440
Eppleton	4.9	4.36	4.60	-0.1170
Thrislington	5.6	6.2	4.20	+0.1430
Coxhoe	6.4	6.5	4.55	+0.0219
Bishop Middleham	5.5	5.70	4.10	+0.0487
Trimdon Colliery	6.0	6.73	4.00	+0.1825

	MEDIAN (50%) (phi units)	MEAN $\frac{(\phi_{16} + \phi_{50} + \phi_{84})}{3}$ (phi units)	SORTING $\frac{(\phi_{84} - \phi_{16})}{2}$ (phi units)	SKEWNESS $\frac{(\text{Mean } \phi - \text{Median } \phi)}{\text{Sorting } \phi}$ (phi units)
<u>Lower Till of Magnesian Limestone</u>				
<u>Plateau (contd).</u>				
Cope Hill	5.7	6.40	4.55	+0.1538
Wood Quarry Wingate	6.0	6.73	5.00	+0.1460
Wingate Quarry D	5.5	5.83	4.40	+0.0750
Sherburn Sand Pit	5.5	6.20	4.45	+0.1570
High Moorsley	3.4	3.10	4.65	-0.0645
South Hetton	5.3	5.53	4.15	+0.0554
Wingate Quarry A	6.5	6.53	4.66	+0.0069
Fulwell	5.9	6.13	4.66	+0.0554
Tuthill	5.3	5.80	4.22	+0.1149
Holy Cross	5.2	5.70	4.22	+0.1234
Bradbury	7.5	7.47	4.55	-0.0065
<u>Lower Till of Coastal Area.</u>				
Blackhall Colliery	5.6	5.70	3.95	+0.0253
Salterfen Rocks	4.7	4.27	5.15	-0.0835
Bedlam Gill	5.4	5.60	4.00	+0.0500
Quarry near Hesleden	5.6	6.20	4.30	+0.1400
Dalton Piercy	4.7	5.30	4.10	+0.1460
Castle Eden Dene	5.2	5.50	4.15	+0.0723
Castle Eden Village	4.0	3.57	6.55	-0.0656
Chourdon Point	4.4	4.27	4.60	-0.0283
A19 Section Castle Eden Dene	4.0	4.40	3.80	+0.1050
Shotton Colliery	3.8	4.03	4.65	+0.0494

	MEDIAN(50%) (phi units)	MEAN $\frac{(\phi_{16}+\phi_{50}+\phi_{84})}{3}$ (phi units)	SORTING $\frac{(\phi_{84} - \phi_{16})}{2}$ (phi units)	SKEWNESS $\frac{(\text{Mean } \phi - \text{Median } \phi)}{\text{Sorting } \phi}$ (phi units)
<u>Lower Till of Coastal Area (Contd).</u>				
Shotton Colliery Brick Pit	3.6	3.33	5.10	-0.0529
Hawthorn Quarry	3.3	2.58	4.15	-0.1580
Seaham Harbour	6.1	6.53	4.55	+0.0945
Dalton-le-Dale	4.7	5.00	4.65	+0.0645
Peterlee Petrol Station	3.4	3.07	4.50	-0.0733
Peterlee Acre Rigg	4.9	4.88	3.99	-0.0050
<u>Upper Till</u>				
Portrack Brick Pit	6.4	6.57	3.85	+0.0440
Cerebros Salt Works	4.9	5.50	3.70	+0.1620
Hawthorn Quarry	7.0	7.00	4.20	0.0
Whelly Hill Quarry	3.4	3.23	5.45	-0.0312
Crimdon Dene	4.6	4.90	4.25	+0.0706
Naisberry Quarry	7.6	7.53	4.60	-0.0152
North of Castle Eden Dene	5.9	6.17	4.10	+0.0659
Foxholes	6.1	6.37	4.70	+0.0574
Hazel Dene	5.7	6.03	4.30	+0.0767
Sheraton Hill Farm	4.2	3.77	5.25	-0.0819
Seaton Carew	6.3	6.66	3.55	+0.0930
South Hylton Quarry	5.3	5.83	4.55	+0.1160
Hilltop East of Sheraton Hill Farm	6.0	6.25	4.25	+0.1010
Hesleden Dene	4.5	4.50	5.00	0.0
Wolviston	3.7	4.75	3.10	+0.0580
Low Burn Toft	6.2	6.50	4.35	+0.0851
South of Hart Road	3.1	3.07	5.56	-0.0053
Hart	5.2	6.06	3.55	+0.2423

	MEDIAN (50%) (phi units)	MEAN $\frac{(\phi_{16} + \phi_{50} + \phi_{84})}{3}$ (phi units)	SORTING $\frac{(\phi_{84} - \phi_{16})}{2}$ (phi units)	SKEWNESS $\frac{(\text{Mean } \phi - \text{Median } \phi)}{\text{Sorting } \phi}$ (phi units)
<u>Upper Wear Clay</u>				
High Buttenby	7.2	7.17	3.85	-0.0442
Railway north of Durham	7.1	7.53	4.45	+0.0966
Sewer Trench Framwellgate	5.6	6.17	3.95	+0.1440
Van Mildert College	6.4	6.73	3.60	+0.0917
Electricity sub-station Ferryhill	5.6	5.73	4.10	+0.0317
Crime Rigg	7.9	8.13	4.75	+0.04840
<u>Upper Tees Clay</u>				
Portrack Brick Pit	7.7	7.57	3.50	-0.0371
Wynyard Hill	7.3	7.23	3.30	-0.0212
Stob Cross	8.3	8.07	3.75	-0.0613
Middlefield Farm	7.2	7.30	4.35	+0.0230
Carlton	5.9	6.27	3.95	+0.0937
Gilly Flat	8.0	8.13	3.20	+0.0406
Low Middlefield	7.7	7.63	3.90	-0.0179
Whitehouse Farm	7.4	7.07	4.10	-0.0805
Sedgefield Road Wolviston	7.9	7.87	4.15	-0.0072
<u>Scandinavian Drift</u>				
Warren House Gill	7.7	7.63	4.0	-0.0175

The means show an absolute variation from 2.5ϕ to 8.1ϕ . As with the median the mean shows a concentration of observations between 4 to 6.5ϕ . The overlap between individual clay types, is similar to that of the median.

What this study does indicate is that all these sediments are basically fine grained, with the median and means tending to fall dominantly in the median silt range between 0.0156 and 0.0312 mm.

2. SORTING.

The sorting was measured using the formula $\frac{1}{2} (84\phi - \phi_{16})$. This technique has the disadvantage of paying too little attention to the tails of the distribution, and therefore tends to estimate the sorting as being better than it really is. Nothing can be done to overcome this difficulty.

The absolute sorting values vary from 3.1 to 6.4, with more than 33% of the observations falling in the category of 4 to 4.5, and almost 80% between 3.5 to 5. (Figs.44 and 45).

One point of interest which does stand out from these values is that the Upper Tees clay appears on the whole to be slightly better sorted than the other clays.

The main conclusion to come out of this analysis is that although the sorting is extremely poor in nearly all cases, there does seem to be some general order to it indicated by the fact that the values fall so closely together.

Folk and Ward 1957 suggested a verbal scale to describe values.

less than 0.35	- very well sorted.
0.35 - 0.5	- well sorted.
0.5 - 1.0	- moderately sorted.
1.0 - 2.0	- poorly sorted.
2.0 - 4.0	- very poorly sorted.
more than 4.0	- extremely poorly sorted.

Using this scale all the Durham clays without exception fall in the very poorly, or extremely poorly sorted categories.

3. SKEWNESS

Skewness is a measure of deviation from the normal distribution. All the values of skewness for the East Durham stony clays are low with the vast majority being less than $\pm 0.1\phi$.

One fact which is very noticeable is that every clay, with the exception of the Tees clay has the majority of its values showing positive skewness. That is, the distribution is skewed toward the finer particles. (Fig.45)

Of these three measures it was considered that the mean and sorting values are the most important in describing the characteristics of the deposits, and it was therefore decided to subject these values to statistical analysis.

The first test used was to decide if the mean values of the six main clay groups had been drawn from the same total population, or from different ones. The data of mean values in Fig.44 and 45. were subjected to an analysis of variance test. In all cases a null hypothesis was postulated that the mean values had been drawn from the same population.

A. Comparison of sample values of the six main clay groups (Data from Fig.44 and 45). The following results were obtained.

$$\text{Sample F value} = 6.80$$

$$\text{Table F value, } F_{5 \ 71 \ .01} = 3.3$$

Therefore the null hypothesis is rejected and the sample values are regarded as having been obtained from more than 1 population.

B. Comparison of sample values of the three divisions of the Lower Till (data from Fig.44 and 45). The following results were obtained.

$$\text{Sample F value} = 5.06$$

$$\text{Table F value, } F_{2 \ 41 \ .01} = 5.20$$

Therefore the null hypothesis is retained and the sample values are regarded as having been obtained from the same population.

C. Comparison of sample values of the Upper Till and the Upper Tees Clay. (data from Fig.44 and 45). The following results were obtained.

$$\text{Sample F value} = 16.89$$

$$\text{Table F value, } F_{1 \ 25 \ .01} = 7.77$$

Therefore the null hypothesis is rejected and the sample values are regarded as having been obtained from more than 1 population.

D. Comparison of sample values of the Lower Till of the Wear Lowlands and the Upper Wear Clay. (data from Fig.44 and 45). The following results were obtained.

$$\text{Sample F value} = 1.46$$

$$\text{Table F value } F_{1 \ 12 \ .01} = 9.33$$

Therefore the null hypothesis is retained and the sample values are regarded as having been obtained from the same population.

E. Comparison of sample values of the Upper Till and the Lower Till of the Coastal Region. (data from Fig.44 and 45). The following results were obtained.

Sample F value = 5.50

Table F value, $F_{1 \ 32 \ .01}$ = 7.40

Therefore the null hypothesis is retained and the sample values are regarded as having been obtained from the same population.

The analysis of mean values shows that the Upper Tees Clay is the only clay deposit which has significantly different mean values from the other clays. (Example C). In this case a marked difference is seen between the Upper Tees Clay and the Upper Till which is in marked contrast to the results obtained for calcium carbonate values in Chapter 7. Also in this analysis it is found that no significant difference is seen between the Upper Till, and the Lower Till of the Coastal Region. (Example E). This illustrates the fact that different types of analysis of the deposits can lead to different results in terms of correlation. It is due to the fact that different properties of the deposits are being measured, some of which appear possibly to be related to genesis (i.e. particle size analysis) and others to the type of material from which the deposits were formed. (i.e. lithologies of the included material).

A comparison of sorting values was also attempted using analysis of variance techniques. A null hypothesis was postulated that the sample values were all obtained from the same population.

A. Comparison of the sample values of the six main clay types. (data from Fig.44 and 45). The following results were obtained.

Sample F value = 2.66

Table F value, $F_{5 \ 71 \ .01}$ = 3.30

Therefore the null hypothesis is retained and the sample values are regarded as having been obtained from the same population.

This shows that at the 1% level of significance all the sorting values of the different clay types are similar.

When the sample mean value is plotted against the sample sorting value for all the clay types a general linear relationship is seen to exist. (Fig.46). The following statistical results were obtained.

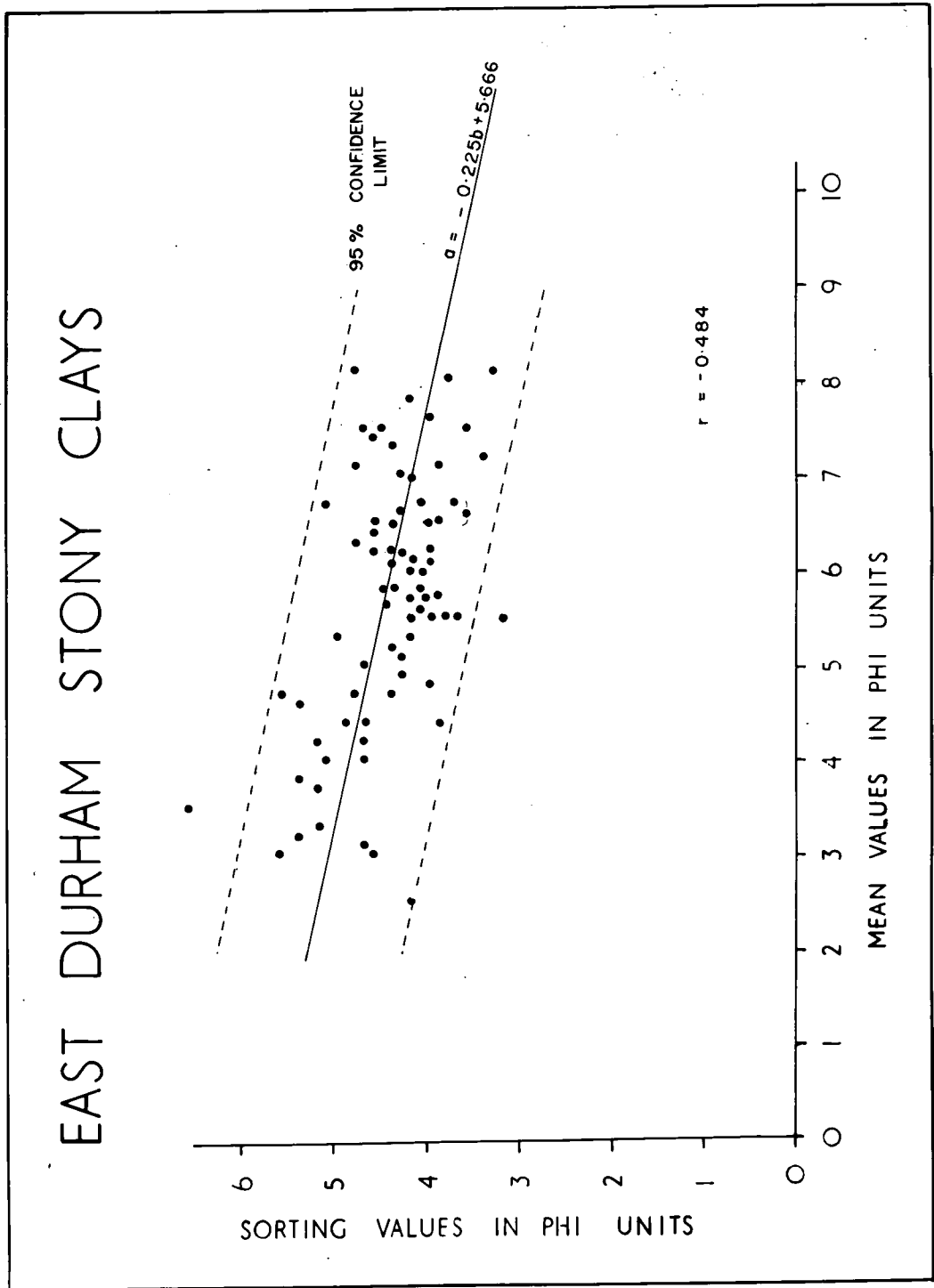
Correlation coefficient = - 0.484 significant at 0.001 level.

Regression equation $a = 5.666 - 0.224b$.

Folk R.L. and Ward W.C. (1957) observed a similar pattern of correlation between mean and sorting values in the offshore deposits of Lincolnshire. The results from Eastern Durham suggest that as the mean size of the sample increases in phi units, or decreases in millimetres the sorting becomes more pronounced. The data available is for mean values of between 3 to 8 phi, and of sorting values between 3 to 5.5 phi units. These sediments are therefore more poorly sorted and of a considerably finer grain size than those analysed by Folk and Ward.

By plotting mean particle size against skewness Freidman G.M. (1961) was able to distinguish beach and dune environments of deposition. A plot of sample mean size against sample skewness for the Eastern Durham stony clays shows a random distribution. (Fig.47) It is noted however that the Upper Tees Clay tends to stand apart from the other clay types, and to be concentrated in the lower right hand portion of the diagram.

Figure 46.



By far the most significant point to emerge from this analysis is the marked relationship between mean size and skewness values for the Lower Till of the Magnesian Limestone Plateau area and the Lower Till of the Coastal Region. This relationship is seen in Fig.47. The following statistical results were obtained.

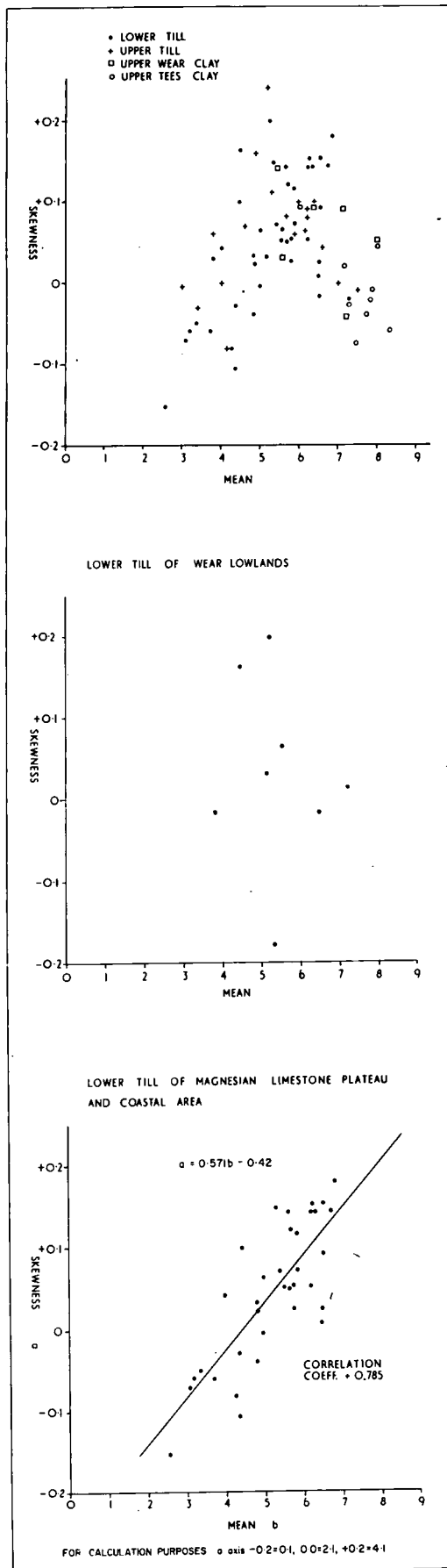
Correlation coefficient = + 0.78 significant at 0.001 level.

Regression equation $a = 0.571b - 0.42$

From this graph it is seen that as the mean size decreases in millimetres or increases in phi units, the skewness of the distribution changes from negative to positive. Both these clay types are resting on Magnesian Limestone parent material. In an up ice direction the Lower Till of the Wear Lowlands does not exhibit the same markedly linear trend (Fig.47). The actual reason for this is unknown but the possibility is suggested that it may be due to the fact that in the Wear Lowlands very varied strata of coal measures age are found. These strata contain material varying in particle size from coarse sand to the finest clay. In contrast the Magnesian Limestone possesses marked similarities in terms of its mechanical composition. From this it is tentatively possible to suggest that in the Wear Lowlands local lithological differences have the most important effect on till particle size distribution, while in an area of more uniform lithology the environment of deposition exerts a stronger influence.

What emerges very clearly from these studies is the ordered nature of the clay deposits of Eastern Durham as a whole, and in particular of the Lower Till sheet. To qualify this statement it must be

Figure 47.



pointed out that the relative importance of parent material and sub-glacial processes in determining the particle size distribution of a deposit is as yet unknown. Until comparative studies are attempted in other areas definite conclusions of any significance cannot be drawn. From such relationships, for it is by no means obvious as to what are the causal factors behind these results.

Using the data from Figs. 44 and 45 diagrams were constructed to show spatial variations in the mean and sorting values of the Lower Till sheet. From these diagrams the data were projected onto a plane parallel to the direction of ice movement, to discover if any variations in either mean size or sorting values could be discerned in a down ice direction across the line of the Magnesian Limestone escarpment. (Fig. 48). The mean values show considerable variation throughout the area. In general terms however no significant difference is noted after the Lower Till has crossed the line of the escarpment.

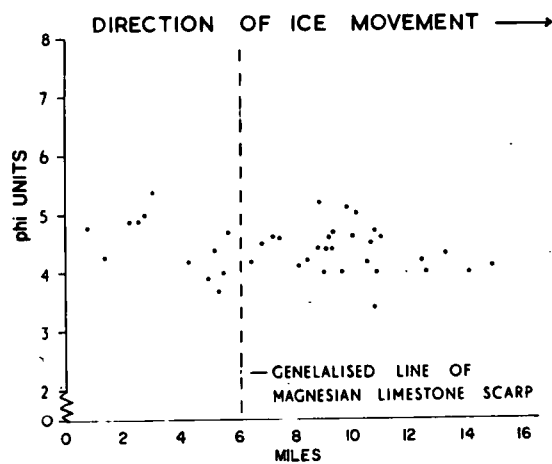
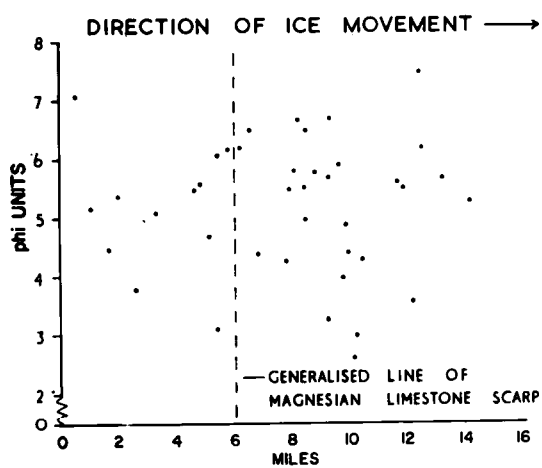
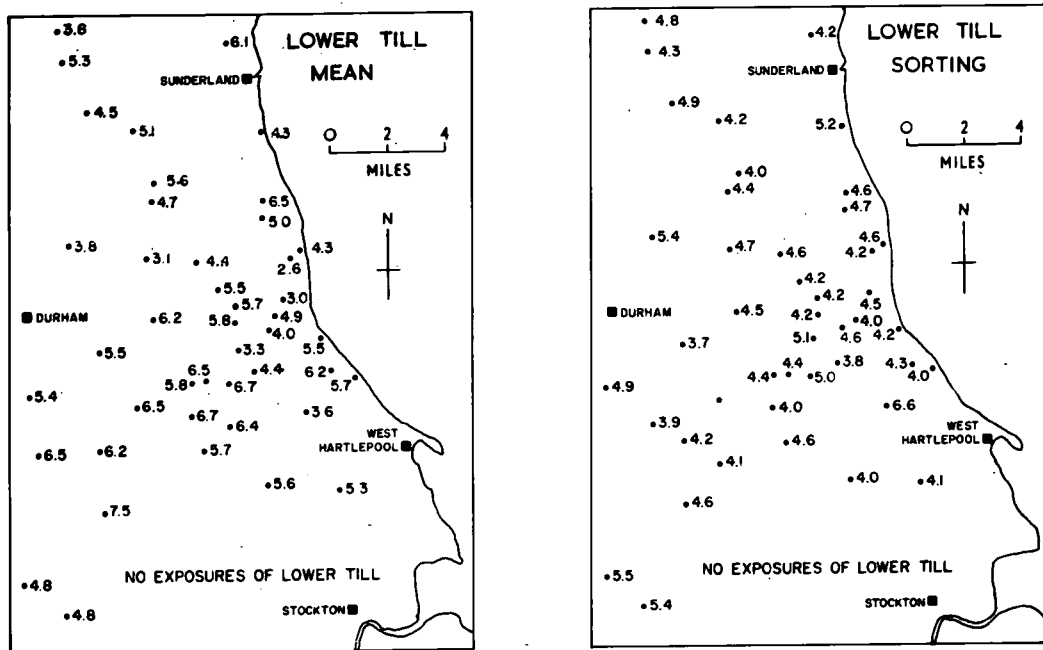
In a similar way the sorting values for the Lower Till sheet show no appreciable difference on either side of the line of the escarpment, and in both areas the majority of sorting values fall between 4 to 5.

To some extent these diagrams give a qualitative estimation of the ability of an ice sheet to encounter a completely new lithological type of parent material, without apparent effect on the mean particle size or sorting values of its associated till sheet (contrast with lithologies Chapter 6).

CUMULATIVE FREQUENCY CURVES.

Although statistical analysis is of vital importance in a study of sediments, it should not be applied in the study of cumulative frequency curves showing particle size distribution to the exclusion of visual and therefore more subjective examinations. For just as statistical analysis reveals correlations which are not immediately

Figure 48.



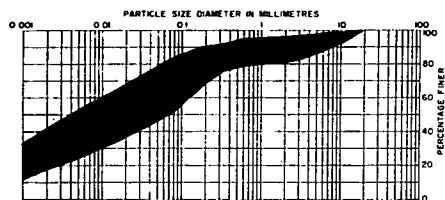
obvious, so visual examinations of graphic distributions can point out relationships which statistical analysis might not clarify. The two methods are in fact equally valuable in their own rights, and complementary.

Statistical analysis has already pointed to the orderly nature of the Lower Till of the coastal and plateau areas and so it is perhaps best to start with this till sheet.

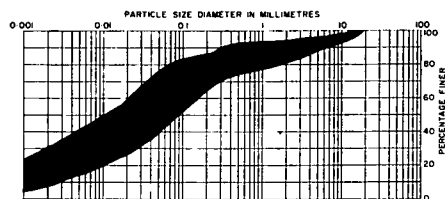
The Lower Till of the coast shows cumulative frequency curves which are extremely similar in shape and therefore general particle size distribution, and when superimposed on one another the curves can be seen to exhibit the same general trends. (Figs.41 and 49).

Similarities are also noted within the samples of the Lower Till of the Plateau area with only a few exceptions.

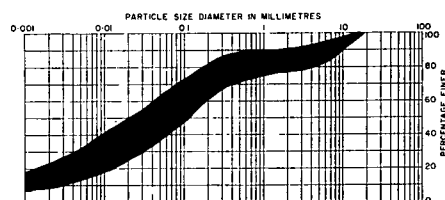
In the Wear valley this marked similarity between the cumulative frequency curves is not seen, and instead one finds curves showing considerable variation. This can be shown to be due to the influence of local bedrock on the composition of the Till. For example at Eighton Banks Quarry (Fig.41) the Till is resting on a Coal Measure sandstone. In the curve it is clearly seen that there is a marked concentration of material between 2-3 ϕ , in the grade size range of fine sand. A different case is seen at Brancepeth Beck, where the till is resting on parent material of Carboniferous shale and mudstone. Here the composition of the till shows a large concentration of material in the less than 6 ϕ grain size - (fine silt and below). (Fig.41). The other clays show intermediate positions between these 2 extremes. Together these two exposures point to the great influence local parent material can have on a till sheet before complete mixing of the till can occur at the glacier base.



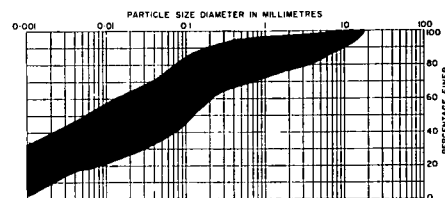
Lower Till of the Wear Lowlands



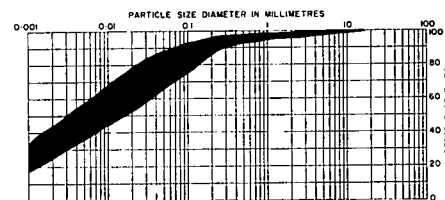
Lower Till of the Magnesian
Limestone Plateau



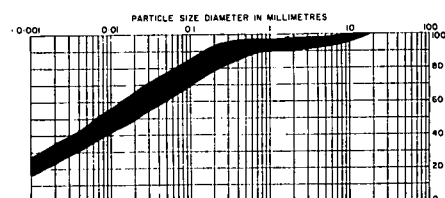
Lower Till of the Coastal
Region



Upper Till



Upper Tees Clay



Upper Wear Clay

The Lower Till of the coastal and plateau areas do show very marked characteristics in common. Almost all the curves are made up of 2 shallow concave sections separated by a small section of varying convexity (Fig.41). What is perhaps most surprising is that this convexity or marked break of slope is found nearly always between 1 and 2 ϕ (in the median sand range 0.2 to 0.8 mms). This break of slope shows a pronounced development also in the Upper Till of the coast and to a lesser extent in the Upper Wear Clay. However the Upper Tees clay on the whole tends to have a different shape of curve with a single large convex segment.

The question arises as to what is the cause of this pronounced break of slope, and whether it is a characteristic of the sub-glacial processes, or is merely connected with parent material lithology.

An attempt was made to evaluate the significance of this break of slope. The first possibility is that it may represent a change in the method of analysis from sieving to sedimentation techniques. This possibility was quickly dismissed, as the break of slope was found to lie in the centre of the sieving range.

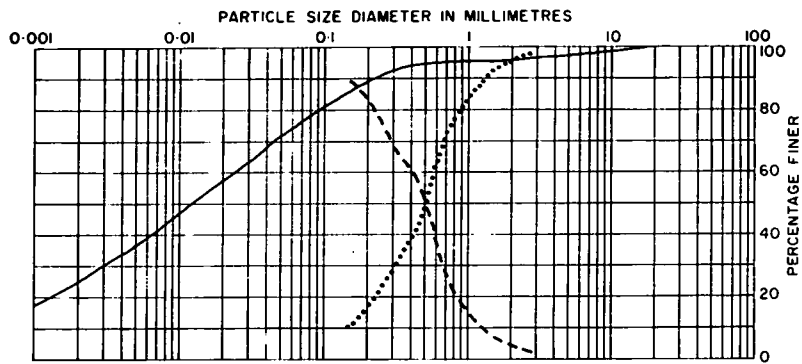
The effect of glacial processes on a cumulative frequency distribution curve is extremely difficult to assess, and so it was decided to examine the sediment itself to see if any differences could be noted within it at the size range associated with the break in slope on the frequency curve. For this purpose the sand fractions, retained on each of the sieves sizes, were examined in detail under a petrological microscope.

A plot was made of the relative proportions of rock fragments and discrete mineral grains present within each of the grade sizes (B.S. sieves Nos. 8, 14, 25, 36, 52, 72, 100). (Figs 50 and 51).

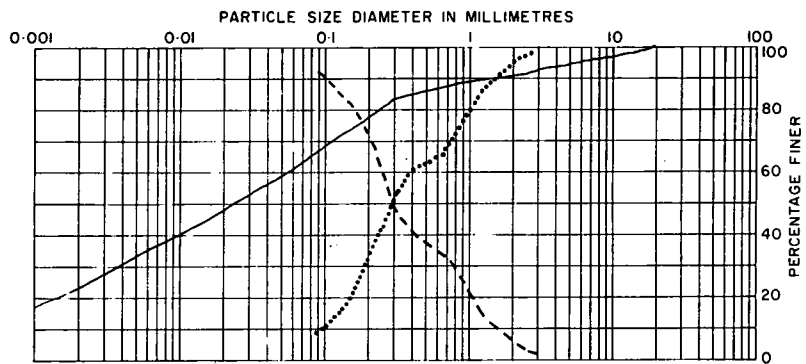
Figure 50.

VAN MILDERT

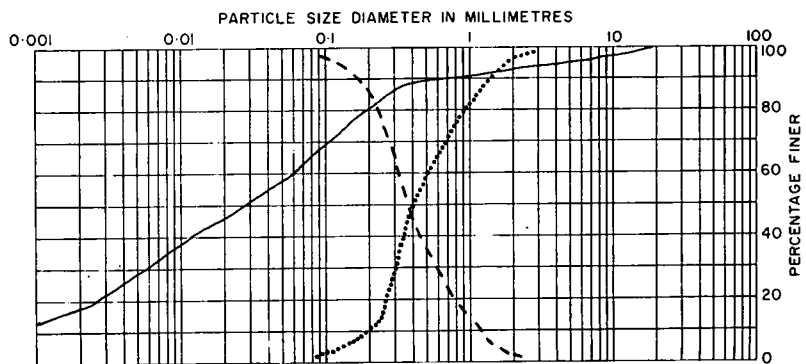
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WINGATE QUARRY D



LOW GRANGE BOWBURN



..... Rock Fragments
 ----- Mineral Grains
 ————— Particle Size Distribution

Fig. 51

Rock fragments and mineral grain.

Low Grange Bowburn		
<u>Sieve size</u>	<u>Mineral grains</u>	<u>Rock fragments</u>
8	1.13	98.87
14	6.55	93.45
25	26.61	73.39
36	47.31	52.69
52	69.51	30.49
72	85.77	14.23
100	93.16	6.84
Wingate Quarry D		
<u>Sieve size</u>	<u>Mineral grains</u>	<u>Rock fragments</u>
8	3.63	96.37
14	13.04	86.96
25	34.85	65.15
36	37.69	62.30
52	51.67	48.33
72	66.82	33.18
100	80.44	19.56
150	86.71	13.29
Van Mildert College		
<u>Sieve size</u>	<u>Mineral grains</u>	<u>Rock fragments</u>
8	4.04	95.96
14	8.57	91.42
25	27.46	72.54
26	59.51	40.48
52	68.44	31.56
72	82.08	17.92
100	87.21	12.79

The analysis shows that on the No.8 B.S. sieve over 95% of the particles present are rock fragments and that less than 5% are discrete mineral grains. With a decrease in sieve aperture sizes proportions of rock fragments decrease, until on the No.36 B.S. sieve the proportion of rock fragments, and mineral grain are approximately equal. (Figs.50 and 51). The No.36 B.S. sieve size coincides with the break of slope on the cumulative frequency curve. On the sieves below the No.36, the mineral grains become dominant over the rock fragments and by the time No.100 B.S. sieve is reached, make up approximately 90% of the total particles present.

The analysis shows that the break of slope is almost precisely associated with a change in the nature of the sediment, from a dominance of rock fragments to one of mineral grains. The break of slope is therefore a reflection of the parent material, in particular of the Carboniferous sandstone, which makes up such a sizeable proportion of the till material. Examination on a number of hand specimens of Carboniferous sandstone, although showing considerable variation in grain size does show a concentration of observations in the grain sizes, 2 to 4 ϕ ; 0.25 to 0.06 mm (i.e. just below the point where the break of slope is observed).

Therefore the break of slope is obviously related to local parent material, and reflects the crushing effect of the ice on the rock fragments within it. In different areas of the country it would appear likely that this break of slope in the cumulative frequency curve would take place at different grain sizes and be a reflection of the nature of the parent material over which the ice was moving.

COARSE FRACTION (2mm to 20mm)

So far in this chapter attention has been concentrated on the finer grain sizes in the particle size distribution curves. The coarse fraction of the particle size distribution can however also be subjected to analysis.

The most common method used by previous workers has been to estimate the gravel content of a till. (That is the percentage of material coarser than a certain grain size). A diameter of 2mm is generally taken as the dividing line between the sand and gravel fractions. The gravel content in percent for the different clays of East Durham is shown in Fig.52.

The total absolute variation is from 2-25%, but the individual clays do show more restricted characteristic distributions.

The Lower Till of the coast is on average the stoniest clay present in Eastern Durham with gravel contents from 9 to 23%. What is particularly significant and of great use for correlation purposes, is the fact that in almost every case the Upper Till of the coast has lower gravel percentages than the Lower Till. Where overlap of values does occur, the Upper Till values are taken from the morainic drift member of the Upper Till succession. No overlap occurs between the normal development of the Upper Till and the Lower Till. In general terms the Upper Till has less than 9% gravel content while the Lower Till has more than 9%.

In the Wear valley the distinction between the Lower Till and the Upper Wear clay is not possible using gravel contents, as the Lower Till in some cases possesses very low gravel values when it has been passing over shale material.

The Lower Till of the plateau area shows considerable variations in gravel content which further emphasises its nature as a

Figure 52

COARSE ANALYSIS

PHI VALUES ON PARTICLE
SIZE DISTRIBUTION CURVE
AT 95% AND 90% FINER.

<u>Lower Till of the Wear Lowlands</u>	Gravel Content Percent	<u>95%</u>	<u>90%</u>
Finchale Priory	17.3	-3.7	-2.9
Windy Nook Quarry	4.7	-1.3	+1.8
Eighton Banks Quarry	9.2	-3.0	+0.5
Brancepeth Beck	12.8	-3.1	-1.8
Biddick Burn	13.8	-3.5	-2.3
Crime Rigg Quarry	12.4	-3.4	-2.0
Spennymoor Industrial Estate	3.9	+0.5	+1.9
Low Grange Bowburn	6.4	-1.7	+0.9
Building site Houghton-le-Spring	11.9	-3.0	-1.3
<u>Lower Till of Magnesian Limestone</u>			
<u>Plateau</u>			
Middridge Quarry	13.7	-3.7	-2.5
Aycliffe Quarry Lower grey clay	14.3	-3.4	-2.5
Middle brown clay	13.7	-3.2	-2.0
Houghton-le-Spring	16.3	-2.0	+1.0
Eppleton	13.5	-3.4	-2.2
Thrislington	5.5	-1.5	+1.7
Coxhoe	7.8	-2.5	+0.7
Bishop Middleham	9.9	-3.0	-1.0
Trimdon Colliery	8.2	-2.2	0.0
Cope Hill	7.7	-2.6	+0.2
Wood Quarry Wingate	6.3	-2.0	+1.0
Wingate Quarry D	8.0	-2.3	-0.5
Sherburn Sand Pit	6.0	-1.3	+1.2
High Moorsley	19.1	-3.5	-2.7
South Hetton	8.4	-2.3	-0.3
Wingate Quarry A	6.8	-2.0	+1.2
Fulwell	6.5	-1.7	+0.6
Tuthill	10.6	-3.3	-1.5
Holy Cross	6.2	-2.0	+0.5
Bradbury	3.5	+0.5	+1.9

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 PHI VALUES ON PARTICLE
 SIZE DISTRIBUTION CURVE
 AT 95% AND 95% FINER
 0

	Gravel content %	<u>95%</u>	<u>90%</u>
<u>Lower Till of Coastal Region</u>			
Blackhall Colliery	24.3	-3.3	-1.5
Salterfen Rocks	15.9	-3.8	-2.8
Bedlam Gill	11.4	-3.6	-2.0
Hesleden Village	8.3	-2.6	+0.1
Dalton Piercy	9.5	-3.2	-1.0
Castle Eden Dene	10.7	-3.1	-1.3
Castle Eden Village	22.8	-3.8	-3.4
Chourdon Point	13.7	-3.3	-2.0
A19 Castle Eden Dene	11.7	-3.3	-1.9
Shotton Colliery	14.5	-3.3	-2.1
Shotton Colliery Brick Pit	19.0	-3.8	-3.0
Hawthorn Quarry	20.5	-3.7	-3.2
Seaham Harbour Brick Pit	5.7	-1.5	+1.2
Dalton-le-Dale	12.7	-3.2	-2.0
Peterlee Petrol Station	18.1	-3.3	-2.6
Peterlee Acre Rigg	10.0	-3.0	-1.1
<u>Upper Till</u>			
Portrack Brick Pit	3.8	-1.4	+2.0
Cerebros Works	6.1	-1.6	+2.0
Hawthorn Quarry	6.0	-1.6	+1.4
Whelly Hill Quarry	22.9	-3.7	-3.0
Crimdon Dene	11.3	-3.3	-1.5
Naisberry Quarry	4.0	+0.5	+2.1
Castle Eden Dene	5.6	-1.2	+1.4
Foxholes	8.2	-2.3	-0.3
Hazel Dene	5.9	-2.3	+0.2
Sheraton Hill Farm	17.5	-3.8	-3.2
Seaton Carew	3.7	0.0	+2.5
Hart	3.6	0.0	+1.3
South Hylton	8.2	-2.5	-0.3
Hilltop east of Sheraton Hill Farm	4.9	-1.0	+1.7
Hesleden Dene	14.8	-3.4	-2.3
Wolviston	2.3	+0.7	+1.5
Low Burn Toft	2.6	+0.8	+1.7
Hart Road	23.3	-3.7	-3.2

	Gravel Content %	PHI VALUES ON PARTICLE SIZE DISTRIBUTION CURVE AT 95% AND 90% FINER	
		95%	90%
<u>Upper Wear Clay</u>			
High Butterby	4.1	-0.3	+2.4
Railway cutting north of Durham	3.0	+1.7	+2.6
Sewer Trench Framwellgate	4.6	-0.6	+1.8
Van Mildert College	3.6	+0.5	+2.4
Electricity Station Ferryhill	8.9	-3.3	0.0
Upper red clay Crime Rigg	3.4	-0.2	+2.4
<u>Upper Tees Clay</u>			
Portrack Brick Pit	5.0	+0.1	+2.9
Wynyard Hall gravel pit	1.5	+2.5	+3.4
Stob Cross	3.0	+1.5	+3.0
Middlefield Farm	4.9	-0.7	+2.1
Carlton	3.5	-0.5	+1.9
Gilly Flat	1.7	+2.7	+3.9
Low Middlefield	3.5	+0.5	+2.5
Whitehouse Farm	5.0	-0.8	+1.7
Sedgefield Road Wolviston	3.5	+0.3	+2.5

transition facies from the Coal Measures till of the Wear Valley to the Magnesian Limestone till of the coastal area.

The Upper Tees Clay shows very low gravel contents with less than 6% in all cases.

The gravel contents of the clay types were analysed statistically using analysis of variance tests. In all cases a null hypothesis was postulated that the results were obtained from the same population.

A. Comparison of sample values of the six main clay types. (data from Fig.52). The following results were obtained.

$$\text{Sample F value} = 7.36$$

$$\text{Table F value, } F_{5 \ 72 \ .01} = 3.20$$

Therefore the null hypothesis is rejected and the sample values are regarded as having been obtained from more than 1 population.

B. Comparison of sample values of the three divisions of the Lower Till. (data from Fig.52). The following results were obtained.

$$\text{Sample F value} = 5.05$$

$$\text{Table F value, } F_{2 \ 42 \ .01} = 5.15$$

Therefore the null hypothesis is retained and the sample values are regarded as having been obtained from the same population.

C. Comparison of sample values of the Upper Till and the Upper Tees Clay. (data from Fig.52). The following results were obtained.

$$\text{Sample F value} = 5.04$$

$$\text{Table F value, } F_{1 \ 25 \ .01} = 7.70$$

Therefore the null hypothesis is retained and the sample values are regarded as having been obtained from the same population.

D. Comparison of sample values of the Lower Till of the Wear Lowlands and the Upper Wear Clay. (data from Fig.52). The following results were obtained.

Sample F value = 8.04

Table F value, $F_{1 \ 13 \ .01}$ = 9.01

Therefore the null hypothesis is retained the sample values are regarded as having been obtained from the same population.

E. Comparison of sample values of the Lower Till of the coastal region and the Upper Till. (data from Fig.52). The following results were obtained.

Sample F value = 7.73

Table F value, $F_{1 \ 32 \ .01}$ = 7.50

Therefore the null hypothesis is rejected and the sample values are regarded as having been obtained from more than 1 population.

These results show that there is a significant difference in the gravel contents between the six main clay types of Eastern Durham. More detailed analysis between individual clay types shows marked similarities between sample values. In the detailed analysis a significant difference in gravel contents is only seen in a single case, between the Lower Till of the Coastal region and the Upper Till. (Example E).

The method of analysis described above owing to its arbitrary nature does not give any emphasis to the shape of the upper part of the cumulative frequency curve. Other workers have also noted this difficulty and to overcome it have plotted the 1% coarser diameter of the cumulative frequency curve distribution against the median diameter. (Bull W.B. 1962). The author however felt that even this

method did not place sufficient emphasis on the coarser grain size fraction, and so it was decided to employ a new technique plotting the 5% coarser diameter against the 10% figure. By doing so a much better estimation of the shape of the coarser part of the cumulative frequency curve is given, which allows differences between the various clays to be seen.

Fig.53a shows a plot of these values. From this the relationship between the two values can be seen following approximately a concave upwards curve.

In diagram A. Fig.53a the Lower Till values are plotted, and these show a marked concentration in the upper right hand portion of the diagram. In diagram B. the Upper Till, the Upper Tees Clay and the Upper Wear Clay are shown, and here the concentration of values is in the lower left hand portion. Some overlap between the two diagrams does occur, but in general terms marked differences are to be seen. As a rapid means of showing differences between deposits this method is extremely useful.

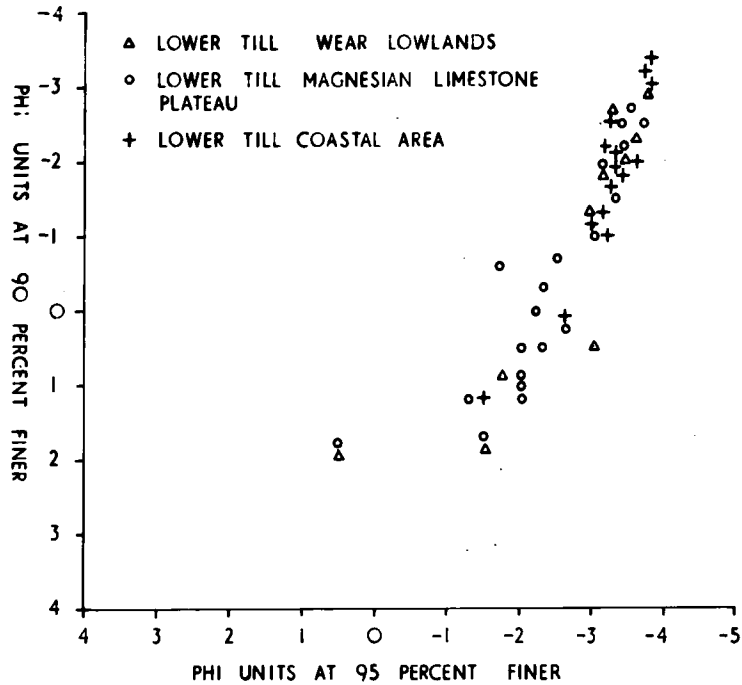
From the gravel content data a map was drawn showing the gravel content of the Lower Till Sheet (Fig.53b). In this case when the data are drawn graphically parallel to the direction of ice movement a noticeable reduction in gravel content is seen once the line of the Magnesian Limestone escarpment has been crossed. It is suggested that this is due to the fact that in this area Magnesian Limestone incorporated diluted the gravel content which existed in the Lower Till of the Wear Lowlands.

WATER LAIN DEPOSITS

For comparative purposes a number of apparently water lain, but non laminated clays were subjected to particle size analysis,

COARSE FRACTION ANALYSIS

A



B

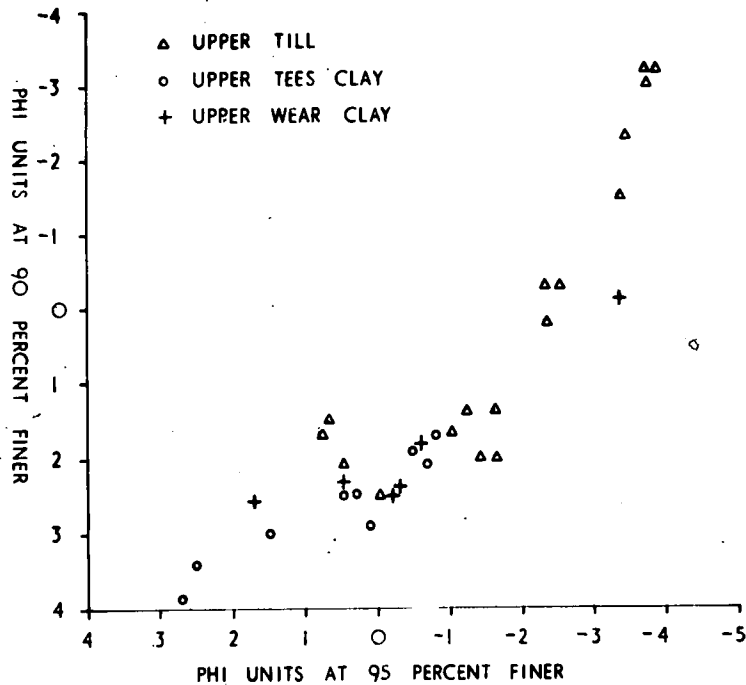
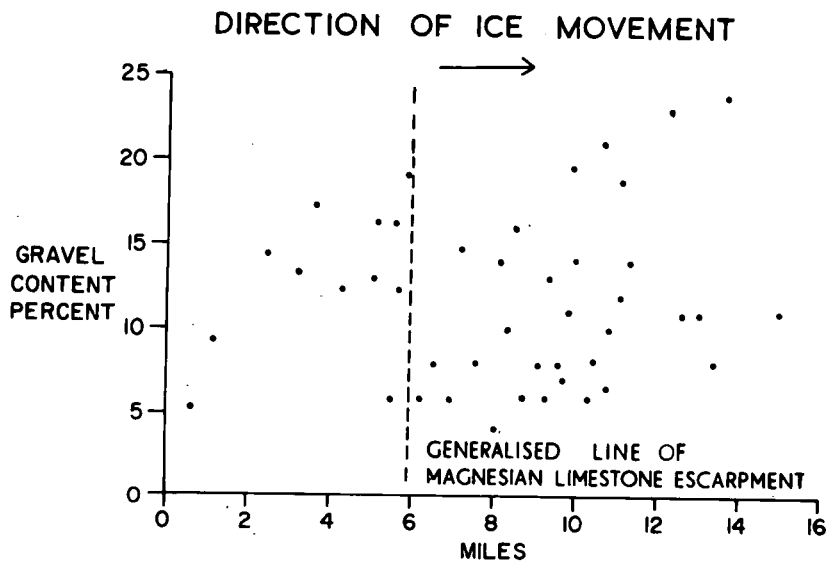
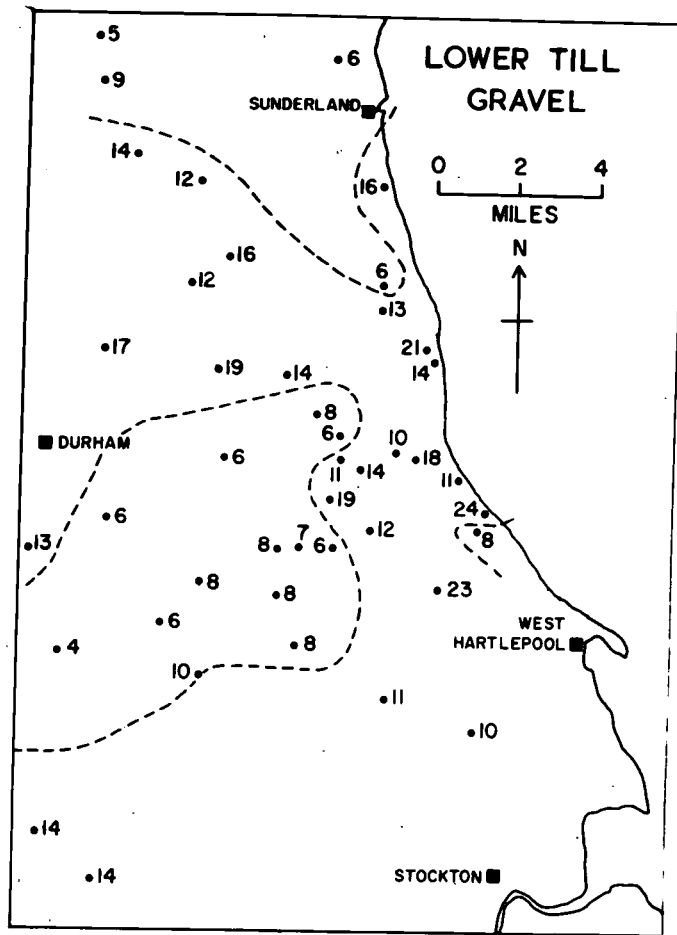


Figure 53 b.



2 examples of which are shown in Fig.54

The great difficulty associated with the study of these particular clays is the high percentage of material which lies in the size ranges, below 2 microns, This necessitated the extrapolation of the curve so that data can be obtained for calculating the mean, sorting and skewness coefficients. Because this extrapolation is in fact only a form of inspired guesswork only a limited number of clays have been analysed. The serious study of such clays requires careful centrifugal methods of particle size analysis not available to the present author.

Up Stoneless Clay - Aycliffe

Median = 8.7 phi

Mean = 9.07 phi.

Sorting = 2.75

Skewness = +0.134

ϕ 5% = 4.6 phi ϕ 10% = 6 phi.

Up Red Clay CED Trench

Median = 8.6 phi

Mean 2 = 8.87 phi

Sorting = 2.85

Skewness = +0.0947

ϕ 5% = 4.4 phi ϕ 10% = 5.4 phi.

The first point to emerge is the high mean, and median values exhibited by such clays with most of the results commonly between 8 and 9 phi. The second point is the low sorting values averaging between $2\frac{1}{2}$ and 3.

Figure 54.

WATER DEPOSITED CLAYS

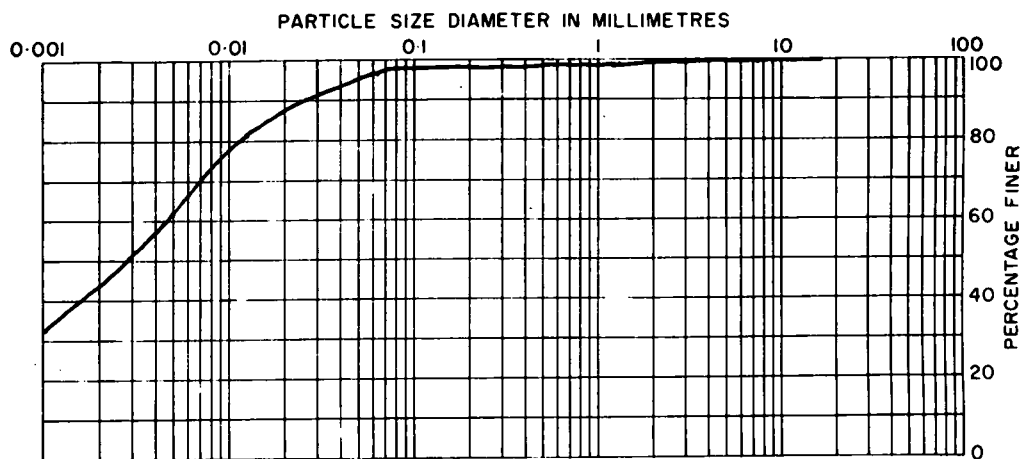
Particle size
diameter in
millimetres.

	1	2
20.0	100.00	100.00
13.0	99.73	99.54
9.7=	99.34	99.44
6.0	98.78	99.37
4.7	98.68	99.32
3.2	98.58	99.28
2.0	98.48	99.22
1.2	98.45	99.21
0.6	98.40	99.04
0.4	98.36	98.94
0.3	98.29	98.77
0.2	98.18	98.53
0.15	98.04	98.24
0.10	97.79	-
0.075	97.60	97.79
0.062	97.39	97.13
0.046	95.56	94.07
0.028	94.78	92.68
0.034	94.00	91.44
0.027	92.43	89.37
0.021	92.04	87.27
0.016	87.33	82.93
0.013	83.40	80.84
0.0090	77.12	74.72
0.0066	70.05	67.42
0.0048	64.56	59.40
0.0033	59.07	53.48
0.0022	51.34	46.33
0.0014	42.58	37.45
0.0010	-	32.94

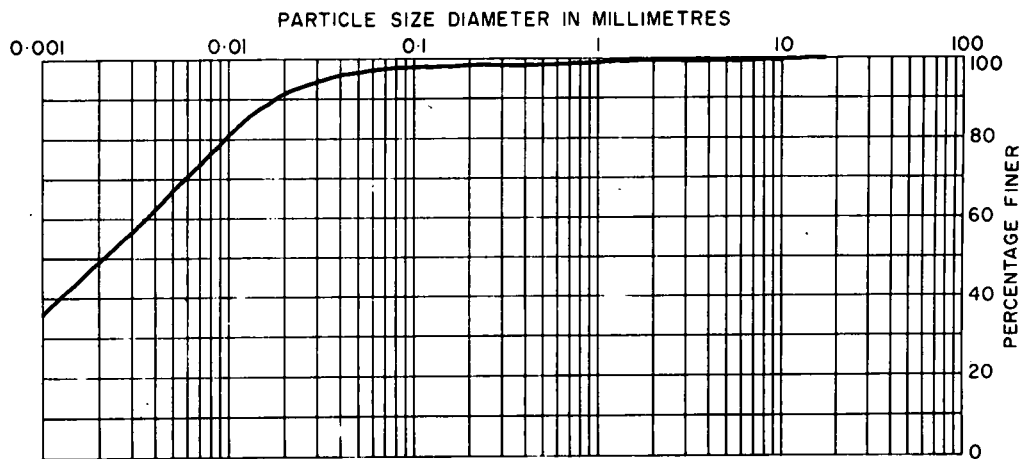
- 1 - Aycliffe Red Clay
2 - Red Clay Castle Eden Dene

Figure 54.

Upper red clay, Castle Eden Dene.



Stoneless clay, Aycliffe.



These results are in marked contrast to the stony clay deposits, which in nearly every case have mean and median values below 8 phi and sorting values of more than 3.

An interesting study, but one which could not be attempted here because of lack of equipment would be to discover if every variation in clay types was to be seen between the stoniest Lower Tills and the water deposited clays. For it may well be that a distinct change in particle size distribution is to be found associated with the change from a sub glacial environment of deposition to that of a sub-aerial condition.

CONCLUSIONS

The results of the particle size analysis of the stony clays of Eastern Durham reveal certain interesting results. They show beyond doubt that analysis in terms of the sand, silt and clay content of a sample, in contrast to American experience, is of little value for purposes of correlation. This fact is possibly due to the very great lithological variety shown by the parent material of the tills, the Carboniferous Coal Measures, in Eastern Durham.

In agreement with Shepps' work, the research has demonstrated that the upper clays in any glacial sequence have a lower percentage of coarse material compared with basal till deposits. This appears to be due to the fact that the upper clays are to a great extent formed by them reworking, of already deposited material.

At specific locations the way in which a till particle size distribution is affected by local parent material is shown, but at the same time on a broad scale the very small effect on size distribution within a till sheet, caused by the erosion of a new and widespread parent material is noted.

A general orderliness and similarity between the different deposits is seen, but on the evidence available it is difficult to assess whether this is due to the processes of deposition, or to basic similarities in the types of parent material from which the deposits were derived.

Statistical analysis of mean values and gravel contents is found to be useful in showing similarities and differences between deposits.

One of the most significant facts to emerge from this study is the nature of the relationships between the various properties making up the total particle size distribution curve. In many cases it must be admitted that a reasoned interpretation of these interrelationships cannot be made owing to the general lack of data within the British Isles at the present time. Unless some standardisation of the reporting of results can be achieved in the near future it would appear likely that it will be a very long time before comparative data for different parts of the country can be obtained.

Chapter 9

CLAY MINERALOGY AND SILT MINERALOGYIntroduction.

Because material of less than 2 microns particle size diameter makes up 20-40% of most of the Durham samples, it is obviously important that some attempt should be made to study this size fraction. A number of techniques are available for such study including X-ray diffraction, differential thermal analysis, infra-red spectrometry, and electron microscopy.

The use of such advanced techniques on glacial deposits has only been employed recently and particularly in the United States. Here work has been concentrated on the X-ray diffraction study of the clay minerals within glacial deposits, in particular, with respect to their weathering characteristics. (Droste J.B. 1956 and Bhattacharya N. 1962).

In the British Isles work on the clay mineralogy of glacial deposit has been restricted. Goodyear. R. (1962) has published analyses of the clay and silt mineralogy of the tills of Holderness, while the Macaunlay Institute in Scotland has undertaken considerable work on the clay mineralogy of Scottish drifts and their associated soils (Glentworth R., Mitchell B.D., and Mitchell W.A. 1964) using X-ray diffraction, and Differential Thermal Analyses. In the Pennines Johnson G.A.L. (1963) includes D.T.A. curves for the clay sized material from soliflution deposits and boulder clays formed within the Moorhouse Nature reserve.

What does not exist within the British Isles is any general knowledge of the clay mineralogy of any of the different till sheets, nor the areal distributions of differing clay minerals. It was with the idea of providing such information for a small area that this work in Eastern Durham was attempted.

Method of Study.

Material of less than 1.4 microns equivalent particle size diameter was separated by sedimentation techniques from the unweathered portion of the tills using a modified method described by Mackenzie R.C. (1955). (Appendix 8).

This material was subjected to X-ray diffraction analysis using Copper radiation produced by a Phillips X-ray diffractometer.

Recognition of Clay Minerals.

The basic principle underlying the identification of minerals by X-ray analysis is that each crystalline substance has its own characteristic atomic structure which diffracts X-rays in a characteristic pattern. The recognition of the pattern uniquely identifies the diffracting substance.

The main clay minerals found to be present in most superficial deposits are kaolin, illite, chlorite and montmorillonite. Each of these minerals gives a characteristic peak at a given Angstrom unit measure on the diffractometer trace.

<u>Mineral</u>	<u>Main Peak position (Angstrom units).</u>
Kaolin	7A
Illite	10A
Chlorite	14A
Montmorillonite	15-17A

Theoretically the identification of clay minerals presents no problem as each mineral gives a characteristic diffraction pattern.

Unfortunately however where mixtures of clay minerals exist, the identification of minerals becomes exceedingly difficult owing to the fact that many of the diagnostic reflections of the different minerals show a marked tendency to overlap. To overcome this problem certain techniques have been developed (heat treatment and glycerol treatment) which in favourable circumstances do allow the positive identification of a mineral in a mixture. Even with these techniques however the identification of some minerals still proves exceedingly difficult.

For comparative purposes pure samples of all the main clay minerals which were likely to be found in quantity in the glacial tills of Eastern Durham were analysed on the diffractometer. (Fig.55). This was done so that the actual diffractometer traces produced by these minerals could be studied in detail.

KAOLIN (Fig.55)

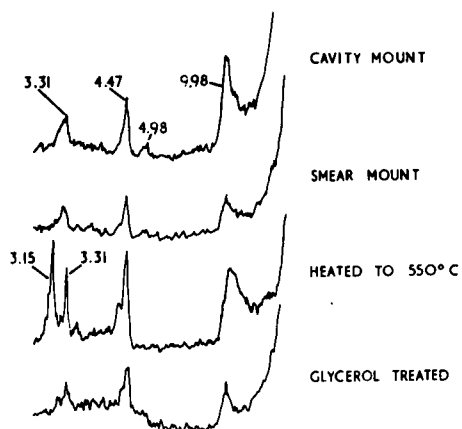
Diffraction Pattern.

Peak spacing in Angstrom Units	<u>Intensity of peak</u>
<u>d (A)</u>	
7.16	10 +
4.46	4
4.36	5
4.18	5
4.13	3
3.84	4
3.174	2
3.57	10 +
3.37	4
3.14	3
3.09	3
2.75	3
2.55	6

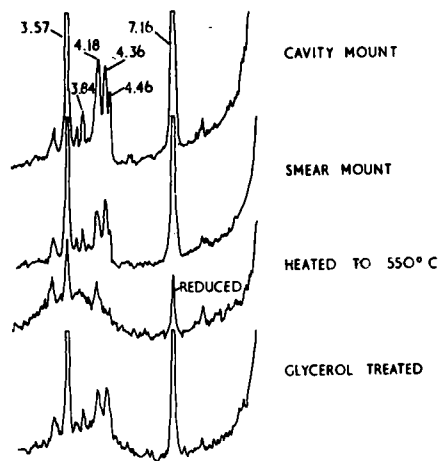
X-RAY DIFFRACTION CURVES OF MAIN
CLAY MINERAL TYPES

PEAK VALUES IN ANGSTROM UNITS

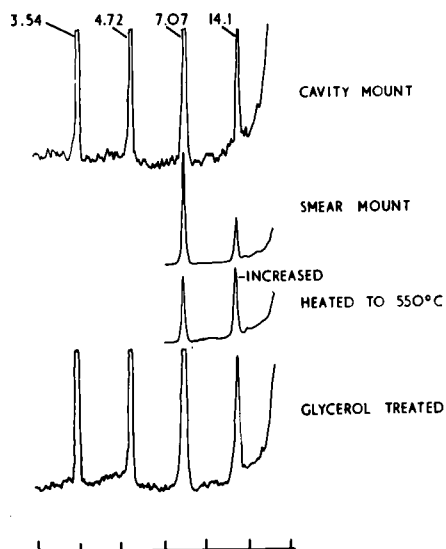
ILLITE



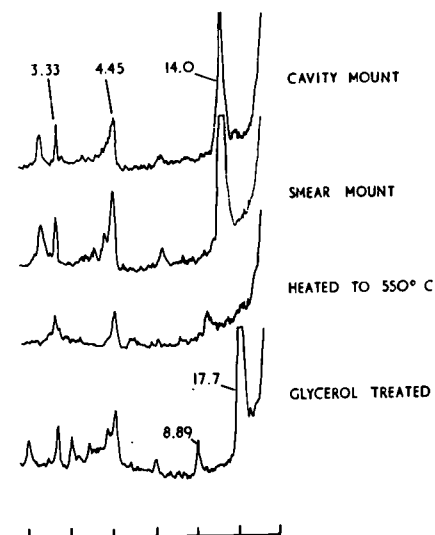
KAOLINITE



CHLORITE



MONTMORILLONITE



Kaolin is recognised by a characteristic basal reflection of between 7.15 to 7.20A, and other diagnostic peaks at 4.18A and 3.57A. Of these the 4.18A reflection is particularly useful as this reflection does not coincide with the peaks of any of the other clay minerals or of quartz.

Upon heating to 550° - 600° the crystallinity of kaolin is destroyed, and the diffraction peaks disappear completely, or are considerably reduced.

No change in the basal spacing is seen after glycerol treatment.

CHLORITE (Fig.55)

Diffraction pattern.

Peak spacing in Angstrom units	<u>Intensity of peak</u>
<u>d (A)</u>	
14.1	7
7.07	9
4.72	8
4.59	1
3.54	10
2.84	5
2.58	3
2.53	6

Chlorite is recognised by the presence of a 14.0 to 14.3A peak, and also by a 4.72A peak.

The second value basal reflection of chlorite at 7.07A is exceptionally close to the basal reflection of kaolin at 7.16A, and causes much confusion in identification procedures. The non-iron rich chlorites generally possess strong intensity peaks for the first five

orders of the basal reflections. On the other hand the iron rich chlorites possess weak, first, third and fifth order reflections, but strong second and fourth order reflections. This of course tends to make the identification of iron rich chlorites in the presence of kaolin very difficult indeed.

The certain detection of chlorite in such conditions needs the identification of the first order basal spacing of between 14.0 - 14.3A, as no similar peak is produced by kaolin. A peak at 4.7 to 4.8A is also a good indication of the presence of chlorite if this can be separated from the basal reflections of the mica/illite group of minerals, which occur between 4.47 - 4.98A.

When present in small quantities the first order basal reflection of the iron rich chlorites are sometimes not detectable on the diffractometer trace. This means that only a 7.07A peak will tend to be visible as the third order reflection at 4.72A will be also weak. Under such conditions the positive identification of chlorite in the presence of kaolin is virtually impossible. In some cases this problem can be overcome by heating the sample to c. 550 - 600°C for 2-4 hours. This has the effect of increasing the first order reflection at 14.1A, and diminishing the second, third and fourth order reflections, so that the 14.1A reflection becomes visible on the diffractometer trace. However if the crystallinity of the chlorite is poor, the mineral may well decompose and no increase in the 14.2A peak will occur. Heat treatment to c 550°C will to some extent destroy the crystallinity of kaolinite as already mentioned.

The basal spacing of the chlorite reflection is not effected by glycerol treatment.

ILLITE. (Mica mineral) (Fig.55)Diffraction pattern.

Peak spacing in Angstrom units.

<u>d (A)</u>	<u>Intensity</u>
9.98	Strong
4.98	Weak
4.47	Strong
4.11	Very weak
3.7	Very weak
3.4	Very weak
3.31	Moderate
3.2	Very weak
2.98	Weak
2.84	Very weak
2.56	Strong

The illite and mica minerals are characterised by first order basal spacings at about 10A. Other diagnostic basal spacings occur at c.4.98A and 3.31A. These spacings are in nearly all cases sufficient to allow positive identification of these minerals. Some difficulty in distinguishing illite from mixed layer clays (illite - montmorillonite) may however occur.

Heat treatment of illite/mica has little effect on these minerals, although a sharpening of the 10A and 3.31A peaks is sometimes noted. A new peak at 3.15A is also developed. Glycerol treatment has no effect on illite (mica minerals). In the presence of mixed layer clay minerals the illite peak is sharpened after glycerol treatment owing to the expansion of the mixed layer minderals to higher values.

MONTMORILLONITE. (fig.55)

Diffraction pattern - Glycerol treated.

Peak spacing in Angstrom units

<u>d (A)</u>	<u>Intensity</u>
17.7	10
8.85	4
5.9	3
4.33	2
3.5	5
2.95	4

In the normally hydrated state the basal spacings of monmorillonite are variable and dependent mainly on the degree of hydration of the mineral. Identification of the mineral is usually achieved by the use of organic complexes (glycerol) which expand the lattice, and at the same time give rise to a high degree of regularity in the spacing. The use of glycerol gives spacings of c 17.7 to 17.8A. for the main peak and also produces a smaller peak at 8.85A to 8.90A.

When heated to temperatures of 550°C the basal spacing is decreased to c 10A and is greatly reduced in intensity.

MIXED LAYER MINERALS (Illite/Montmorillonite).

These are a complex series of minerals, composed of the interstratification of more than one clay mineral. The commonest mixed layer structure, is the random irregular interstratification of layers in which there is no uniform repetition of the layers. Mixed layers of illite-montmorillonite seem fairly common in nature and are

particularly difficult to study. In many cases investigations have failed to recognise their presence. (Grim R.E. 1953).

In the case of such random stratification of layer clay minerals a non-integral series of reflections is obtained from the basal planes. The basal reflections are in fact composites of adjacent reflections of the same orders of the different layers and at an intermediate position between them, or composites of overlapping reflections of different orders of the different layers. The actual position and intensity of the composite reflections varies with the relative abundance of the different individual layers.

Illite-montmorillonite mixed layer minerals generally give peaks between 10-17Å when they are dry, collapsing to 10Å after heat treatment. After glycerol treatment the layers are expanded to high angstrom values, generally about 17Å.

Other non clay minerals have also been identified in the clay sized fraction of the Eastern Durham stony clays. These include quartz, calcite, dolomite, and feldspar.

QUARTZ.

Quartz is a very common constituent in natural soils, and is characterised by a strong diffraction pattern which enables the detection of quartz in possible quantities below 5%. The reflections are almost invariable.

Diffraction pattern.

Peak spacing in Angstrom units	<u>Intensity</u>
<u>d (Å)</u>	
4.26	3.5
3.343	10.0
2.438	1.2
2.282	1.2

CARBONATECalcite and Dolomite

Calcite and dolomite are important constituents of the less than 2mm size fraction of the Durham tills. Both have a characteristic X-ray pattern.

CALCITE.Diffraction pattern

Peak spacing in Angstrom units	<u>Intensity</u>
<u>d (A)</u>	
3.86	1.2
3.035	10.0
2.845	0.3
2.495	1.4
2.285	1.8

DOLOMITE.Diffraction pattern

Peak spacing in Angstrom units	<u>Intensity</u>
<u>d (A)</u>	
4.025	0.3
3.690	0.5
2.886	10.0
2.670	1.0
2.540	8
2.405	1.0
2.192	3.0

FELDSPAR

These were present in only minor quantities.

PLAGIOCLASE is recognised by :

- i) 2 very strong reflections in the region 3.17 to 3.22 Angstrom.
- ii) a medium reflection. 6.4 to 6.5A.
- iii) 3 medium to strong reflections - spacing 4.03 to 4.05A.
3.74 to 3.78A and 3.61 to 3.67A.

ORTHOCLASE is recognised by :

- 1. Strong reflections at 3.79A.
- 2. Strong reflections at 3.32A.

A. The Clay mineralogy of the Stony Clays of East Durham.

- Qualitative assessment.

Introduction

A total of more than 75 samples were subjected to X-ray diffraction analysis. Samples were prepared initially as cavity mounts and run between 2 to 32 degrees on the X-ray goniometer. (20 to 2.3 Angstroms). In this range the majority of the diagnostic clay mineral reflections are found.

The diffractometer trace was then analysed and the main minerals identified. When no definite chlorite peak was noted at about 14.0 Angstroms, the sample was heated to 550 degrees C. for two hours and re-run through the diffractometer. This often allowed the detection of a chlorite peak. When a broad and diffuse peak was noted at about 10.0 Angstroms, the sample was glycerol treated, and re-run through the

diffractometer. This sometimes revealed a new peak at about .17 Angstroms, indicating the presence of illite/montmorillonite mixed layer clay minerals.

Results

1. The Lower Till

The clay mineralogy of the Lower Till shows very pronounced similarities in its three divisions (Fig 56). All the samples are characterised by the presence of illite (and mixed layer minerals) (peaks at 9.8 to 10.0 , and 4.45 Angstroms), kaolin (peaks at 7.16 , 4.45, 4.18, and 3.5 Angstroms), quartz (peaks at 4.26 and 3.33 Angstroms).

The diffuse nature of a number of the 10 Angstrom peaks suggests the presence of at least small quantities of mixed layer clay minerals. This is very marked in the Houghton-le-Spring, and Holy Cross samples. Other samples show very pronounced 10 Angstrom peaks indicating well crystalised illite and only subsidiary amounts of mixed layer minerals. (e.g. High Moorsley and Spennymoor Industrial Estate).

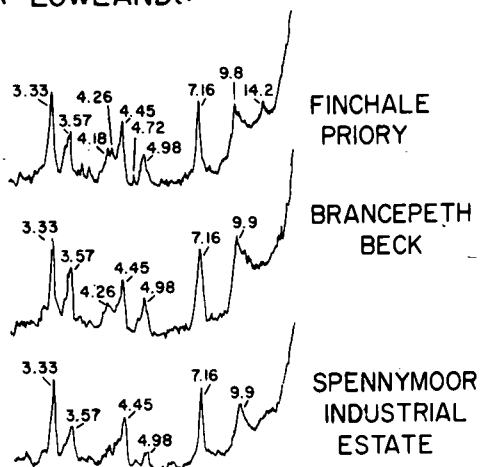
Chlorite is detected in a number of the samples by the presence of a 14 Angstrom peak. (e.g. Finchale Priory, Holy Cross, and Shotton Colliery). The absence of a peak at 14 Angstroms does not necessarily preclude the presence of chlorite in small quantities, below the resolving power of the diffractometer. Heat treatment of samples which did not show a 14 Angstrom peak sometimes revealed one. (e.g. Spennymoor Industrial Estate and Castle Eden Dene Fig. 58). In these samples the 7.16 Angstrom peak was completely destroyed suggesting very strongly that kaolin was present in considerably greater quantities than chlorite.

The quartz peaks at 4.26 and 3.33 Angstroms indicate that colloidal quartz is present with diameters of less than 1.4 microns.

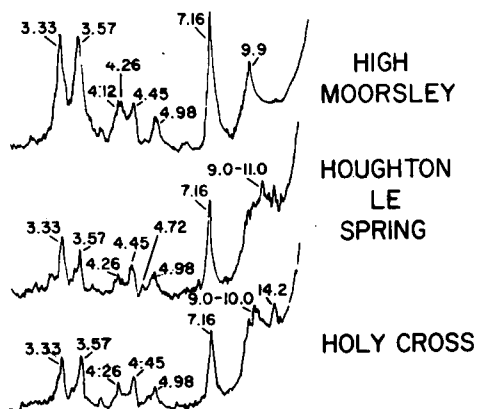
X-RAY DIFFRACTION CURVES OF LOWER TILL

PEAK VALUES IN ANGSTROM UNITS

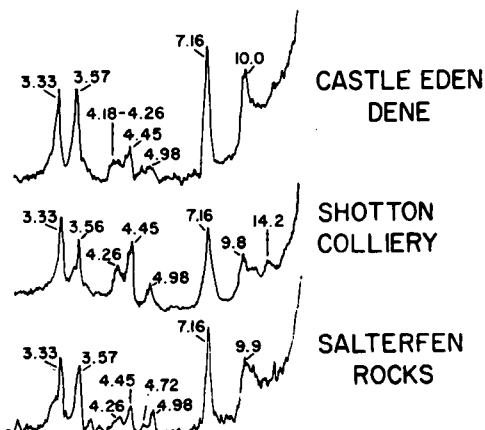
WEAR LOWLANDS



MAGNESIAN LIMESTONE PLATEAU



COASTAL AREA



2. Upper Till

The Upper Till shows an almost identical clay mineralogy to that of the Lower Till. Two slight differences are noted (Fig 57). The first is that a 14 Angstrom peak is nearly always present in the Upper Till. This suggests that chlorite is either better crystallised in these samples or occurs in greater proportions than in the Lower Till. The second point is that the 9.9 Angstrom peak is generally much sharper than in the majority of the Lower Till samples. This suggests that mixed layer clay minerals are of lesser importance in the Upper Till than in the Lower Till.

The main minerals present in the Upper Till are illite (peaks at 9.8 to 9.9, 4.98, and 4.45 Angstroms), kaolinite (peaks at 7.16, 4.45, 4.1, and 3.5 Angstroms), quartz (peaks at 4.26 and 3.33 Angstroms) and chlorite (peaks at 14.2, 7.16, 4.72, and 3.54 Angstroms).

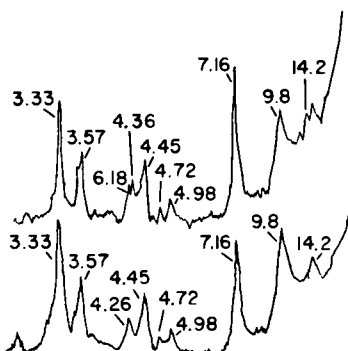
3. Upper Tees Clay.

The Upper Tees Clay is characterised by the presence of considerable quantities of mixed layer clay minerals, and the lesser importance than usual of the clay mineral illite (Fig 57). The importance of the mixed layer minerals is shown by a series of broad diffuse peaks between 9.0 to 11.0 Angstroms. Kaolin is present in all the samples (peaks at 7.16, 4.45, 4.1 and 3.5 Angstroms), as is quartz (peaks at 4.26 and 3.33 Angstroms). Chlorite nearly always appears to be present and is identified by a rather diffuse 14.0 Angstrom peak and a marked hump to the 4.98 Angstrom illite peak at 4.72 Angstroms. Glycerol treatment of the Upper Tees samples expands the lattice of the mixed layer clay minerals, and allows the small illite peak to be visible. (Fig. 58).

X-RAY DIFFRACTION CURVES OF STONY CLAYS

PEAK VALUES IN ANGSTROM UNITS

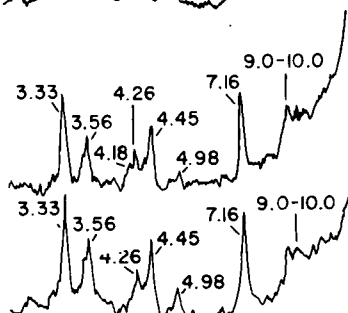
UPPER TILL



UPPER TILL
CASTLE EDEN
DENE

HART ROAD

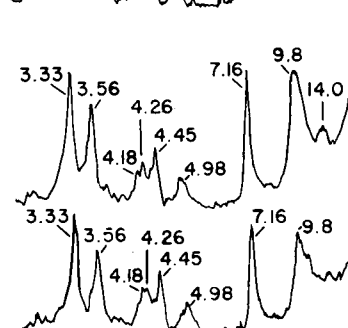
UPPER TEES
CLAY



GILLY FLAT

WYNYARD
HALL

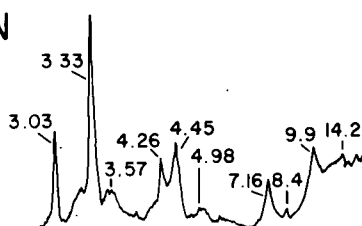
UPPER WEAR
CLAY



RAILWAY
CUTTING
NORTH OF
DURHAM

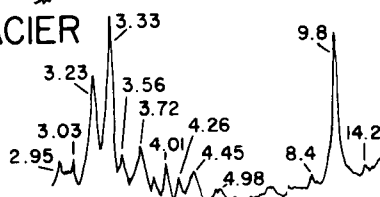
HIGH
BUTTERBY

SCANDINAVIAN
DRIFT



WARREN
HOUSE GILL

MODERN GLACIER
(NORWAY)



SVARTISEN
GLACIER

4. Upper Wear Clay.

The Upper Wear Clay is characterised by X-ray diffraction traces almost identical to those of the Lower Till of the Wear Lowlands (Fig.57) Kaolin (peaks at 7.16, 4.45, 4.18, and 3.5 Angstroms), illite (peaks at 9.8 to 10.0, 4.98, and 4.5 Angstroms) together with mixed layer minerals, and quartz (peaks at 4.26 and 3.33 Angstroms) are dominant, although chlorite appears present in nearly all samples (peaks at 14.0 to 14.2, 7.16, 4.72 and 3.54 Angstroms). Of particular interest with these samples is the effect produced by glycerol treatment. In many cases this leads to the almost complete disappearance of the 10 Angstrom peak, and the appearance of new peaks close to 17 Angstroms. This strongly suggests that montmorillonitic minerals dominate the mixed layer structures. (Fig 58).

5. The Scandinavian Drift.

The Scandinavian Drift is the only clay deposit within East Durham which shows any variation from the normal sequence of clay minerals as set out above. Even in this case the variations are of degree rather than of kind. (Fig.57).

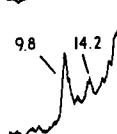
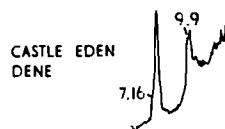
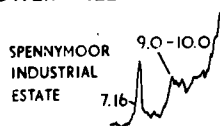
The clay sized material of the Scandinavian Drift is dominated by the presence of quartz (peaks at 4.26, and 3.33) to a degree not seen in the other Eastern Durham stony clays. Illite together with mixed layer minerals are indicated by a series of diffuse peaks between 9 to 11 Angstroms, and a well marked peak at 4.45 Angstroms.

In this sample the 7.16 peak of kaolin is very small, and this coupled with the weakness of both the 4.1 and 3.5 Angstrom peaks, suggests that kaolin is present in only small quantities. A small peak at 14.2 Angstrom indicates that some chlorite is also present.

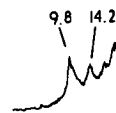
X-RAY DIFFRACTION CURVES

PEAK VALUES IN ANGSTROM UNITS

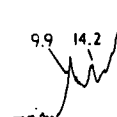
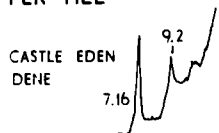
LOWER TILL



HEATED TO 550° C

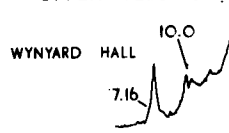


UPPER TILL

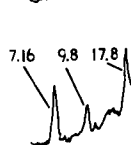
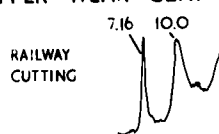


HEATED TO 550°

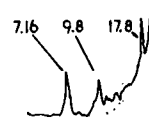
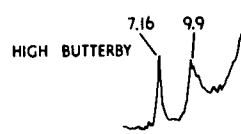
UPPER TEES CLAY



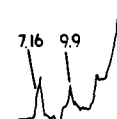
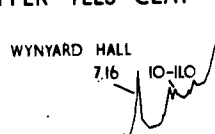
UPPER WEAR CLAY



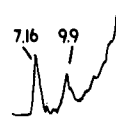
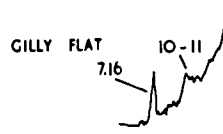
GLYCEROL TREATED



UPPER TEES CLAY



GLYCEROL TREATED



Of particular interest in this sample are two peaks at 8.4 and 3.03 Angstroms which are generally not found in any of the other stony clays of East Durham. Both of these peaks however represent rock minerals rather than clay minerals. The 8.4 Angstrom peak represents an amphibole mineral, and therefore strongly suggests at least partial derivation from igneous material. The 3.03 Angstrom peak represents calcite, and is probably due to the grinding of Chalk material which is found in this deposit.

7. Svartisen Glacier.

For comparative purposes a till deposit from a present day glacier in Norway, the Svartisen Glacier was analysed. (Fig 57). In contrast to the Durham stony clays this sample is made up almost exclusively of rock minerals rather than clay minerals. To all intents and purposes this is a "rock flour" composed of muscovite mica (peak at 9.8 Angstroms), feldspar (peak at 3.23 Angstroms), and quartz (peak at 3.33 Angstroms). A small peak at 8.4 Angstroms indicates the presence of an amphibole type of mineral. No other minerals appear to be present in any quantity.

GENERAL

From the above study it can clearly be seen that the differences between the clays of Eastern Durham are matters of degree rather than of kind.

In all the stony clays without exceptions, illite and mixed layer clays, kaolin and quartz are found. Only chlorite appears to be variably present, and this may well be due to the fact that in most of the clays it is present in quantities which either just allow, or no not allow positive identification. The inability to make a positive

identification of chlorite does not exclude its possible presence in small quantities.

B. Quantitative estimation of clay minerals.

Introduction.

The types of equipment used in this analysis did not allow the accurate determination of the actual quantities of clay minerals present within each sample.

However certain deductions about the relative abundance of clay minerals can be made. Quantitative analysis by X-ray diffraction is based on measurement of diffracted X-ray intensity. It is assumed that the intensity in terms of peak height or peak area of a given mineral is a direct measure of the proportion of that mineral in a mixture. Complications to this general rule are introduced by the crystallinity of the mineral being diffracted, as it has been found that in constant proportions the more crystalline mineral will produce the more intense peaks. It is therefore essential that the relative crystallinity of the materials being analysed is known. This is generally achieved by diffracting standard minerals and observing differences in intensity of the diffraction patterns. The one serious drawback with this method however is the fact that crystallinity of the mineral in the sample being analysed may bear little relation to the standard mineral being analysed.

Of all the minerals commonly found in the Eastern Durham stony clays in the size range of below 1.4 microns quartz is undoubtedly the most crystalline. This means that its presence can be detected when only very small amounts of this mineral are present. Fig.55 shows the relative intensity of the peaks produced by the clay minerals when these are diffracted as single minerals. These indicate that the crystallinity

of chlorite, kaolin and montmorillonite is of a high order, and gives well pronounced peaks. Of great significance however is the fact that illite even when present as the sole mineral does not give rise to particularly well developed peaks.

The relative crystallinity would therefore appear to be as follows :

1. Quartz
2. Chlorite
Kaolin
Montmorillonite
3. Illite and mixed layer mineral

The result of this means that the occurrence of two equally intense peaks in a sample mixture of quartz and illite, would indicate that illite was present in considerably greater proportions than quartz. It also means that illite is unlikely to be detectable in small quantities.

Results.

In order to gain more exact information of the quantities of the different clay minerals present in the less than 1.4 micron size range of the Eastern Durham stony clays a series of clay mineral mixtures using standard clay mineral types were made up.

In all a total of 30 mixtures were prepared and subjected to X-ray analysis, until results approximating those of the Durham clays were obtained.

Fig.59 shows the diffractometer trace of a mixture of 25% quartz, 25% kaolin, 25% chlorite, and 25% illite to illustrate the relative crystallinity of the minerals present. It will be seen that peaks occur at all values similar to those of actual Durham clays, (Figs.55,56,57,59) but that the relative heights of the peaks show considerable discrepancies. In particular Illite is very greatly under represented

X-RAY DIFFRACTION CURVES OF PREPARED MIXTURES OF STANDARD MINERALS

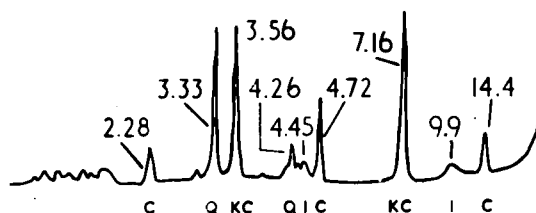
PEAK VALUES IN ANGSTROM UNITS. FIGURES IN PERCENT

ILLITE 25

KAOLINITE 25

QUARTZ 25

CHLORITE 25

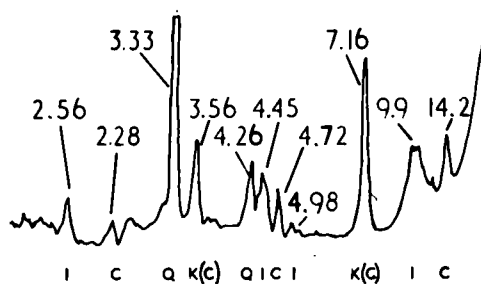


ILLITE 60

KAOLINITE 20

QUARTZ 15

CHLORITE 5

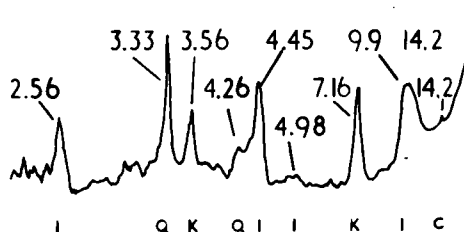


ILLITE 72.5

KAOLINITE 20

QUARTZ 5

CHLORITE 2.5



I ILLITE K KAOLINITE Q QUARTZ C CHLORITE

and chlorite over represented in Fig.59.

With all the 30 prepared mixtures tried, no exact fit with the Durham clays could be achieved, probably due to differences between the crystallinity of the minerals in the laboratory mixtures, and those in the actual field samples.

However it was found that the majority of the Durham clays fitted closely to two of the sample mixtures.

These mixtures had compositions of :- (Fig.59)

	<u>A(%)</u>	<u>B(%)</u>
Illite	60	72.5
Kaolin	20	20
Quartz	15	5
Chlorite	5	2.5

It can therefore be stated that illite (together with mixed layer clay minerals) is the dominant clay mineral present in all the Durham stony clays with the possible exception of the Scandinavian Drift. The actual quantity present probably varies from 40-70% in individual samples, but it seems likely that in many samples illite (and mixed layer clays) make up more than 50% of each individual sample.

Kaolin is the mineral of second importance in terms of percentages. It shows less absolute variation than the illite with the majority of the samples containing between 15-25% kaolin. In a few isolated samples greater percentages of kaolin probably do occur.

Despite the height of the peaks produced by quartz it is certain that this mineral occurs in only minor quantities of less than 15% in almost every case. A figure of 5%-10% would appear to be an approximate modal value. What is of interest is the fact that quartz is

detectable in every sample analysed, even at this particularly fine grain size.

In every sample analysed chlorite, if it occurs at all is present in quantities of less than 10% and possibly less than 5%. Below 5% even with the chlorite of the standard mixtures this mineral is detectable only with difficulty using diffractometer techniques, and at concentrations of 2.5% only the slightest indication of its presence is seen. It may well be the case that if a poorly crystalline chlorite occurred in the Durham clays it would not be detected in concentrations below 15% with any degree of certainty.

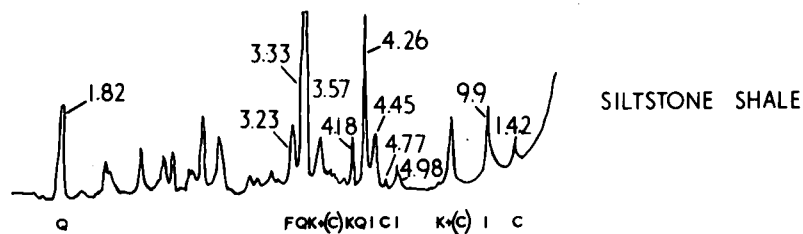
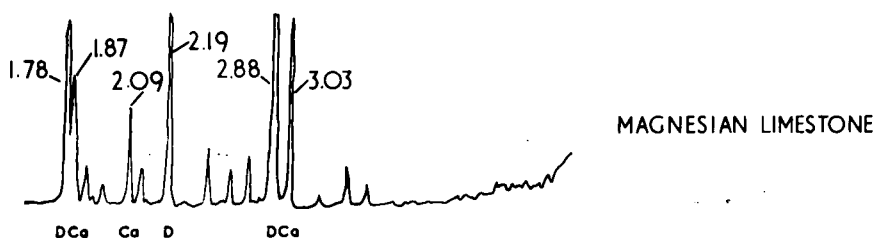
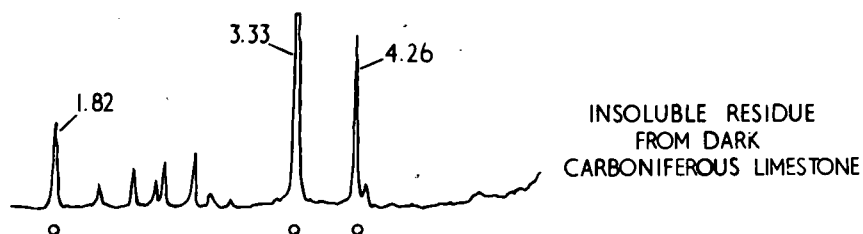
Origin of the Clay minerals

The great similarity of the clay mineral content is one of the main features noted in this study of the different stony clays of Eastern Durham. The question arises as to whether this mineralogy is explicable in terms of the environment of deposition e.g. wetting of the clay minerals in a metamorphic environment at the base of a glacier or whether all the clay minerals have been derived solely from the erosion of nearby rock types.

To test this second hypothesis studies of the clay mineralogy of the local parent materials were made.

By far the largest outcrop within the area of detailed study is made up by the Magnesian Limestone. X-ray analysis of this rock reveals that only the minerals dolomite and calcite are present in any quantity and therefore the contribution of this rock type to the clay mineralogy of the tills would be negligible (Fig.60). Analysis of the clay deposits strongly suggests that the material of the Magnesian Limestone is not broken to such very fine grain sizes by ice action. (i.e. to below 1.4 microns).

X-RAY DIFFRACTION CURVES OF PARENT MATERIAL IN EAST DURHAM AREA



Q QUARTZ
Ca CALCITE
D DOLOMITE
C CHLORITE
I ILLITE MICA
K KAOLINITE
F FELDSPAR

PEAK VALUES IN ANGSTROM UNITS

The only other limestones of any importance within the area are the Lower Carboniferous Limestones of the Pennines. These are dominantly composed of calcite, but the dark colours of many of them suggests the presence of impurities. As a consequence pieces of this limestone were dissolved in weak hydrochloric acid, and the insoluble residue subjected to X-ray analysis. The analysis showed that the vast majority of the insoluble residue within these limestones is composed of quartz with very minor amounts of illite and mixed-layer minerals. (Fig.60).

The key to the clay mineralogy of the tills of Eastern Durham is to be found in the Coal Measure deposits which encircle Eastern Durham to the north and west. The coal measure deposits are made up of sandstone, siltstone, and shales and of these the shales are the most likely contributors to the clay sized material of the tills. A number of shale samples were X-rayed and all proved to have similar mineralogies.

Fig.60 is a representative example. In this sample all the clay minerals commonly found in the Durham tills are to be seen. Because no size separation was attempted before analysis quartz dominates the diffractometer trace (peak at 3.33A). Illite (and mixed layer clays) is present in considerable quantities, and owing to the extreme sharpness of the 9.9A peak, muscovite is also thought to be present. Kaolin is present though not in very large quantities. (7.16A) Chlorite also is an important and easily recognisable constituent of this shale material. (14.2A).

The only mineral present in this sample, which is not found in the Durham stony clays is feldspar (peak at 3.23A). This is almost certainly due to the fact that the mineral occurs in the size range of more than 2 microns in the shale sample. In the till samples it seems highly likely that this feldspar would weather to form kaolin.

The clay mineralogy of the stony clays of Eastern Durham can therefore be explained solely in terms of the clay minerals already present in nearby parent rock types. This goes a long way to explaining the fact as to why the Lower and Upper Tills should have such similar mineralogies, when these two clays are thought to have originated from different directions. The point is that both these till sheets, from the Lake District, and the Cheviots respectively, have crossed areas with very similar Carboniferous successions before reaching Eastern Durham. It is therefore little wonder that their clay mineralogies are so similar.

Differential Thermal Analysis. (D.T.A.)

Introduction.

To complement the X-ray analysis of the clay minerals, and to obtain further information on the clay minerals present, differential thermal analysis of the clay sized material was carried out.

Differential thermal analysis determines the temperature at which thermal reaction take place in a mineral when it is heated continuously to an elevated temperature, and also the intensity and general character of each reaction.

When used with clay minerals D.T.A. gives characteristic endothermic reactions due to dehydration, and to loss of crystal structure, and exothermic reactions due to the new phases of the mineral being formed at very high temperatures.

The results are recorded as a continuous curve, in which the thermal reactions are plotted against furnace temperatures, with endothermic reactions shown as upward deflections and exothermic reactions as downward deflection from a horizontal base line. The size of the peak is a measure of the intensity of the thermal reaction.

Method of Analysis.

A sample of less than 1.4 microns equivalent particle size diameter is packed into one hole of a specimen sample holder, and an inert material which experiences no thermal reaction when heated to the temperature of the experiment (e.g. calcined kaolinite) is placed in the other one. Thermocouples are attached to the centre of each of the sample holders. The holders, together with the thermocouples are placed in a furnace, controlled to produce a uniform temperature increase of c. $10^{\circ}\text{C}/\text{minute}$.

The temperature of the inert material rises gradually as the temperature of the furnace increases. When a thermal reaction takes place in the sample, the temperature is greater or less than that of the inert material, depending on whether the reaction is endothermic or exothermic. This difference is recorded by the thermocouples and plotted on a chart as a function of the temperature of the furnace.

To avoid oxidation of the sample nitrogen is passed through the furnace. When the experiment is being carried out, each of the clay minerals, and many of the standard rock minerals react in a characteristic fashion to differential thermal analysis.

Standard Minerals

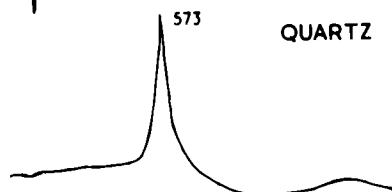
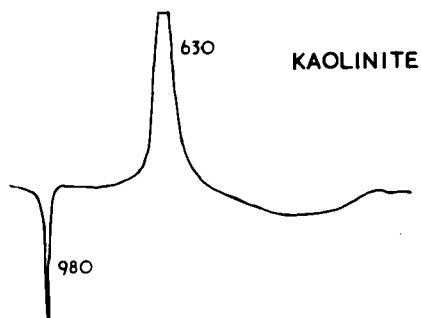
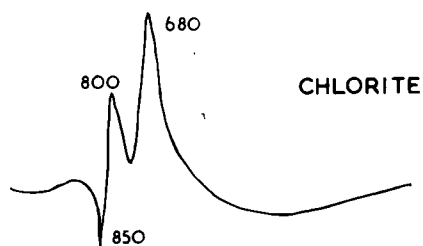
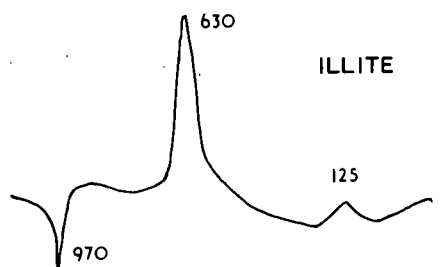
For comparative purposes a series of standard clay minerals were subjected to D.T.A. analysis. The following results were obtained.

KAOLIN (Fig 61).

Differential thermal analysis of kaolin reveals a large endothermic peak, and a smaller exothermic peak.

DIFFERENTIAL THERMAL ANALYSIS CURVES FOR STANDARD MINERALS

PEAK VALUES IN DEGREES CENTIGRADE



DEGREES C.

1000 800 600 400 200 50

The endothermic peak corresponds to the loss of hydroxyl water from the clay mineral lattice. This reaction begins at about 400°C and reaches a peak at 600 to 650°C .

Between 900° - 1000°C a pronounced exothermic reaction is noted when the kaolin changes to mullite.

ILLITE (Fig.61)

Illite is characterised by two endothermic peaks and one exothermic peak.

The initial endothermic peak, found at 125°C , is generally small and represents the loss of interlayer water (hygroscopic moisture).

The second endothermic reaction begins at 450°C , and reaches a peak at 600 to 650°C . As with kaolin this represents the loss of hydroxyl water.

Between 950 to 1000°C a strong exothermic reaction occurs due to the probable formation of spinel.

CHLORITE (Fig.61)

Chlorite is distinguished by two endothermic peaks and one exothermic peak. An initial and pronounced endothermic reaction is found between 500 to 700°C , followed by a second endothermic reaction at 800°C . These two peaks are thought to be due to the fact that the hydroxyl water of chlorite is driven off in two stages, and are considered diagnostic of chlorite.

Immediately following the 800°C endothermic peak is a pronounced exothermic peak at 830 - 900°C believed to be due to the formation of olivine.

QUARTZ (Fig.61)

Differential thermal analysis of quartz reveals a sharp endothermic reaction at 573°C at which temperature quartz undergoes an inversion reaction to form beta quartz.

These results indicate the difficulty of using D.T.A. for positive identification of clay minerals within mixtures by showing the very similar reaction patterns exhibited by the common mineral types found in the clay sized range e.g. quartz, kaolin, chlorite and illite. (Fig.61)

For example kaolin, illite and quartz all show endothermic reactions between $570-630^{\circ}\text{C}$, and both kaolin and illite show exothermic reactions at about 950°C .

Only chlorite possesses a distinctive differential thermal trace. This is of extreme value as it permits the detection of small quantities of chlorite within mineral mixtures, This does however depend on the assumption that the composition of the standard chlorite is similar to the chlorite present within a natural rock sample.

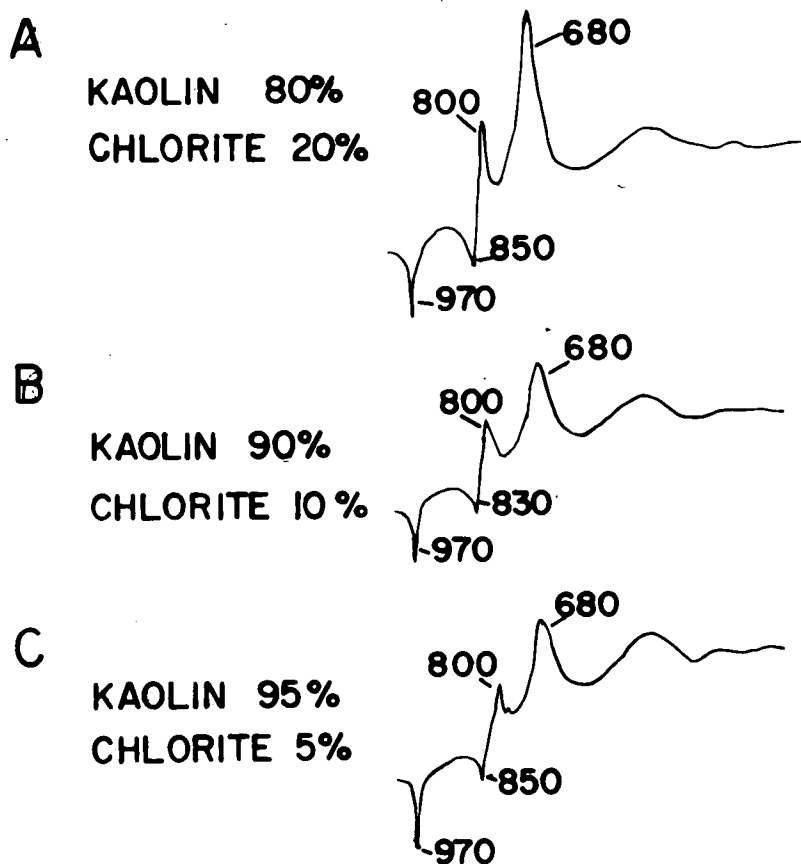
In Fig.62, differential thermal curves are shown for prepared mixtures of kaolin and chlorite.

Figures in percent.

	<u>A</u>	<u>B</u>	<u>C</u>
Kaolin	80	90	95
Chlorite	20	10	5

DIFFERENTIAL THERMAL ANALYSIS CURVES OF MIXTURES OF KAOLINITE AND CHLORITE

PEAK VALUES IN DEGREES C.



These clearly indicate that the second endothermic peak of chlorite and its exothermic peak are detectable when chlorite is present in quantities of as low as 5%.

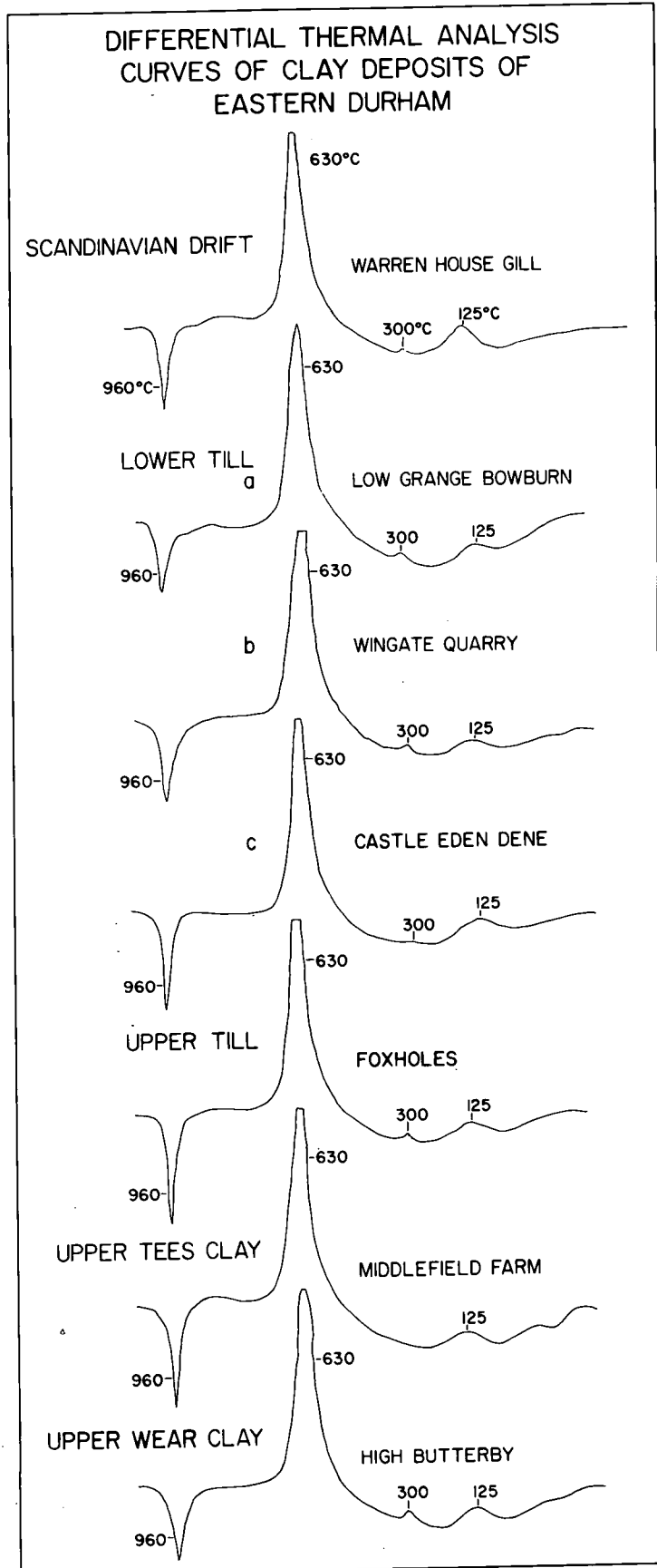
Results for East Durham stony clays.

Differential thermal traces of representative sample of the Durham stony clays are reproduced in Fig.62.b These all indicate very marked similarities between the clays.

Almost all the deposits show small endothermic peaks at 125°C, and 300°C, a large endothermic peak at 600°C, and an exothermic peak at 960°C.

The endothermic peak at 125°C is caused by the loss of interlayer water of the illite minerals. The nature of the small, but consistent endothermic peak at 300°C is unknown. It may however be associated with mixed layer clay minerals. The main 680°C endothermic peak is undoubtedly a composite peak made up of superimposed reactions of kaolin, illite and quartz. In a similar way the exothermic reaction at 950°C is made up of a kaolin and illite reaction. Not one of these samples indicate the presence of chlorite and it therefore seems reasonable to conclude that chlorite when present must be so in quantities of possibly less than 5%, or else be of a different variety from that of the prepared mixtures.

The differential thermal analyses give strong supporting evidence to the conclusions of clay mineralogy reached by X-ray analyses. It must be stated however that of the two techniques of X-ray analysis and D.T.A., X-ray analysis is the better method for clay mineralogy study.



SILT SIZE FRACTION ANALYSIS

Introduction

The mineralogy of silt sized material is a much neglected field of sedimentary study. Therefore in Eastern Durham attempts were made to study the silt sized fraction of the tills using X-ray diffraction analysis. Material in the size range 0.06mm to 2 microns was used. This material was ground down in an agate mortar and pestle and finely mixed before analysis.

Analysis was concentrated on the three main till sheets of the coastal area - the Scandanavian Drift, the Lower Till and the Upper Till.

Typical diffractometer traces for the silt content of these three till sheets are seen in Fig.63.

Results.

Scandanavian Till.

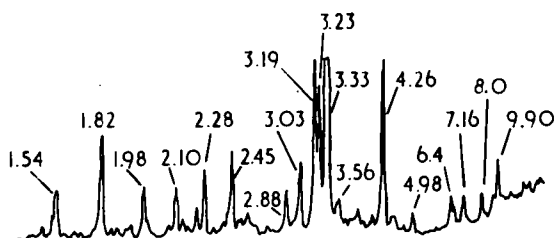
The Scandanavian Till is characterised by a very varied mineralogy in the silt size range. The main mineral component as one might expect is quartz (peaks at 4.26 and 3.33A), and this probably comprises up to 30% of the sample.

The second most important mineral is feldspar which appears to be of the low plagioclase variety (peaks at 6.4A, 3.56A, 3.23A, 3.19A). One puzzling feature with this mineral is the very low intensity peak at 4.04A. With most published examples of feldspar the 4.04A peak is invariably more intense than the 6.4A peak. There is however no doubt that this mineral is feldspar, though it does seem to be an unusual variety.

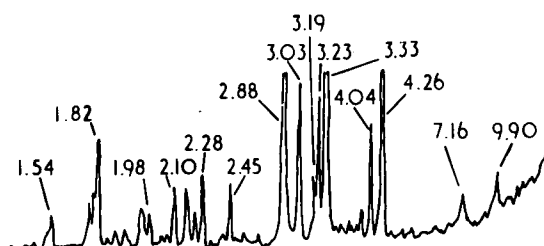
X RAY DIFFRACTION CURVES OF SILT SIZED MATERIAL FROM GLACIAL TILL

PEAK VALUES IN ANGSTROM UNITS

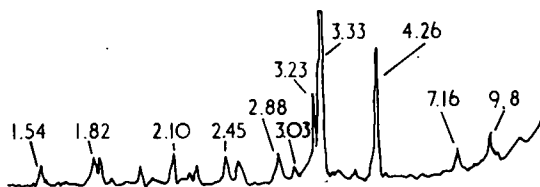
SCANDINAVIAN
DRIFT
WARREN HOUSE GILL



LOWER TILL
CASTLE EDEN DENE



UPPER TILL
CASTLE EDEN DENE



Other minerals appear in much smaller quantities. Muscovite is present in a well crystallised form and is shown by a sharp peak at 9.9A and 4.98A. Of particular interest is a well marked peak at 8.0A. This is almost certainly a ferromagnesian mineral of the amphibole variety, and appear to be present in fairly sizeable proportions.

A 7.1A peak, and the absence of a well developed 14A peak suggests that Kaolin is present, probably in the smaller part of the size range being studied.

The only other two minerals present in detectable quantities are calcite 3.03A, and dolomite 2.88A, with the calcite slightly more abundant than the dolomite.

The mineralogy of the silt fraction therefore strongly suggests derivation from an igneous rock type material (quartz, low plagioclase, muscovite, and amphibole), with the possible later addition of limestone material (calcite and dolomite).

LOWER TILL.

The dominant mineral in the Lower Till is undoubtedly quartz (peaks at 4.26A and 3.33A).

The second most important mineral in this deposit is dolomite (2.88A) and this possibly makes up at least one third of the sample. Dolomite in this till, unlike the Scandanavian Clay is more abundant than calcite, the next most frequently occurring mineral. The very high dolomite and calcite content reflects the very close association between the Lower Till and the Magnesian Limestone throughout its exposure, and suggests that these two minerals, dolomite and calcite were derived solely from erosion of the Magnesian Limestone.

Feldspar is an important constituent of the Lower Till silt range, but it appears to be a very different type from that found in the Scandinavian Till. In the Lower Till the 3.23A peak is considerably greater than the 3.19A peak, and the 4.04A peak is extremely well developed. No peak at 6.4A is seen. Absolute identification of the different feldspar types is extremely difficult without detailed chemical analysis, but it appears likely that the feldspar in the Lower Till is a high plagioclase variety. The difference between the feldspar in the Scandinavian Drift and the Lower Till is sufficiently great to allow positive distinction to be made between the two varieties.

Muscovite is also present and by the sharpness of its peak (9.9A) appears well crystallised. Quantities of this mineral appear very similar to those found in the Scandinavian Drift.

A 7.1A peak is seen, and this together with a possible 14.0A peak suggests that both kaolin and chlorite are present, although both in small quantities.

An amphibole peak was not detected in this sample.

UPPER TILL.

The silt fraction analysis of the Upper Till indicates the presence of fewer mineral varieties than in either the Lower Till or the Scandinavian Drift.

In this sample quartz (3.33A and 4.26A) dominates the mineralogy to the exclusion of nearly all other mineral types.

The only other mineral in any quantity is feldspar (3.23A). This feldspar is a variety similar to that found in the Lower Till with the maximum peak found at 3.23A. In the Upper Till feldspar peaks at

3.19A and 4.04A were not detected. This is probably due to the fact that the quantities of this mineral are lower than those found in the Lower Till.

Dolomite (2.88A) and calcite (3.03A) peaks are present in this sample, but in contrast to the Lower Till only in very small quantities. This is probably a reflection of the fact that the Upper Till is not in such close contact with the Magnesian Limestone as is the Lower Till.

Small quantities of muscovite are indicated by a sharp peak at 9.8A and of kaolin by a 7.1A peak.

CONCLUSIONS

This analysis of the silt fraction further emphasises the difference between the Scandinavian Drift and the Upper and Lower Till Sheets, and the basic similarity between the Upper and Lower Till.

The silt fraction of the Scandinavian Till can be shown to be that derived from the breakdown of dominantly igneous and metamorphic material, while both the Upper and the Lower Tills appear largely to be the result of the breakdown of sedimentary rocks including shales, sandstone, and limestone.

Comparison of clay fractions with till deposits from other areas.

In the British Isles as a whole very little research so far has been carried out specifically on the clay mineralogy of glacial deposits. Because of the general similarity between the Holderness deposits and those of Eastern Durham it was considered useful to briefly study the similarities and differences between them.

Goodyear's work in Holderness was carried out on the silt and clay sized fractions of the tills. He described quartz, calcite and micaceous material as the principal constituents of all the Holderness clays, but also indicated that kaolin, feldspar and possibly chlorite were also present.

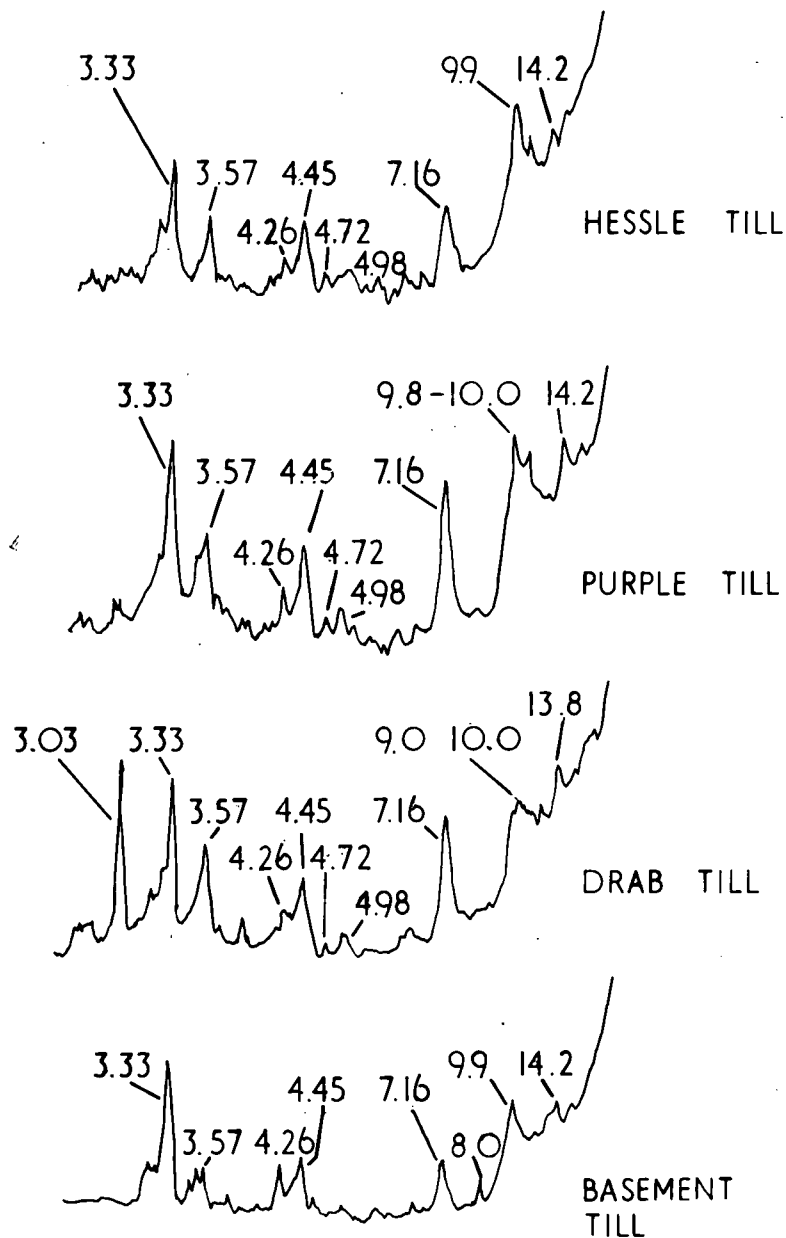
For comparative purposes the author obtained samples of the four tills of Holderness; the Hesse, the Purple, the Drab, and the Basement and after separation by sedimentation subjected the clay minerals to X-ray analysis.

The diffraction traces of these clay minerals are seen in Fig.64. The similarity of these traces with the Durham samples is very marked. Illite and mixed layer clays (peaks at about 9.9, 4.98, and 4.5 Angstroms) are the dominant components, followed in order of abundance by kaolin, (7.16A), quartz (3.33A) and chlorite (14.2A). A small chlorite peak at about 14A, is identifiable in all 4 clays. Two points of interest do stand out. The first is that a very pronounced calcite peak (3.03A) is found in the Drab Till, while no such marked peak occurs in the Basement Till beneath, or in the Purple and Hesse clays above. This is almost certainly due to the incorporation of very fine grained Chalk material into the till during the movement of the Drab ice sheet over the Chalk. The fact that the Basement clay beneath, which is generally considered a till deposit and which must have moved across the chalk outcrop does not contain such a peak is somewhat puzzling, and comparable to the lack of Magnesian Limestone shown in the Scandinavian Till of County Durham.

The existence of a peak in the Basement clay at about 8A is also noted. This possibly represents a fine grained ferromagnesian mineral e.g. amphibole, but the masking of the higher reflections by the clay mineral peaks makes positive identification impossible.

X RAY DIFFRACTION CURVES OF THE GLACIAL TILL SHEETS OF HOLDERNESS

PEAK VALUES IN ANGSTROM UNITS



On the basis of this clay mineralogy these clays could have been sampled from anywhere within the Eastern Durham area.

From this study the basic similarity between the clay mineralogy of the Holderness and Durham Till is clearly demonstrated. The fact that no new clay minerals have been identified, nor changes in the relative proportion of these minerals are seen during the southward passage of the ice sheet towards Holderness suggests that once the clay mineralogy of a till sheet is established, it remains a very stable assemblage.

Work on glacial clays in Scotland using X-ray and D.T.A. analysis have revealed considerably different mineralogies from those found in Eastern Durham. In Central Aberdeenshire, Glenworth, Mitchell and Mitchell have described glacial clays dominated by the presence of illite (70-80% of the sample), but also including vermiculite and montmorillonite. Neither of the latter two minerals have been specifically identified in the Eastern Durham clays, and they are considered by the author to be present in Scotland because of the vastly differing lithological type of the areas where these ice sheets originated.

Conclusions

This work has shown that the clay mineralogies of the glacial clays of Eastern Durham are extremely similar and show only very small, and apparently non-diagnostic minor variations. The fact that the clay mineralogy of the glacial deposits is solely derived from local parent material is clearly illustrated. In almost all samples illite is the dominant clay mineral present.

Chapter 10

WEATHERING STUDIES

Introduction

The weathering characteristics of glacial deposits have for long provided a useful tool for understanding the sequence and nature of glaciation within an area. (Allen V.T. 1930; Bryan K. and Albritton C.C. 1943; Goldthwaite R.P., Thorpe J, and Gamble E. 1959; Goldthwaite R.P. 1959; Gooding A.M. and Gamble E. 1960; Gravenor C.P. 1954; Grim R.E., Bray R.H. and Leighton M.M. 1936; Leighton M.M and MacIntock P. 1930; Phemister T.C. and Simpson S. 1949; Thornbury W.D. 1940; White G.W. and Shepps V.C. 1952).

Similar studies have formed the basis of the division of the glacial deposits of the British Isles into the Older and Newer Drift Sheets, and in the United States of America different depths of calcium carbonate leaching have been widely accepted as evidence for age differences between deposits.

The great difficulty in undertaking weathering studies on glacial deposits is the fact that one is generally dealing with what is already highly weathered material. For most fine grained glacial deposits have a matrix consisting almost exclusively of quartz particles and clay minerals:- material which is usually the end product of the weathering processes.

Weathering studies of glacial till have generally been undertaken with the specific aim of identifying buried soil profiles, (evidence of earlier sub-aerial weathering in a multi-till sequence), or for showing age differences between deposits in juxtaposition. One of the earliest and most comprehensive of such studies is the work of

Leighton and MacIntock (1930) on the drift deposits of Illinois. In this study they were able to distinguish four weathering zones on glacial material which appeared to be present irrespective of the topographic or vegetative environment, and which underwent orderly stages of development.

Horizon 1 - Superficial soil

Horizon 2 - Chemically decomposed till

(Alteration products and resistant constituents of original till, very unlike original till).

Horizon 3 - Leached and oxidised till, but otherwise little altered.

Horizon 4 - Oxidised till, but unleached

Horizon 5 - Unaltered till

It is this work which has provided the basis for more recent and quantitative research on glacial drifts.

In the present study the author concluded that the best way to recognise buried profiles on glacial till in Eastern Durham was by initially studying in detail the soil profiles developed at the present day on similar material, and then comparing these results with those obtained from supposed palaeosols.

Jenny H.(1941) suggested five main factors which affected soil formation :- climate, organisms, major relief form, parent material and time. The effects of these factors in differing proportions resulted he claimed in the major soil groups which are found throughout the world.

Polynov B.B. (1937) in his cycle of weathering concentrated on the time element, and suggested an order of relative mobility of elements during the weathering cycle.

Phase 1	Cl.	SO ₄			
Phase 2	Ca.	Na.	Mg.	K	F.
Phase 3	SiO ₂	(colloidal) Mn.			
Phase 4	Fe ₂ O ₃	Al ₂ O ₃	TiO ₂		

(The most mobile elements of Phase 1 being removed from the soil first, though not necessarily to exhaustion before those of Phase 2 begin to be removed).

A similar but more refined classification was set out by Jackson M.L. (1948) which described minerals removed from the soil profile in terms of increasing weathering intensity. These are :- gypsum, calcite, hornblende, biotite, albite, quartz, illite, montmorillonite, kaolinite, gibbsite, haematite, and anatase.

Although there is general agreement as to the validity of Polynov's and Jackson's weathering sequences, and also on Jenny's five major factors affecting soil formation, there is considerable dispute as to the relative effects of these factors.

The depth of leaching of calcium carbonate, one of the minerals most readily removed from the soil profile in Jackson's sequence, has been considered by many workers to represent an index of the length of weathering to which a deposit has been subjected. (Boulton G.S. and Worsley P. 1965). But as Bunting B.T.(1965) pointed out :- "the apparent depth of weathering and soil horizon differentiation are not sure guides to the relative amount of weathering, for the intensity of weathering is as significant as its depth of penetration".

Carroll D (1962) claimed that the most important factor in the weathering cycle was ... "the amount and the pH. of the water which

passes through the soil and then interacting upon the parent material is responsible for the mineralogical changes there and within the mineral and organic complex which is the soil". It is obviously true that the pH. of a soil governs the leaching of carbonates, and also that the acidity of the ground water will have considerable effect on the decompositions of other more resistant minerals. But it is important to remember that even this factor cannot be considered independently of the time over which the processes operate.

All these factors and their interplay emphasise the complexity of the weathering processes, and the inherent danger in overemphasising any single factor to the relative exclusion of others.

SECTION I

Methods of study within Eastern Durham.

This section consists of the detailed description of samples taken at 1 foot intervals from surface and buried till profiles within Eastern Durham.

Six criteria were used in the examination of each profile.

These are:-

1. Depth of root penetration
2. Depth of gleying
3. pH. values
4. Calcium carbonate content
5. Organic matter content
6. Sand content

In a few cases studies of clay mineralogy, iron content and pollen content were also made. In all more than 60 profiles were

studied.

1. Depth of root penetration.

The presence of roots is an important characteristic of the soil profile. Roots penetrate to a much greater depth than the base of the A horizon, although the roots of both trees and grasses are dominantly confined to the top 2 to 3 feet of the soil profile. Occasional roots penetrate much deeper than this, and in Eastern Durham a survey was made of the maximum normal penetration of roots of different plant species in till-like material. As a general rule it was found that penetration of roots through the clay itself is limited to a depth of 5 to 6 feet, but that in some of the better drained clays fine roots are found along the joint surfaces of the clay to depths of more than 10 feet.

2. Depth of gleying.

Gleying is commonly seen along the joint faces of the till. It is particularly visible in the Upper Till of the coastal area where the blue grey mottling along the joints contrasts very markedly with the reddish brown matrix of the till material. Gleying is concentrated, as with root growth in the upper horizons of the soil, but penetration down joints can occur to considerable depths. In both the Upper Till and the Lower Till gleying along the joint faces is commonly found to depths of 6 to 8 feet, and in a number of isolated cases occasionally to depths of 14 feet.

3. pH. values.

The pH of the soil is the simplest test giving an indication of the environmental conditions within a soil profile. As already mentioned in Chapter 7 it is a dynamic measurement summarising the conditions within a soil at a given moment in time. It is not an

absolute property of the soil and can show considerable changes with time, and changes in the physical environment. However it remains the best reflection of present day weathering conditions, and indicates the acidity or alkalinity of the weathering environment.

The value of pH recordings in studies of buried weathering profiles is in many cases of little value, as these readings will tend to reflect the nature of the present day ground water environment, and be unrelated to the actual conditions experienced by the buried soil during its formation.

4. Calcium carbonate content. (Appendix 5)

On the other hand the carbonate content of a soil profile is an absolute value, and represents the summation of both past and present conditions. Any carbonate which was leached out of a profile, owing to past weathering conditions is unlikely to be replaced, even though the present environment, in terms of pH values, strongly suggests that leaching is no longer active.

With the carbonate content, one is dealing with a total loss of material from the profile, and one must start with the assumption that the carbonate was present initially in equal quantities throughout the profile. In the light of work described earlier in this thesis this seems a reasonable assumption to make. Therefore by a study of the degree and depth of decalcification a particular clay has undergone, it should be possible to calculate the degree of weathering to which a particular clay has been subjected. Similarly if a decalcified zone is found in a buried sequence it is generally accepted as being indicative of sub-aerial weathering conditions at that particular horizon. (e.g. Catt J.A. 1963, weathering of the Basement Clay in Holderness).

5. Organic Matter Content. (Appendix 9).

In contrast to carbonate contents, organic matter concentrations represent additions which have been made to the soil profile by the decay of vegetation and micro-fauna remains. In general humus decomposes slowly in the soil through oxidation processes, but if the supply of humus diminishes, total organic matter in the upper part of the soil profile will be fairly rapidly oxidised. In a typical profile organic matter concentrations tend to remain fairly constant in amount in the upper parts due to a balance between formation and destruction, although it must be stressed that the type of vegetation to a large extent determines the position of the organic matter in the profile. Forest soils have the bulk of their organic matter close to the soil surface, and this organic matter can only be brought to the sub surface layer by worms and other soil animals. Grassland soils by way of contrast, with their deep root systems have a considerable proportion of their organic matter in the deeper horizons.

(Russell E.W. (1961) - Soil conditions and plant growth).

Organic matter contents

Depth	Hardwood Forest	Prairie Grassland
0	4.4	2.3
6"	1.2	2.2
12"	0.7	1.7
18"	0.5	1.2
24"	0.4	0.7
30"	0.4	0.4
36"	0.3	0.3
48"	0.3	0.2

The rate of decomposition of organic matter depends on the soil aeration, calcium supply and temperature. The more favourable a soil is for animal life by being well aerated and adequately supplied

with calcium, the more rapid is the decomposition. High temperatures also encourage high rates of decomposition.

In a reducing environment, with the exclusion of oxygen the rate of organic matter decay is greatly inhibited and may even halt completely. This means that a soil profile, if buried by deposition, and which through the presence of ground water remains in a perpetually reducing environment, may under favourable conditions preserve almost indefinitely its original organic matter content. Therefore a buried profile might also be distinguished by means of organic matter concentrations as well as by the leaching of calcium carbonate.

With the technique of analysis used (Walkley Black Method, see Appendix 9), the amount of organic carbon, in the form of charcoal or coal registered in the analytical technique is generally considered to be very small. In the Eastern Durham stony clays however, with their often fairly high concentrations of fine grained weathered coal fragments, this is not the case and a "background value" recording derived from an estimation of this weathered coal is always found. True organic matter contents are superimposed upon these "background values".

6. Sand Content.

The sand content of a profile gives a measure of the homogeneity of the material being analysed. It can also provide under some circumstances an index of the amount of weathering that sand sized material has undergone, and the degree to which this size material has been broken down to finer grain sizes. In some surface horizons sand concentrations also indicate the removal of clay and silt sized particles, probably by wind action under the possible stimulus of man's cultivations of the land, or by the washing of fine grained material down the profile.

SECTION 2

Analytical results

The section is divided into two parts,

- A. Profiles developed at the present day on glacial deposits.
- B. Buried soil profiles or Palaeosols.

A. Present day soil profiles.

In this section weathering profiles from the stony clays of Eastern Durham are included. Attention has been concentrated on the profiles in the coastal zone as in this region all the differing stony clays tend to have fairly high calcium carbonate contents in their matrix. (more than 8%). In the Wear Lowlands the low calcium carbonate contents of the stony clays (less than 5%), makes it extremely difficult to detect leaching effects.

Typical profiles for the following stony clay deposits are included :-

- a. Upper Tees Clay
- b. Upper Wear Clay
- c. Upper Till
- d. Lower Till

In the coastal area the succession is :-

Upper Tees Clay
Upper Till
Lower Till

Each of these clays form surface exposures in some parts of the area, and it seems possible to suppose that these three surface topographies may represent different lengths of time of weathering, provided that nothing has happened to these deposits since their deposition. If this is the case, one would expect the Upper Tees Clay to have been subjected to the least weathering, and the Lower Till to the most. It was hoped that if this were the case, these differences in weathering might be detectable.

a. THE UPPER TEES CLAY (Fig 65 and 66).

The Upper Tees Clay is stratigraphically the youngest of the stony clays within the area. It also has the most uniform visual composition, and as mechanical analysis shows in Chapter 8, the highest clay and least stone content. Throughout its exposure the weathering profiles are almost identical in depth irrespective of topographical situation - a fact which suggests that it is the lithological composition of the material which plays the dominant part in controlling weathering rather than aspects of micro-topography. The colour of the unweathered clay is reddish brown but in the top one foot of the profile lighter yellowish brown colours were common.

The Tees Clay is unusual in the fact that within the weathering profile a series of concretionary forms is found. These are irregular nodules composed of clay minerals and calcium carbonate. They are found chiefly in the joints of the clay, and appear to represent a depositional form, caused by downward movement of clay material due to weathering in the upper reaches of the profile. They are found at depths of between 2 to 6 feet, and often seem to be concentrated in an approximately linear belt at about three to four feet below the ground surface.

Fig.65

Lower Till of the Magnesian Limestone PlateauNo.1

Coxhoe Quarry.

<u>Depth in feet.</u>	pH.	Carbonate Content %	Organic Matter Content %	Sand Content %
1	7.4	1.3	1.9	30.6
2	7.4	1.3	1.3	31.6
3	7.7	1.1	1.3	32.6
4	7.9	0.5	1.0	30.6
5	8.3	1.9	0.8	28.4
6	8.5	3.9	0.8	28.4
7	8.7	33.0	0.1	36.2
8	9.0	88.5		

(8' sample - powdered Magnesian Limestone)

No.2

Houghton-le-Spring.

<u>Depth in feet.</u>	pH.	Carbonate Content %	Organic Matter Content %	Sand Content %
1	7.7	1.5	2.22	49.6
2	7.7	0.5	1.17	52.6
3	7.9	1.0	1.13	38.4
4	7.8	1.0	1.60	35.6
5	7.8	1.0	1.00	50.8
6	7.8	0.0	0.90	52.4
7	7.9	0.0	2.11	33.6
8	7.9	3.0	1.76	36.4

No.3

Thrislington.

<u>Depth in feet.</u>	pH.	Carbonate Content %	Organic Matter Content %	Sand Content %
1	6.7	0.0	3.24	27.6
2	7.4	1.0	2.85	32.8
3	7.6	0.5	2.69	26.8
4	8.1	2.0	2.22	34.4
5	8.1	8.5	2.50	36.4
6	8.2	5.0	2.22	31.2
7	8.3	2.5	2.38	40.0

Fig.65 continued :

Lower Till of the Magnesian Limestone PlateauNo.4

Wingate Quarry D

<u>Depth in feet.</u>	pH.	Carbonate Content %	Organic Matter Content %	Sand Content
0.5	7.4	4.0	4.45	44.8
1	7.6	2.0	1.68	32.8
2	7.7	1.5	1.64	33.2
3	7.5	1.5	2.77	32.4
4	7.5	2.5	2.11	26.4
5	8.1	22.6	1.83	30.0
6	8.0	22.0	1.60	28.4
7	8.4	55.0	1.17	28.0
8	8.8	79.5	0.62	17.2

No.5

Bishop Middleham

<u>Depth in feet.</u>	pH.	Carbonate Content %	Organic Matter Content %	Sand Content
1	7.3	0.8	3.78	57.4
2	7.9	31.0	2.46	28.0
3	7.9	32.0	2.26	18.8
4	8.1	36.0	1.72	20.4
5	8.2	37.0	1.64	22.4
6	8.1	60.5	1.05	25.4

No.6

Hawthorn Quarry

<u>Depth in feet.</u>	pH.	Carbonate Content %	Organic Matter Content %	Sand Content
1	7.9	1.5	4.8	32.4
2	8.1	1.5	4.7	17.6
3	8.7	11.25	4.2	18.4
4	8.7	15.5	3.9	20.4
5	8.5	18.0	4.2	25.6
6	8.6	33.0	3.6	37.6
7	8.4	31.5	2.9	48.0
8	8.6	31.5	3.2	48.4

Fig.65 continued :

Upper TillNo.1

Upper Till north of Castle Eden Dene.

<u>Depth in feet</u>	pH.	Carbonate Content%	Organic Matter Content %	Sand Content
1	5.6	0.80	2.96	76.8
2	6.3	1.30	1.80	40.0
3	7.3	1.81	1.21	32.4
4	8.5	7.0	1.17	32.8
5	8.6	9.80	1.29	34.4
6	8.6	10.3	1.29	33.6
7	8.6	11.0	1.29	33.6
8	8.7	9.8	1.21	31.6
9	8.6	9.0	1.29	34.8
10	8.6	9.3	1.44	37.6

No.2

Crimdon Dene

<u>Depth in feet</u>	pH.	Carbonate Content %	Organic Matter Content %	Sand Content
1	6.0	1.0	1.76	43.2
2	7.3	1.0	1.09	43.6
3	8.8	12.5	0.98	39.2
4	8.9	12.5	1.09	41.0
5	8.9	13.0	1.13	40.4
6	8.7	17.5	0.86	38.0
7	8.8	17.5	1.09	35.6

No.3

Blackhall Rocks

<u>Depth in feet</u>	pH.	Carbonate Content	Organic Matter Content	Sand Content
1	7.0	2.6	2.10	38.5
2	8.0	1.6	1.72	29.3
3	8.6	13.0	1.52	31.6
4	8.6	13.6	1.38	32.6
5	8.7	14.5	1.42	31.6
6	8.6	11.0	1.36	20.6

Fig.65 continued : Upper Tees clayNo.1

Scrapyard near Low Middlefield.

<u>Depth in feet</u>	pH.	Carbonate Content	Organic Matter Content	Sand Content
1	7.1	2.0	2.26	14.0
2	7.7	2.3	1.17	17.6
3	8.4	6.5	1.60	13.6
4	8.6	10.0	0.80	16.4
5	8.7	10.5	1.83	16.0
6	8.5	10.5	1.60	15.8

No.2

Redmarshall

<u>Depth in feet</u>	pH.	Carbonate Content	Organic Matter Content	Sand Content
1	7.8	1.5	1.60	41.2
2	8.4	2.5	1.37	21.6
3	8.4	11.8	1.29	22.4
4	8.6	12.3	1.60	23.0
5	8.7	11.8	1.40	14.8
6	8.8	12.5	1.48	20.0

No.3

Stob Cross

<u>Depth in feet</u>	pH.	Carbonate Content	Organic Matter Content	Sand Content
1	7.3	2.0	1.56	15.2
2	8.1	6.8	1.64	14.4
3	8.3	11.8	1.60	14.8
4	8.5	12.5	1.76	15.2
5	8.7	11.5	1.68	14.0
6	8.6	10.8	1.60	12.8
7	8.6	12.0	1.64	10.6
8	8.7	10.0	1.68	10.6
9	8.8	9.5	1.91	12.4
10	8.8	9.0	1.87	9.0

Fig.65 continued:

Upper Wear ClayNo.1

High Butterby

<u>Depth in feet</u>	pH.	Carbonate Content	Organic Matter Content	Sand Content
1	5.1	0.5	1.56	38.8
2	5.4	1.8	1.76	40.4
3	6.1	1.3	1.83	38.8
4	6.7	1.3	1.79	38.0
5	7.3	1.8	2.22	24.4
6	8.4	3.0	2.46	19.2

No.2

Electricity sub station, Ferryhill.

<u>Depth in feet</u>	pH.	Carbonate Content	Organic Matter Content	Sand Content
1	5.8	0.5	2.15	27.6
2	5.1	1.0	2.15	27.2
3	4.8	1.0	2.24	30.4
4	4.9	1.0	2.18	32.8

No.3

Belmont Railway Cutting

<u>Depth in feet</u>	pH.	Carbonate Content	Organic Matter Content	Sand Content
1	6.8	0.8	2.73	36.8
2	6.7	0.8	1.48	37.3
3	5.2	1.0	2.03	34.8
4	5.8	0.3	2.42	37.3
5	5.9	0.5	3.20	25.3
6	6.2	1.0	3.74	9.6

No.4

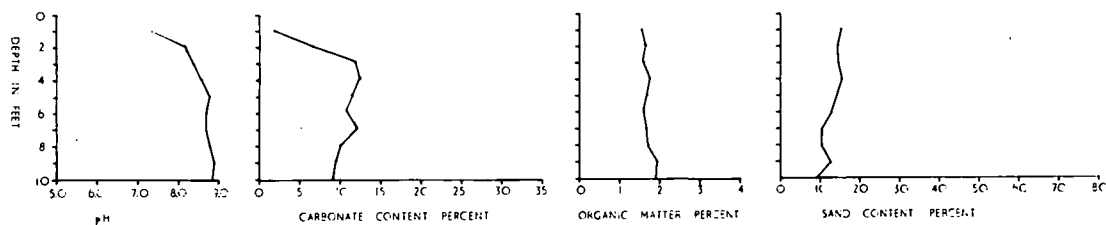
Railway cutting North of Durham

<u>Depth in feet</u>	pH.	Carbonate Content	Organic Matter Content	Sand Content
1	5.8	0.0	1.52	18.0
2	5.2	0.5	1.56	16.4
3	5.2	0.5	1.64	20.8
4	5.0	0.0	1.76	20.4
5	5.8	0.0	1.56	40.8
6	5.5	0.0	1.78	12.0

WEATHERING PROFILES

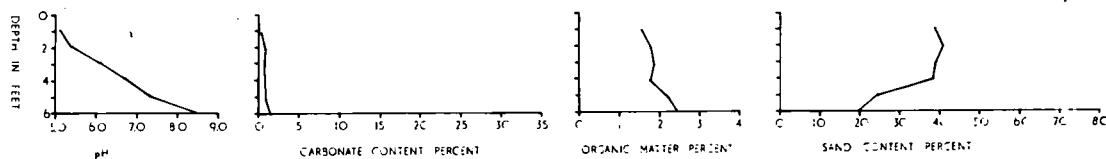
UPPER TEES CLAY

STOB CROSS



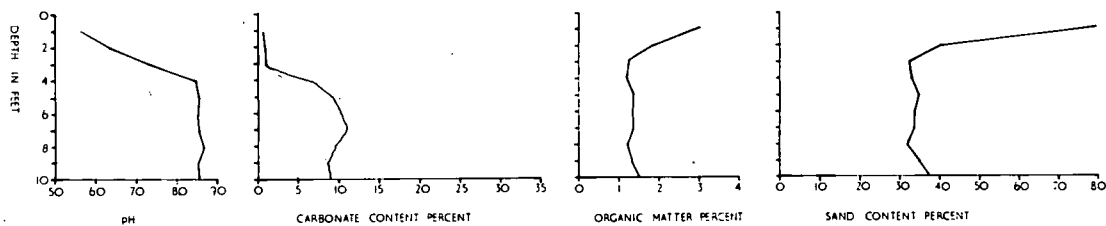
UPPER WEAR CLAY

HIGH BUTTERBY



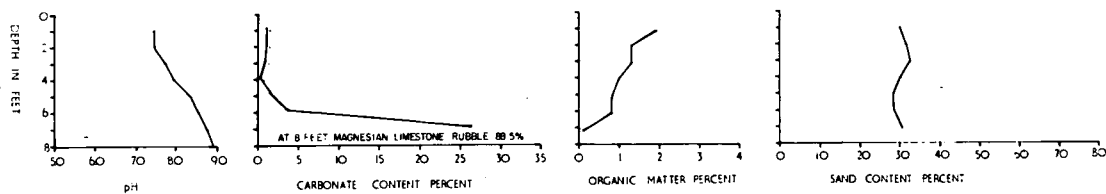
UPPER TILL

CASTLE EDEN DENE

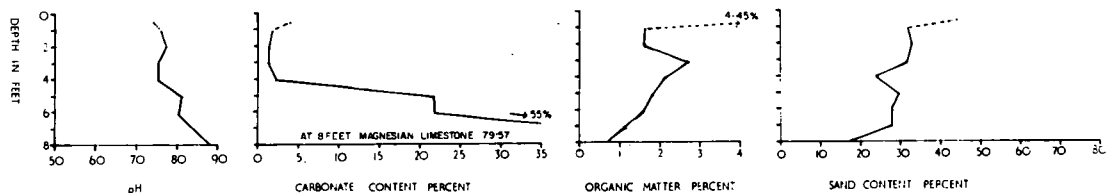


LOWER TILL

A COXHOE QUARRY



B WINGATE QUARRY D



1. Depth of root penetration.

Owing to the high clay content, and consequent heavy nature of the soil, root penetration is not great and rarely exceeds 3 feet. The great majority of the roots are indeed concentrated in the top 18 inches of the soil profile.

2. Depth of gleying

Gleying along the joints is particularly well developed in this clay, and commonly extends below the level of the profile pit to depths of at least 6 to 7 feet. A maximum depth of gleying to 10 feet was noted in one section. As this clay is often only 6 to 10 feet in thickness, gleying often extends completely through the deposit.

3. pH values

All the profiles within the Tees Clay exhibit remarkably high pH values. The general pattern shows the sample at one foot depth to have a pH between 7.5 to 8.0, while below this depth the pH stabilises at a high value of between 8.5 to 8.8. Profile No.1 (Upper Tees Clay) is an example of where both the 1 foot and 2 foot samples below the surface give values below pH 8. The important point to note is the very high pH of the present day environment, and the resultant fact that at the present day rates of leaching away from root micro-environments must be exceedingly slow.

4. Calcium carbonate content

The calcium carbonate figures show that some decalcification has taken place to a depth of 2 feet, but that below 3 feet decalcification is negligible, and figures of around 10 to 12% calcium carbonate content are consistently found. Occasionally a

profile may show some slight leaching to 3 feet (e.g. Profile 1, Upper Tees Clay), but in no case is any leaching seen to a depth of 4 feet. For the Upper Tees Clay the average depth of leaching is less than 2 feet.

5. Organic matter content.

The organic matter content of the Tees Clay is remarkably low throughout the profile, and varies ^{mainly} between 1.4 and 1.6%. Most of this appears to be due to the measurement of weathered coal material, and in most cases no evidence of the superimposition of true organic matter is seen even at the 1 foot level. Further analysis showed that true organic matter concentrations are limited to the top 4 to 6 inches of the profile. In all the Upper Tees Clay samples total organic matter contents are low, with few results giving a figure of more than 2%.

6. Sand content.

Sand contents are uniformly distributed in the unweathered portion of the profile, and vary from 10 to 25%. In a number of cases the 1 foot in depth sample contains almost double the percentage of sand found in the soil below. This is interpreted as being due to the removal of the fine grain particles by the action of the wind following ploughing. The existence of the clay carbonate nodules suggests that some movement of clay sized material does take place down the joint faces of the profile.

The Upper Tees Clay commonly overlies laminated clays, although exposures of this junction are rare. At Stob Cross (No.3 profile) a change in the calcium carbonate, organic matter and sand contents is seen at a depth of 8 to 9 feet. Although no colour difference was seen at this level, this change is thought to represent the boundary between the two deposits.

b. THE UPPER WEAR CLAY (Figs. 65 and 66).

The Upper Wear Clay always forms surface exposures when present, and stratigraphically appears comparable with the Upper Tees Clay. Exposures of this clay are poor and usually confined to brick pits, where it is commonly found overlying laminated clays or laminated clays and sands. Its unweathered colour is a dark brown, but the top 2 to 5 feet of the weathering profile often exhibited bright yellow and orange colouration due to the oxidation of iron minerals.

1. Depth of root penetration

Root development in this clay shows considerable variations depending on the topographic situation. In well drained soils root penetration can be found to depths of 4 to 5 feet, but in soils showing more evidence of gleying root penetration rarely exceeds 18 inches.

2. Depth of gleying

Gleying along the joint systems is unusual in this clay and instead tends to be found as a more widespread phenomenon throughout the whole profile. A gleyed horizon indicating seasonal waterlogging of the soil is also sometimes found.

3. pH values.

The pH values found in this clay are nearly always below neutrality in the top 4 feet. However with depth a rapid rise in pH is seen in some profiles, and a pH of 8.4 is sometimes reached at a depth of 6 feet. Where the Upper Wear Clay is thinner and overlies laminated clays pH values rarely rise above 6.5, and indicate a much more acid environment than that found in the Tees Basin associated with the Upper Tees Clay. The lowest pH value noted in the sub-soil of the

Upper Wear Clay is a value of 4.9 at Ferryhill. (No.2 profile).

4. Calcium carbonate values.

Calcium carbonate contents are always low in the Upper Wear Clay and average about 2%. In no case is a figure of more than 4% found. Because of these very low values depths of leaching can not be ascertained with any accuracy.

5. Organic matter content.

Organic matter concentrations are nearly always fairly high (c. 2%) in this clay, owing to the presence of considerable weathered coal material. Concentrations of true organic matter are only rarely seen at a depth of 1 foot.

6. Sand content.

The relatively high sand content of the Upper Wear Clay means that its basal junction with weathered laminated clay deposits can be easily detected by sand content analysis. For example in profile No.3 (Upper Wear Clay) the top 4 feet with a sand content of between 34 to 38% represent the Upper Wear Clay. The 5 foot sample, with a sand content of 25% represents a mixture of the Upper Wear Clay and laminated clays, while the 6 foot sample with only 10% sand content represents uncontaminated laminated clay. The junction between the Upper Wear Clay and the underlying laminated clays is often marked by an increase in organic matter content. This is difficult to explain in terms of true organic matter, and probably reflects the very fine and easily weathered nature of the coal fragments found in the laminated clays. It almost certainly cannot be used as evidence for a sub-aerial weathering profile at this level.

In a sample of the Upper Wear Clay at a railway cutting north of Durham (No.4) the sand content is considerably lower than usual at about 20%. This is particularly strange as below 6 feet, the clay appears to grade into a pure sand deposit. This gives some indication of the variability of this type of deposit.

c. THE UPPER TILL OF THE COASTAL AREA. (Fig.65 and 66).

The Upper Till outcrops in a linear north to south belt from Easington to Sedgfield, and is best exposed along the coastal cliff sections. The unweathered clay is a red brown to dark brown colour, and weathers in the top 1 to 2 feet to a lighter yellowish brown or reddy brown colour. A marked prismatic structure below 9 inches is often developed.

1. Depth of root penetration.

Root penetration in this clay is considerable with the finer roots commonly reaching down the joints within the clay to depths of 5 to 8 feet. Most of the larger roots are however confined to the top 3 feet of the profile.

2. Depth of gleying.

In this clay as with the Upper Tees Clay gleying tends to be confined to the joint faces. This clay is unusual in the fact that such gleying commonly penetrates to depths of 10 to 12 feet.

3. pH values.

pH values in the unweathered part of the Upper Till are always high, and vary between 8.5 and 8.9. In the surface horizons the pH values are much lower, with recordings below neutrality commonly being observed in the top 2 feet of the profile. In almost

all cases pH values above neutrality are recorded at a depth of 3 feet.

4. Calcium carbonate content.

Decalcification in the Upper Till is very similar to that noted in the Upper Tees Clay. In the majority of cases evidence of leaching of carbonates is recorded in the upper 2 feet of the profile, but below this decalcification is generally not seen. Occasionally in topographical hollows decalcification to depths of 3 to 4 feet is seen in some of the coastal sections.

5. Organic matter content.

Organic matter concentrations show variable results with high values seen only in the 1 foot in depth sample. Slightly higher than usual values are sometimes noted at the 2 feet level but this is rare. In this deposit, owing to the well drained nature of the sub-soil oxidation of the organic matter appears to be rapid.

6. Sand content.

Concentrations of sand in the surface horizons of the Upper Till are common, and values of up to 75% sand content are found. Such concentrations of sand are believed to be due to the removal of finer material by wind action.

d. THE LOWER TILL. (Figs. 65 and 66)

The Lower Till covers the whole area within the study region. In the Wear Lowlands and the coastal region it is generally deeply buried beneath other superficial deposits, and good weathering profiles developed upon it are confined to the area of the Magnesian Limestone Plateau.

The variations in the colour of this clay are greater than in any of the other deposits studied, and appear to be due to the varying amounts of Magnesian Limestone in the clay, and also to the different oxidisation states of the iron minerals. In its unweathered form the clay varies from dark grey to brown, but on weathering considerable colour changes take place leading to extensive yellow and brown mottling.

1. Depths of root penetration.

Root penetration in the Lower Till varies considerably depending on conditions of drainage within the soil. In some areas of the plateau where waterlogging of the sub-soil is common in the winter months roots are confined to the top 9 to 12 inches of the soil profile. In better drained areas the roots are seen to pass down through c. 6 feet of the Lower Till, and into the Magnesian Limestone parent material below.

2. Depth of gleying.

Owing to the varied environmental conditions found on the Magnesian Limestone Plateau average figures for gleying are difficult to record, and as might be expected show considerable variation. One characteristic of the Lower Till in this area is the fact that gleying is a widespread phenomena throughout the profile and is not confined to the joint faces.

3. pH values.

Considering the fact that in the Plateau area the Lower Till everywhere overlies the Magnesian Limestone, pH values are often suprisingly low. Values below pH 8.0 are commonly observed in the top 3 to 5 feet of the profiles studied.

4. Calcium carbonate content.

Along the line of the Magnesian Limestone Escarpment the Lower Till began to incorporate considerable quantities of limestone into the matrix of its clay. At a number of quarries along the escarpment the results of this process are well seen. In the upper parts of the profile of the Lower Till calcium carbonate figures are low, and similar to those found in the Lower Till of the Wear Lowlands. In the basal samples however immediately overlying rockhead the carbonate figures have risen to as high as 60% in some cases, and these are considered by the author to reflect the grinding action of the ice sheet as it was forced to rise over the edge of the Magnesian Limestone escarpment. (No.1). In such cases depths of decalcification is a rather meaningless concept as the basic assumption of such studies, the idea that calcium carbonate is initially uniformly distributed in the original profile is not met. For here one is dealing with a depositional profile in which the calcium carbonate has never been uniformly distributed throughout the profile.

Further east down the dip slope of the Magnesian Limestone considerable changes are noted. The basal 1 foot of the till directly overlying the Magnesian Limestone still possesses very high calcium carbonate contents, but above this is always a layer of till which exhibits a more uniform calcium carbonate content. (Nos. 4 and 5). This suggests that beyond a certain minimum distance of transport a till with uniform characteristics in terms of Magnesian Limestone content is soon developed.

Decalcification studies are also complicated by the fact that in this area, on the steeper slopes (above 5 degrees) soil creep is actively taking place, with the result that some of the profiles show

decalcification only to a depth of 1 foot (No.5). In such cases it appears that soil creep is removing the till almost as rapidly as it is being leached. Such a process probably explains why considerable areas of the Magnesian Limestone Plateau area at the present day have such a very thin drift cover.

On the more gently sloping areas decalcification is more pronounced and commonly found to depths of 5 feet. Such figures are almost double those found associated with the Upper Till in the coastal region.

5. Organic matter content.

Variations in organic matter content within the Lower Till are considerable. Very high figures up to 4% are found in some of the surface horizons, and high values down to depths of 5 feet are noted in those profiles where weathering appears to have been intense. (Sample 4). Such high figures are considered to be due to the weathering of coal fragments within the clay, rather than to true organic matter.

6. Sand content.

Sand contents within the profiles of the Lower Till show considerable variation and often high values. Some evidence of sand concentrations is found in the superficial horizons, (No.4 and No.5).

Further detailed analysis on the weathering profiles of the Lower Till was attempted to evaluate the changes which have occurred in this clay which is considered to have been weathered for the longest period.

Iron contents were measured for a number of profiles but it was found that no systematic variation existed in the results obtained, even though considerable colour changes in the deposits were

to be seen. This fact suggests that it is the state of the iron, rather than total amounts which vary in the profile, and that these reflect the balance of oxidizing and reducing conditions.

Detailed clay mineral studies were also attempted at a number of quarries. The results from Coxhoe Quarry are shown in (Fig.57). These results show that there is no variation of clay minerals with depth, suggesting that the original depositional assemblage of clay minerals are stable under the normal processes of weathering. The dominant minerals present as stated in the last chapter are illite, kaolin and quartz.

One interesting point found at Coxhoe Quarry is the presence of the iron mineral lepidocrocite (peak at 6.26A) in the surface horizon. The existence of this mineral appears to indicate fairly intense and perhaps long weathering conditions.

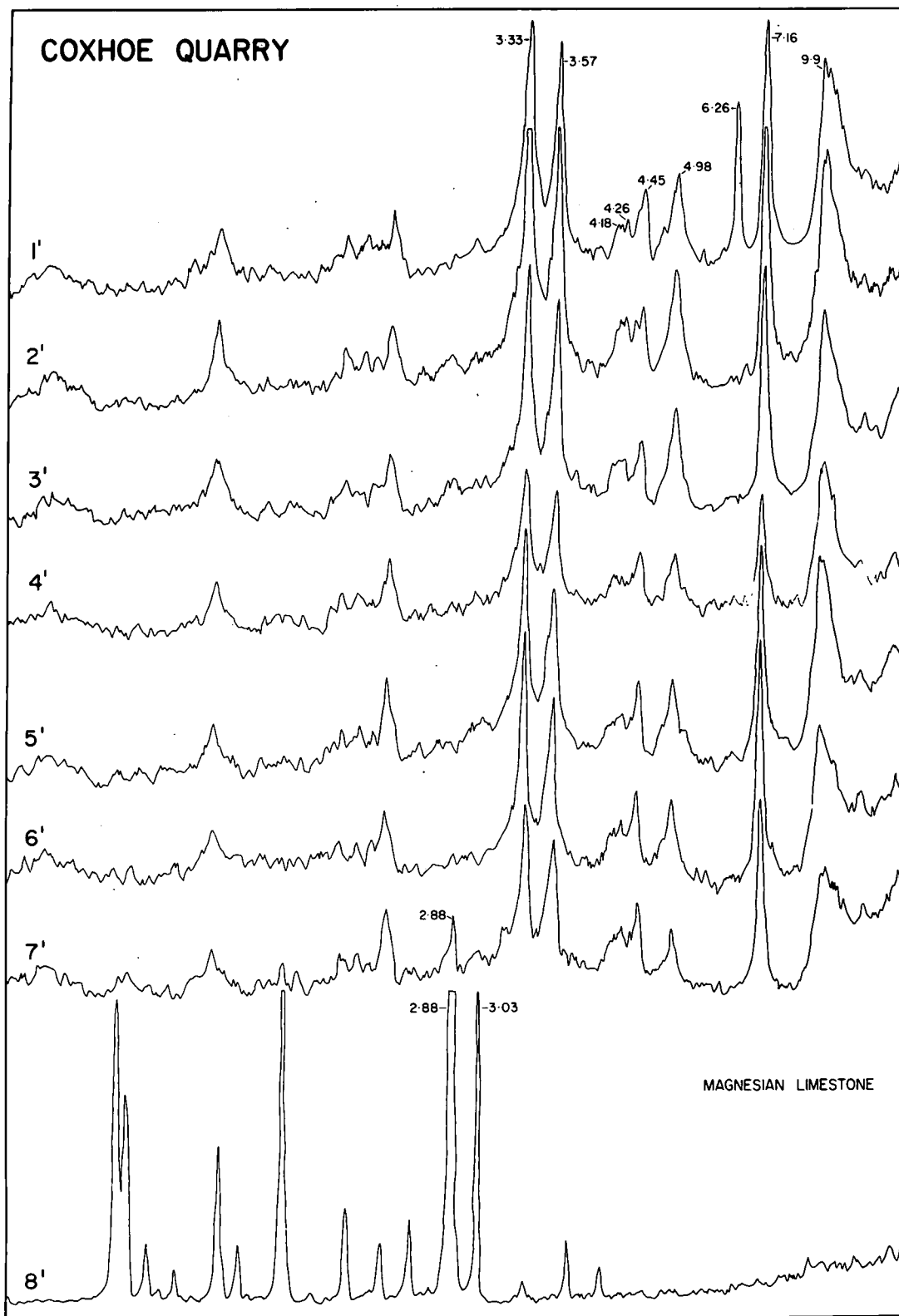
The presence of dolomite (2.88A) is detectable in the sample immediately overlying rockhead, and indicates that this mineral has been incorporated from the Magnesian Limestone beneath.

Summary of Results.

A comparison of the results of these present day weathering profiles reveals certain interesting facts. By far the most important point to emerge from this study is the very shallow imprint that the effect of the weathering of the last 15,000 years or so has had on the Eastern Durham clays. At all the sites examined no evidence was found for weathering to depths of more than 6 feet, and in the coastal sections of the Upper Till depths of decalcification are normally half this value. The implication of this is that if the present day surface was buried by some agency which was not completely depositional, only 2 to 4 feet

Figure 67.

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of the present day surface profile would have to be removed to make it completely impossible to detect the effects of present day weathering. If the area was to be overwhelmed by an ice sheet it would appear highly likely that no remains of the former weathering surface would be left at all, except where specific local conditions have aided its preservation.

The second point to emerge is the very marked differences in present day environmental conditions which exist between the Wear Lowlands, as shown by the results of the Upper Wear Clay, and the rest of Eastern Durham. In the Wear Lowlands the surface pH environment is generally below neutrality, whereas elsewhere high pH environments with values above pH 8.0 are found. Under such conditions rates and depths of decalcification at the present day even in what is a small and relatively uniform area would be expected to differ considerably. As a result differences in depths of leaching may not represent differences in time of weathering, but rather basically differing types of weathering environments.

Even on the Magnesian Limestone Plateau itself where environmental conditions are relatively similar, the differences in depths of leaching between the Upper and the Lower Till still provide difficulties of interpretation. In general terms it can be stated that the Lower Till shows decalcification to between 3 to 5 feet, whereas the Upper Till shows values of between only 1 to 3 feet. The question at issue is whether this difference represents a difference in the time of weathering to which these respective clays have been subjected.

The main complication is the fact that the Lower Till rests directly on the Magnesian Limestone, whereas the Upper Till rests almost invariably on considerable thicknesses of other glacial deposits. Such a difference will obviously effect the rate of water movement through the profile, and as a result to some extent determine the rates of leaching. When such a factor is borne in mind the difficulties in

interpreting weathering profiles become obvious.

Of the other factors analysed in the present day weathering profiles no great variations are found between the different deposits, or between different areas. Therefore the following figures are considered representative of the present day environment in Eastern Durham.

Depths of root penetration	0 to 7 feet.
Depths of gleying	11 to 10 feet (along joint faces)
Organic matter concentration	3 inches to 2 feet

B. Palaeosols

Introduction.

Weathering studies reach their maximum value when they allow the recognition of a buried palaeosol, formed by sub-aerial weathering conditions during an earlier interglacial or interstadial period. With this aim in view a series of profile studies was made on the buried clay deposits of Eastern Durham. As has already been shown in this chapter the effects of weathering have left a clear imprint only on the topmost layers of the soil profile, and that it would be these layers which would be most likely to be removed by whatever agency caused the burial of the weathered profile. Bearing this in mind it is not suprising that so few palaeosols have been described in the literature of the British Isles. It is worth recording that in the course of this research, no weathering or soil profile has ever been noted by the author on the surface of the Magnesian Limestone, where this rock is

buried beneath glacial till. If one used this fact as negative evidence it would be possible to argue that no weathering has occurred between the deposition of the Magnesian Limestone in Permian times and the deposition of the Lower Till during the Pleistocene glaciation. In this instance it is obvious that such cannot be the case, and yet similar evidence has been used by Catt J.A. and Penny L.F. (1966) to suggest that the three till sheets of Holderness, the Hesse, Purple and Drab are of the same age.

Results

In this section the analytical results obtained from a series of possible palaeosols in Eastern Durham are recorded. The palaeosols are described under the following headings:-

- A. Tees area
- B. Lower Till of the coastal area
- C. Scandinavian Drift

A. Tees Area.

The only undoubted palaeosol found within Eastern Durham was discovered near the mouth of the Tees during foundation exploration for the proposed nuclear power station at Tees Mouth. 4½ inch diameter samples, at 2 to 3 feet intervals were obtained for the author by Mr. D.B. Smith of the Geological Survey. These samples revealed a sequence of three red-brown stony clays separated by almost stoneless material, overlying a dark grey basal till. This basal till is thought to represent the Lower Till of Eastern Durham. The fact that three red-brown stony clays exist at this location poses something of a problem as a similar succession is not found to north of this area. A possible explanation for this succession is that one or more

of these red-brown clays is the product of an ice sheet from over Stainmore.

What is particularly interesting in this sequence is the fact that the junction between the upper and the middle of the red-brown stony clays, at a depth of 48 feet beneath the present ground surface, appears to exhibit undisputed evidence of sub-aerial weathering. (see Fig.68)

Analytical evidence

1. Presence of roots.

Between 48 and 53 feet beneath the present ground surface, a series of vertical carbonised root remains was found in the borehole cores. (Fig.69). No root remains were discovered above 48 feet or below 53 feet.

2. Presence of gleying.

Between 48 to 50 feet the clay was extensively gleyed, and gleying was noted along the joints to a depth of 61 feet. No gleying was seen in the cores above 48 feet.

3. Calcium carbonate values.

The calcium carbonate content in the clay immediately above 48 feet averaged 13%. At 48 feet the carbonate content was 4%, rising to 7.5% at 49 feet, and 10% at 50 feet. Below this average figures of c. 11.5% were found.

These results therefore strongly suggest a decalcification horizon between 48 to 50 feet.

Fig.68

Nuclear Power Station Borehole

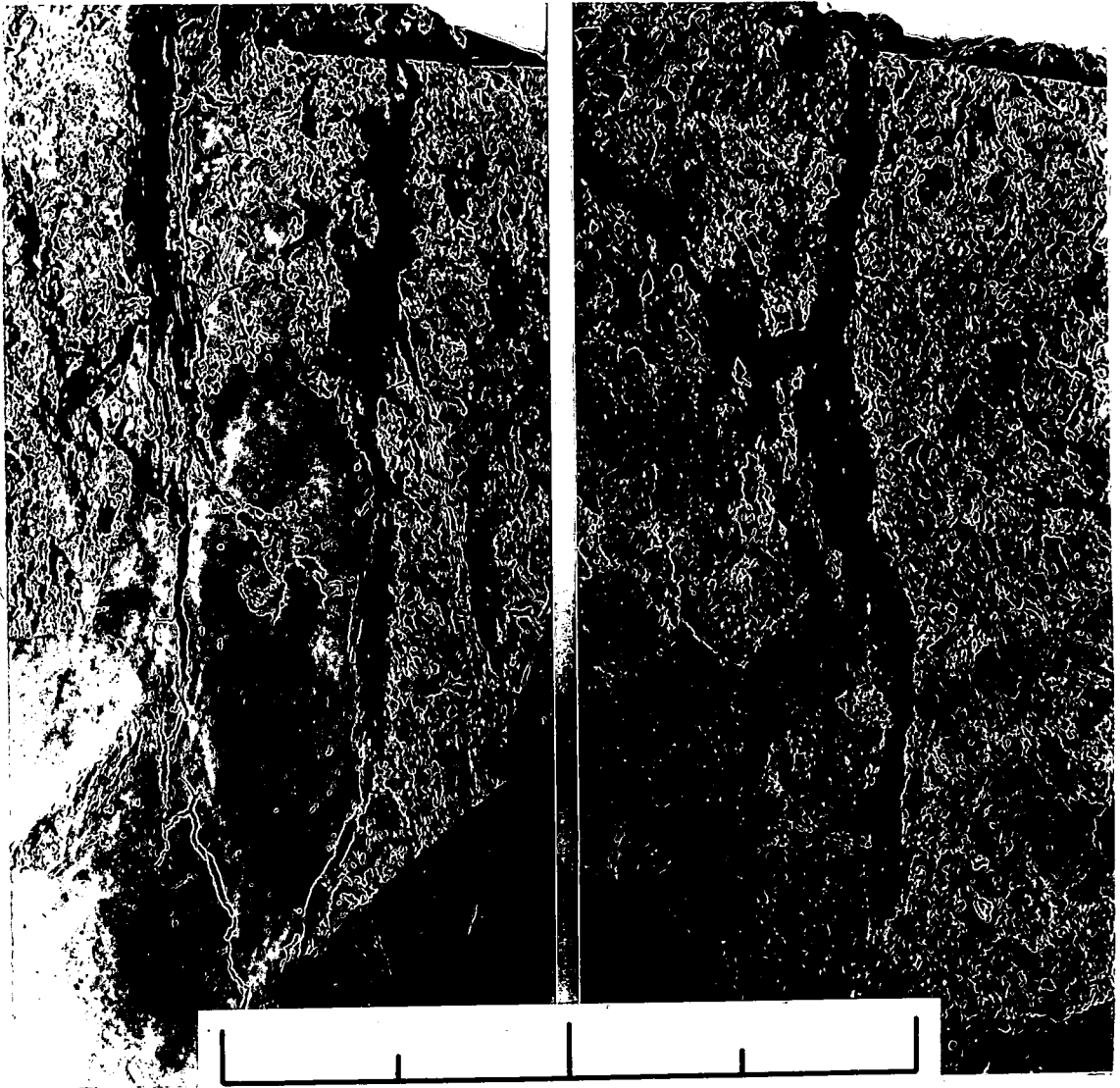
Visual Evidence

Depth below ground surface				Colour	Presence of roots	Gleying
40	10 YR	4/2		Dark greyish brown	No roots	No gleying
43	5 YR	4/3		Reddish brown	No roots	No gleying
45	10 YR	4/2		Dark greyish brown	No roots	No gleying
48	7.5 YR	4/4		Brown to dark brown	Roots present	Heavily gleyed
49	5 YR	4/3		Reddish brown	Roots present	Heavily gleyed
50	7.5 YR	4/2		Brown to dark brown	Roots present	Gleyed
51	5 YR	5/3		Reddish brown	No roots	Gleyed
52	5 YR	5/3		Reddish brown	No roots	Gleyed
53	7.5 YR	5/4		Brown	Roots present	Gleyed
56	7.5 YR	5/4		Brown	No roots	Gleyed
59	7.5 YR	5/4		Brown	No roots	Gleyed
61	10 YR	5/3		Brown	No roots	Occassion- ally gleyed

Analytical Evidence

Depth below ground surface	Calcium Carbonate Content	Organic matter Content	Sand Content
40	13.5	1.57	12.0
43	13.0	1.64	25.6
45	12.5	1.38	24.8
48	4.0	2.60	15.2
49	7.5	2.36	13.2
50	10.0	2.11	14.4
51	10.5	1.79	26.4
52	11.0	1.76	27.2
53	12.5	1.68	21.6
56	11.5	1.79	20.8
59	12.5	1.95	16.8
61	12.0	1.99	18.4

Figure 69 .



1 INCH

4. Organic matter content.

Organic matter analysis revealed concentrations at 48 and 49 feet with 2.60% and 2.36% respectively being present at these levels. Above 48 feet organic matter contents were below 1.65% while below 50 feet averages about 1.8% were found.

Four different and unrelated types of analysis therefore indicate strong evidence for a former ground surface between 45 to 48 feet below the present ground level.

In summary the palaeosol shows:-

- a. root penetration to a depth of at least 5 feet.
- b. gleying to a depth of 13 feet.
- c. decalcification to a depth of 2 feet.
- d. organic matter concentration to a depth of 2 feet.

The similarity between these figures and those obtained from the present day weathering environments is to be noted.

Of great interest with this palaeosol is the fact that the ground surface of the borehole is situated at a height of 5.71 feet above Ordnance Datum. This means that the weathered profile on the surface of the middle red-brown stony clay is found at a depth of 42 feet below present sea level, and is therefore undoubted evidence for a lower sea level in the area.

The age of this weathering profile is unknown but the fact that it is overlain by a till-like deposit would suggest that it possibly pre-dates the final cold phase experienced in the area. The problem of interpretation with this profile is further complicated by

the fact that the relationship of these three red-brown stony clays with the Upper Till of Eastern Durham is as yet unknown.

B. Lower Till of the coastal area.

It is with the Lower Till of the coastal area that the study of palaeosols becomes so important in evaluating the stratigraphic sequence for the area as a whole. For if a palaeosol is found to exist between the Lower and the Upper Till sheets, it would be conclusive evidence that these two deposits are not the product of a single ice advance.

Visual examination of the upper part of the Lower Till at a number of exposures revealed no evidence for the presence of roots or of gleying. Analysis of both carbonate contents and organic matter concentrations also gave similar negative results at a number of places. Particular attention was paid to two exposures, at Shotton Brick Pit, and Sheraton where the Lower Till is directly overlain by laminated clays. At both these exposures it was felt that any weathering horizon which had existed might not have been destroyed under the tranquil lacustrinal conditions associated with the deposition of the laminated clays. However at both these sites no evidence of root penetration, gleying, decalcification, or organic matter concentration was to be found. In both cases the laminated clays were found to have been deposited on completely unweathered Lower Till. This does not mean necessarily that no weathering has taken place at this horizon. All it suggests is that if any weathering had taken place its imprint has been removed by some agency prior to the deposition of the overlying laminated clays.

In the coastal area of Eastern Durham one of the great problems is the inaccessibility of the upper part of the Lower Till in the cliff sections. When the cliffs are being subjected to marine erosion the cliffs are vertical and the Lower Till is found above about 30 feet of Magnesian Limestone. When the cliffs are not being eroded slumping of superficial material makes it difficult to discover the exact position of the junction of the Lower Till and the overlying Middle Sands. However at a number of places it proved possible to examine the nature of the junction of the Lower Till and the deposit above it. At two exposures profiles on the upper surface of the Lower Till have been discovered which seem to indicate possible weathering conditions at this horizon.

These two profiles are situated at :-

- A. The mouth of Castle Eden Dene
- B. Green Steps, Crimdon.

A. The Mouth of Castle Eden Dene. (Fig.70)

CASTLE EDEN DENE MOUTH.

? weathering profile on Lower Till.

Horizon	pH	Calcium Carbonate content	Organic matter content	Coal Content
1	7.5	6.25	2.3	.17
2	8.2	37.6	1.5	.40
3	8.1	37.4	1.1	.36
4	8.1	36.9	1.1	.36

All figures except pH in percent.

This profile is situated 50 yards north of the mouth of Castle Eden Dene where the Lower Till is overlain by a calcreted gravel deposit. The nature of the junction between the gravel and the Lower Till is clearly erosional, and it is fairly certain that some portion of the Lower Till has been removed. The upper part of the Lower Till was subjected to analysis.

Analytical Evidence.

1. Root remains

No evidence of root remains or former root channels were found.

2. Gleying

No evidence of gleying was found.

3. pH values

A pH of 7.5 was recorded in the superficial horizon, rising to above pH 8.0 in the clay below this.

4. Calcium carbonate content

The uppermost horizon showed a low calcium carbonate figure of 6.3%. Below this horizon the carbonate figure stabilised at about 37%.

5. Organic matter content

The organic matter content showed a concentration in the superficial horizon and much lower figures below this. A coal analysis of this profile showed that the lowest coal figures were found, where the organic matter content was highest.

The evidence seems to suggest that the uppermost horizon of the Lower Till at this point showed evidence of decalcification, and organic matter concentration. The fact that neither root remains nor gleying are found means that this profile can not be claimed to be a palaeosol with as much justification as that in the Tees area. It is

possible that the decalcification of the top horizon could have been due to the water associated with deposition of the overlying gravels, but the presence of an organic matter concentration at this level is much more difficult to explain without some kind of weathering horizon being present at this level. Any evaluation of the possible type of weathering environment is impossible with the evidence available. The fact that the gravel above the Lower Till at this point may represent a beach deposit, suggests the possibility that the weathering of the upper part of the Lower Till may have taken place under estuarine or marine conditions.

B. Green Steps, Crimdon (Figs. 71 and 72).

At this point 23 feet of the Lower Till overlies the Magnesian Limestone. At the upper surface of the Lower Till there is a marked stone horizon, and this in turn is overlain by a brown sand deposit of at least 4 feet in thickness. Above this is found a further 50 feet of glacial deposits, but slipping along the cliff face made a detailed evaluation of the stratigraphy impossible.

The whole thickness of the Lower Till at this point was subjected to analysis with samples of the clay being taken at 1 foot intervals. A visual examination of the total clay thickness at this point was also made.

The basal 4 feet of the Lower Till immediately above rockhead shows evidence of a very rough bedding, but no real sorting of material. Occasional horizontal sand wisps up to 12 inches in length, and $\frac{1}{4}$ inch in thickness are seen.

Above this basal zone the Lower Till is exposed as a very dark grey and compact stony clay, which possesses extremely uniform visual characteristics up to a height of 19 feet above rockhead. At 10.5 feet above rockhead a layer of red and green silt is found. This layer, between 3 to 9 inches in thickness, is very persistent along the

Fig.71

Lower Till Green Steps Crimdon.

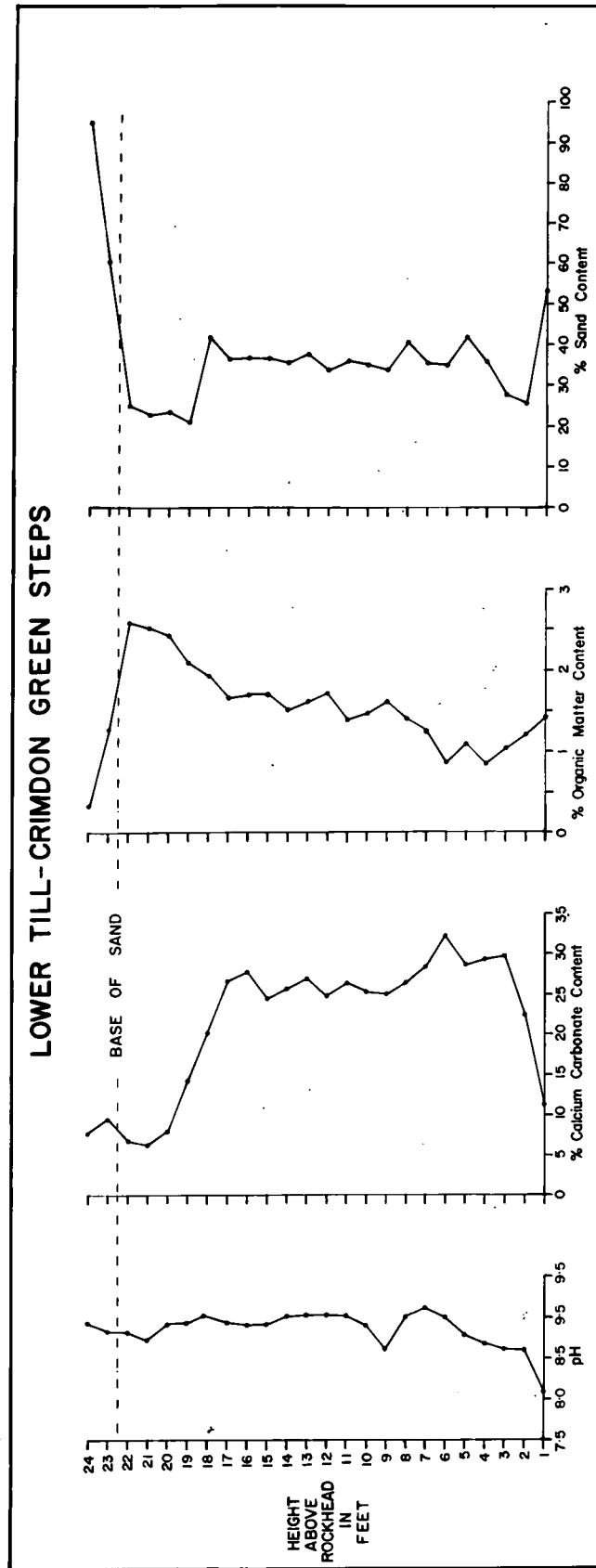
Height above rockhead	Colour		
24	10 YR	4/3	Dark brown to brown
23	5 YR	3/1	Very dark grey
22	5 YR	3/1	Very dark grey
21	5 YR	3/1	Very dark grey
20	5 YR	3/1	Very dark grey
19	10 YR	3/2	Dark brown
18	10 YR	3/1	Very dark grey
17	10 YR	3/1	Very dark grey
16	10 YR	3/1	Very dark grey
15	10 YR	3/1	Very dark grey
14	10 YR	3/2	Very dark greyish brown
13	10 YR	3/1 to 3/2	Very dark grey to very dark greyish brown.
12	10 YR	4/1	Dark grey
11	10 YR	3/1	Very dark grey
10	10 YR	3/1	Very dark grey
9	10 YR	3/1	Very dark grey
8	10 YR	4/1	Dark grey
7	10 YR	4/1 to 4/2	Dark grey to dark greyish brown.
6	10 YR	4/2	Dark greyish brown
5	7.5 YR	4/2	Dark brown to brown
4	7.5 YR	4/2	Dark brown to brown
3	7.5tYR	3/2	Dark brown
2	10 YR	3/4	Dark yellowish brown
1	10 YR	3/3	Dark brown

Fig. 71 Continued.

Lower Till

Green Steps - Crimdon.

Height above rockhead	<u>pH</u>	<u>Carbonate content</u>	<u>OMC</u>	<u>Sand</u>
24	8.9	7.6	0.31	94.9
23	8.8	9.5	1.24	60.2
22	8.8	7.0	2.57	25.1
21	8.7	6.2	2.49	23.7
20	8.9	8.0	2.38	24.5
19	8.9	14.3	2.18	21.1
18	9.0	20.0	1.95	41.6
17	8.9	26.5	1.64	37.4
16	8.9	27.5	1.67	37.6
15	8.9	25.0	1.72	37.3
14	9.0	25.5	1.52	36.8
13	9.0	27.0	1.60	38.0
12	9.0	25.0	1.72	34.6
11	9.0	26.5	1.40	36.0
10	8.9	25.5	1.44	35.6
9	8.6	25.0	1.60	34.9
8	9.0	26.5	1.37	41.4
7	9.1	28.0	1.24	36.1
6	9.0	32.5	0.86	35.6
5	8.8	28.5	1.09	42.6
4	8.7=	29.5	0.86	36.7
3	8.6	30.0	1.05	28.0
2	8.6	22.5	1.21	26.2
1	8.1	11.2	1.44	53.3



face of the cliff at this point. A further layer of this material 2 feet 6 inches in length, and 4 inches in height was found at 15 feet above rockhead.

At 19 feet a slight colour change to a more reddish hue is noted in the till. No lithological change, nor break in lithological continuity is seen at this level.

At 23 feet the till changes markedly into a compact and very stony clay, and above this at 24 feet the brown sand is exposed. The nature of the junction of the stony till with the brown sand is extremely sharp, and appears to be of an erosional nature. The thickness of the brown sand above the till is at least 4 feet, but slipping of material above this point makes it impossible to assess the total thickness.

Analytical evidence

1. Depth of root penetration.

No evidence of roots or root remains is found.

2. Depth of gleying.

No evidence of gleying is found.

3. pH values.

The pH values for the samples are remarkably uniform and through most of the till show variations from only pH 8.6 to 9.1. The basal 5 feet of the deposit does however show lower values with the pH dropping to 8.1 at 1 foot above rockhead. These figures are not considered to represent any intrinsic property of the till but to be merely a reflection of the present ground water environment to which the clay is subjected. Under such conditions the present day leaching of carbonates is expected to be minimal.

4. Calcium carbonate content.

The carbonate contents in the profile shows considerable variation, although in the central portion of the clay from 7 to 17 feet above rockhead carbonate contents are remarkably uniform and vary only between 25 to 28%. Above 17 feet there is a steady drop in the total carbonate present from 26 to 7%. at the top of the till proper (22 feet).

The basal 7 feet of the Lower Till shows considerable variation in carbonate content. Between 3 and 7 feet above rockhead the carbonate content is very high and averages nearly 30%, while below 3 feet the carbonate content drops sharply to as low as almost 10% at 1 foot above rockhead. This low carbonate figure immediately above the Magnesian Limestone poses something of a problem, as one generally finds in the plateau sections of the Lower Till that carbonate contents reach their highest values in this zone. The reason for these low carbonate figures may be associated with the bedded nature of the till in this lower portion, and be explained by the fact that water action may have caused leaching in this zone during deposition.

5. Organic matter content.

In the sand overlying the stone horizon the organic matter content is very low at 0.31%. Below this there is a marked rise to 2.6% at the top of the till proper at 22 feet. High figures above 2% are noted also at the 21 and 20 feet levels. Below the 20 feet sample the organic matter contents drops steadily, though not uniformly to about 1.0 to 1.2%.

These figures indicate a marked concentration of organic matter in the top 3 feet of the till, similar to organic concentrations found in some present day till weathering profiles.

6. Sand content.

In the brown sand deposit above the till the sand content is naturally very high with an average figure of c. 95%. Below this in the stone horizon the sand content drops to 55%, while in the top 4 feet of the till proper the sand content is even lower averaging 22%. Between 19 and 5 feet above rockhead the sand content is much higher and averages between 35 to 41%. The pronounced uniformity of the till in this zone is well seen in Fig.72. Below 5 feet above rockhead the sand content drops markedly from over 40% to almost 25% at 2 feet. At 1 foot above rockhead the sand content shows a marked rise to over 50%. The reason for these variable sand contents in the lower zone is probably associated with crude water sorting at the time of deposition.

This profile therefore seems to show possible evidence of a weathering profile on the upper surface of the Lower Till.

A slight colour difference is noted in the top 4 feet of the profile. Leaching of carbonates to 6 feet is seen, and organic matter concentration is found in the top 3 feet. These facts seem to suggest evidence of weathering, although it must be conceded that neither root fragments nor gleying are observed in this profile.

So far these are the only two possible weathering profiles which have been discovered on the Lower Till of the coastal area. Their very existence however would appear compelling evidence for arguing the fact that following the deposition of the Lower Till there was a period of deglaciation and weathering before the subsequent

deposition of the Upper Till and its associated suite of deposits. The nature of this period of weathering, whether interglacial or interstadial cannot be assessed on the evidence available. To decide this point other evidence such as the nature of the flora and fauna associated with this period of weathering would be needed.

At Green Steps, Crimdon the brown sand overlying the Lower Till forms part of the upper division of the Middle Sands. As already stated in Chapter 4 Smith D.B. has suggested that the lower division of the Middle Sands represents outwash associated with the deglaciation of the Lower Till, while the upper division is regarded as pro-glacial outwash from the advancing Upper Till. If this is the case one would not expect any weathering profile to be developed on the upper surface of the Lower Till when it is directly overlain by the lower division of the Middle Sands.

To assess this point an analysis was undertaken on the Lower Till where it is overlain by the lower division of the Middle Sands. At Warren House Gill 25 feet of the Lower Till (the average thickness of the Lower Till) is overlain by a thin brown iron stained sand, and thick red sand deposits, both of the lower division of the Middle Sands.

Only the top 12 feet of the Lower Till could be studied as slipping of the cliff made the lower portions inaccessible.

Analytical evidence at Warren House Gill. (Fig.73 and 74).

1. Depth of root penetration.

No evidence of root remains were found.

2. Depth of gleying.

No evidence of gleying was found.

3. pH values.

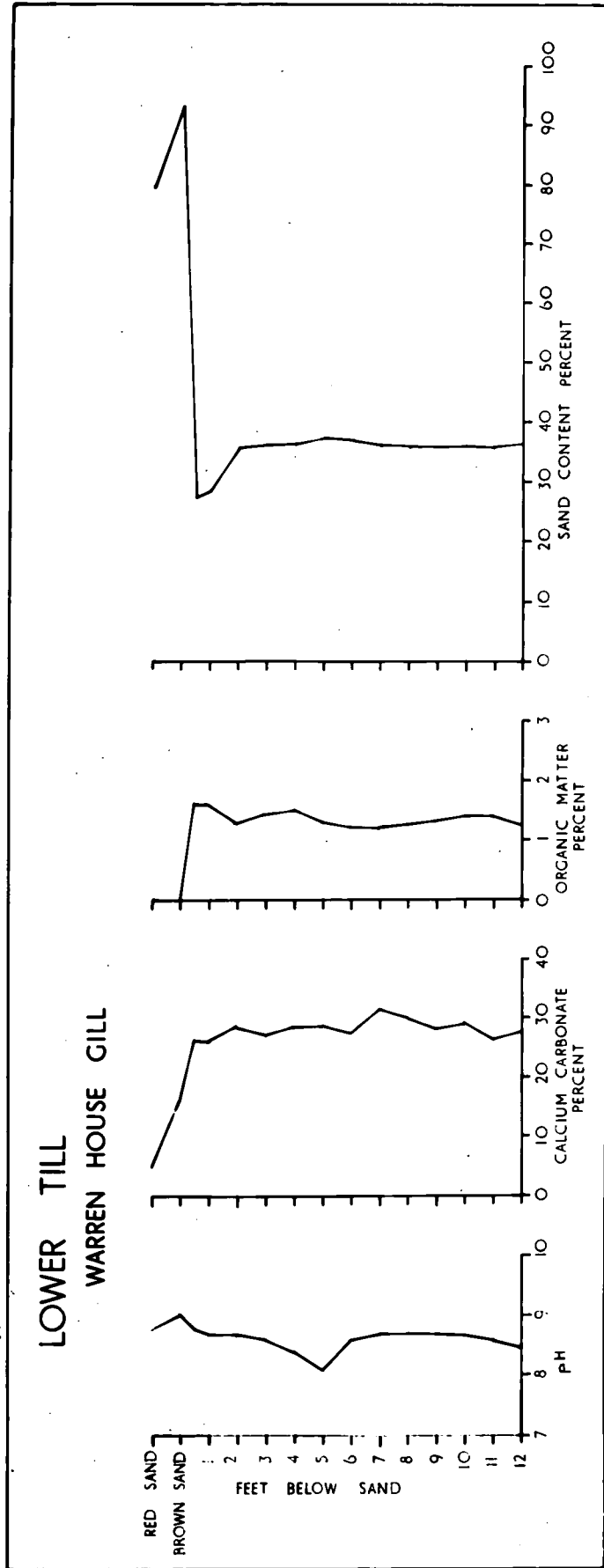
The pH of the present day environment is everywhere high and only two values are less than 8.4. A pH of 9.0 is recorded in the

Fig. 73

Lower Till - Warren House Gill.

Depth below sand layer.	Colour	pH value	Calcium carbonate content	Organic matter content	Sand content
Red sand	2.5 YR 4/4 light reddish brown.	8.8	5.0	0.0	80.0
Brown sand	5 YR 5/4 reddish brown	9.0	15.5	0.0	94.0
6"	10 YR 4/2 dark greyish brown.	8.8	26.0	1.60	28.0
1	10 YR 3/2 very dark greyish brown.	8.7	26.0	1.60	28.8
2	10 YR 3/2 very dark greyish brown.	8.7	28.5	1.29	36.0
3	10 YR 3/1 very dark grey	8.6	27.0	1.40	34.4
4	10 YR 3/2 very dark greyish brown.	8.4	28.5	1.52	36.8
5	10 YR 3/2 "	8.1	28.5	1.33	37.6
6	10 YR 3/2 "	8.6	27.5	1.17	37.2
7	10 YR 4/2 dark greyish brown.	8.7	31.5	1.21	36.4
8	10 YR 3/2 very dark greyish brown.	8.7	30.0	1.25	36.0
9	10 YR 3/2 "	8.7	28.5	1.33	36.0
10	10 YR 3/2 "	8.7	29.0	1.37	36.0
11	10 YR 3/2 "	8.6	26.5	1.37	36.0
12	10 YR 3/2 "	8.5	27.5	1.25	34.0

Figure 74.



sand immediately overlying the till surface. In this environment as at Green Steps, Crimdon the leaching of carbonates is considered to be minimal at the present day.

4. Calcium carbonate content.

In the red sand a low carbonate content of 5% is found. Below this in the brown sand the figure has risen to 15.5%, and in an intermediate sample 6 inches below the upper surface of the till the carbonate content has risen to 26%. Below this the carbonate content remains remarkably constant between 26 and 27%. The very pronounced similarity between these figures and those obtained from the unweathered portion of the Lower Till at Green Steps, Crimdon, some three miles to the south should be noted. (Fig. 75) In nearly all the samples the difference between the two sites is less than 3%. At Warren House Gill no evidence of leaching in the upper part of the Lower Till is seen, and the constant high carbonate content characteristic of the unweathered portion of the till continues up to within at least 6 inches of the overlying sand.

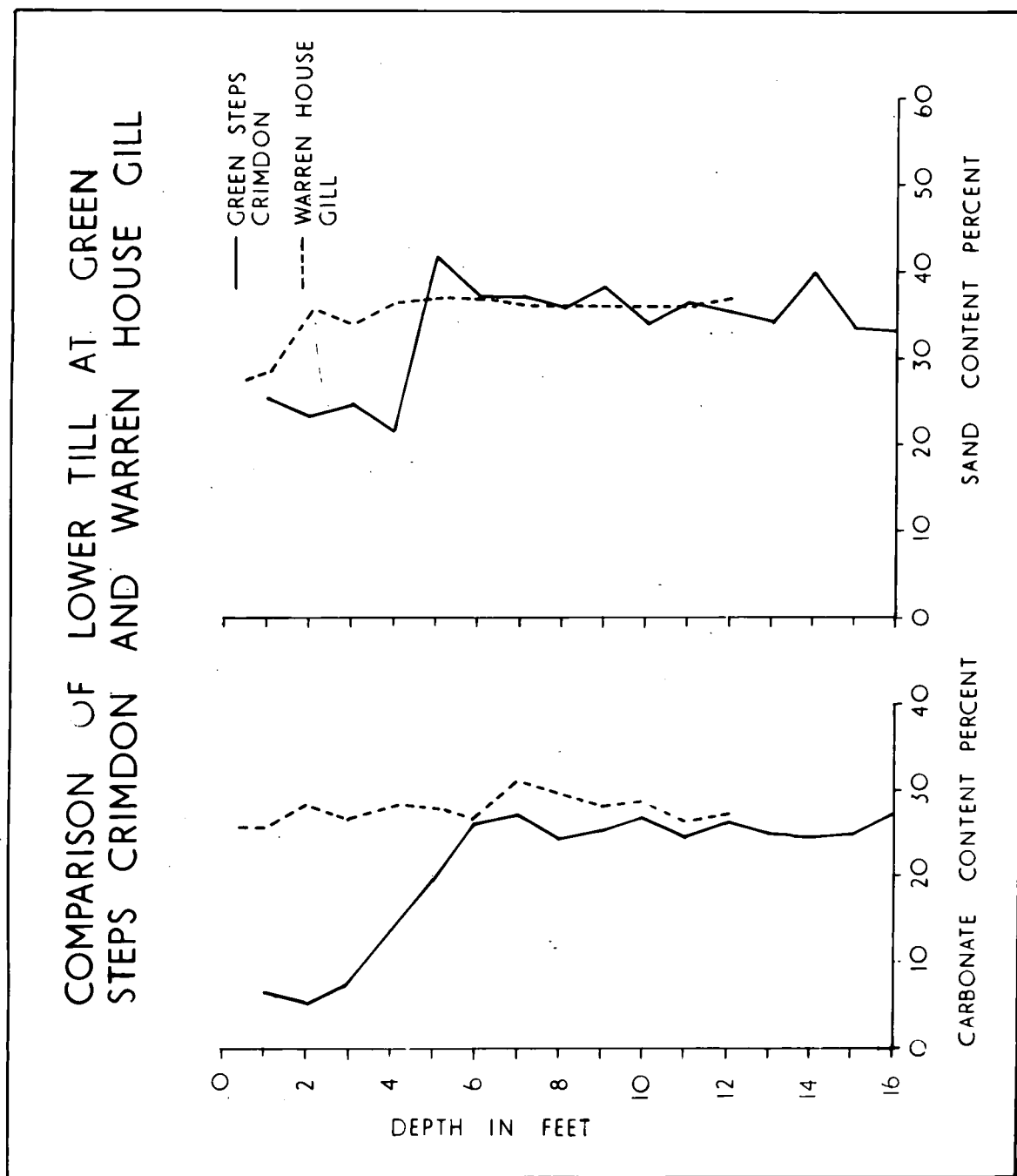
5. Organic matter content.

In the two sand deposits above the till no organic matter at all is found. In the till itself no evidence of organic matter concentration is found in the upper horizons, and throughout the deposit the organic matter contents averaged c. 1.3%. These figures for organic matter content are considered to represent the estimation of weathered coal fragments within the till matrix.

6. Sand content.

In the red sand the sand content is 80% rising to 94% in the underlying brown sand. In the red sand deposit considerable silt

Figure 75.



sized material is also present..

The upper 1 foot of the Lower Till shows an average sand content of 28%, but below this the sand content rises rapidly to 36% and remains constant throughout the rest of the profile.

As with the carbonate content, an extremely marked similarity in sand content is to be found between the unweathered portion of the till at Green Steps, Crimdon, and the till at Warren House Gill. (Fig.75).

This analysis shows that the present upper surface of the Lower Till at Warren House Gill has not been subjected to weathering. It cannot be used however as negative evidence to suggest that no weathering took place at this horizon. The fact 25 feet of the Lower Till is present at this point does suggest the possibility that little of this deposit has been removed by erosional processes since deposition.

C. Scandinavian Drift. (Figs.76 and 77).

The other main stratigraphical horizon on which palaeosol development may have been expected to have taken place on a clay deposit is on the upper surface of the Scandinavian Drift.

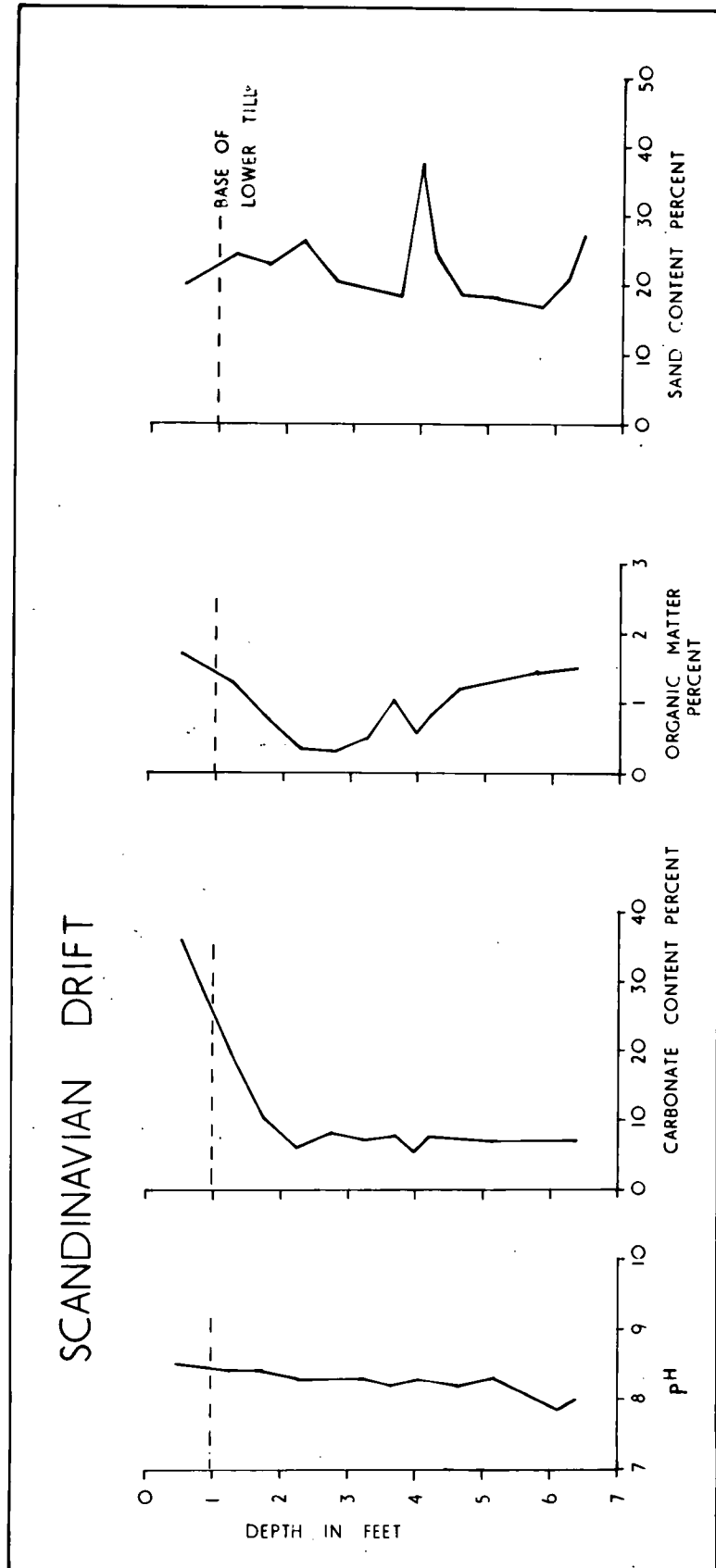
The Scandinavian Drift has always been considered by most workers in the Durham area as being separated by an interglacial episode from the Lower Till which overlies it. (Trechmann C.T. 1915, 1919; Woolacott D. 1921; Raistrick A. 1931; Smith D.B. in press).

The main evidence for interglacial weathering in the period between the deposition of the Scandinavian Drift and the Lower Till is claimed by Trechmann to be the loess deposit which is found overlying the Scandinavian Drift proper. The fact that this deposit is unfossiliferous, in marked contrast to the European deposits is he claimed due to the fact that the "... prolonged weathering and decalcification that it (the loess) has undergone may have dissolved

Fig. 76

Scandinavian Drift exposure at
Warren House Gill

Depth below surface		Colour		pH values	Calcium carbonate values %	Organic Matter Content %	Sand Content %
Up to 1'	10 YR	7/3	Very pale brown	8.5	36.0	3.36	20.8
1' to 1½'	10 YR	7/4	Very pale brown	8.4	19.5	2.64	25.2
1½' to 2'	2.5 YR	7/2	Light grey	8.4	10.5	1.68	23.6
2½'	2.5 YR	7/4	Pale yellow	8.3	6.0	0.84	27.2
2½' to 3'	5 YR	7/3	Pale yellow	8.3	8.0	0.72	21.6
3 to 3½'	2.5 YR	6/2	Light brownish grey	8.3	7.0	1.08	20.0
3½' to 3¾'	5 YR	6/1	Grey	8.2	7.5	2.16	19.2
3¾' to 4¼'	10 YR	6/4	Light yellowish brown	8.3	5.5	1.20	38.4
4¼' to 4½'	2.5 YR	6/4	Light yellowish brown	8.3	7.5	1.68	25.2
4½' to 4¾'	2.5 YR	6/2	Light brownish grey	8.2	7.5	2.40	19.6
4¾' to 5½'	5 YR	6/2	Light olive grey	8.3	7.0	2.64	18.8
5½' to 6'	5 YR	6/2	Light olive grey	8.0	7.0	2.88	17.2
6 to 6¼'	5 YR	6/1	Light grey/ grey	7.9	7.0	3.00	21.2
6¼' to 6½'	5 YR	6/1	Light grey/ grey	8.0	7.0	3.00	28.0



out any land shells or calcareous tubules". p.61 Trechmann also quoted evidence of rotting and decomposition of boulders and stones embedded in the loess near its upper surface and also near the surface of the Scandinavian Drift. This evidence he claimed very strongly suggested a period of intense weathering following the deposition of the Scandinavian Drift and preceeding the deposition of the Lower Till.

Investigation of the Scandinavian Drift by the author revealed a number of interesting problems. Rotted and rounded pebbles of granite and gneiss are reasonably abundant in the exposure which remains at the present day. The fact that many of these rocks are rounded strongly suggests that the rotting of the rock must have followed deposition. At the same time in the Scandinavian Drift in juxtaposition with the rotted igneous and metamorphic material, is a rich shell fauna with fine detail preserved on its valves, which shows no evidence whatsoever of having been subjected to weathering processes. The great problem is to concieve how the weathering of the granite and gneiss could have been achieved in an environment which has had no effect on the shell material. The problem is particularly pertinent as calcium carbonate, the material making up the shells is one of the first minerals to be affected by the weathering processes. (See Polynov and Jenny).

Two explanations seem to offer themselves. The first is that the Scandinavian Drift has been weathered at one period with the resultant rotting of the igneous material, and that the emplacement of the shell fauna within the deposit has taken place at a later date, perhaps associated with the water redeposition of the loess which Trechmann had described.

The second possibility is that the rotted material was brought to its present position in frozen blocks, and that while it was being dragged across the sea bed it incorporated the shell fauna.

In order that analytical evidence could be collected on the weathering profile of the Scandinavian Drift an auger hole was sunk to 6.5 feet below beach level into the Scandinavian Drift. It proved impossible to auger below this depth owing to the presence of what appeared to be large stones. Samples from this auger hole were obtained at 6 inch intervals for field and laboratory analysis.

In the top 4 feet of the profile the auger passed through a mixture of grey clay and "loessic" type layers, while below 4 feet only grey clay was obtained.

Two loessic layers can be distinguished in the sequence. The first at $2\frac{1}{2}$ to 3 feet, and the second at $3\frac{3}{4}$ to $4\frac{1}{2}$ feet. Both these layers are characterised by higher sand contents than the clays immediately above and below, and by a yellow colour. From all the clay layers abundant shell fragments were found.

Analytical results.

1. Depth of root penetration.

No evidence of root or root remains were found.

2. Depth of gleying.

No evidence of gleying was found.

3. pH values.

The pH in the Scandinavian Drift show consistently high values. Only one reading of below pH 8.0 is found. A trend towards decreasing pH with depth can be seen in the profile.

4. Calcium carbonate content.

The carbonate contents show a range of values from 36% to 55%. The top three readings of the profile indicate the transitional layer from the Lower Till to the Scandinavian Drift, where the two

clays are intermixed. In the Lower Till of the coastal sections the carbonate content is nearly always more than 20%. Beneath the junction between the two clays the carbonate figures remain constant with values of between 6 to 8%, although a slight decrease in carbonate content is seen accompanying the loess layers. No evidence of a decalcification zone is noted in the Scandinavian Drift, and the fact that the fine detail on the shell fragments has been preserved suggests that decalcification has not occurred at this horizon.

5. Organic matter content.

The high organic matter content of the top two horizons (Figs. 76 and 77) is explained by the fact that this is a weathering profile at the present day, with a well developed vegetation cover. It is however of only very recent development, and as the carbonate content indicates, weathering has so far been unable to produce any significant leaching effect.

Immediately below the top of the Scandinavian Drift very low organic matter contents of less than 1% are found. These however rise rapidly with depth and level out at the very high figure of c. 3%. These high figures are possibly due to the presence of minute peat fragments which have been observed in the Scandinavian Drift. It is noted that a low organic content is associated with the lower loess layer in the profile.

As with the carbonate figures, the organic matter results give no indication of any weathering horizon being present on the surface of the Scandinavian Drift.

6. Sand content.

The sand content of the clayey portions of the Scandinavian Drift shows a variation between 19 to 24% in the top 4 feet of the profile. Below this depth the sand content increases to almost 30% at the bottom of the hole where augering ceased. This increase is not

associated with the presence of a loess layer, and represents an actual sand increase in the clay material. It is not however associated with any increase in carbonate contents.

Both loess layers possess higher sand contents than the clays above and below them. The upper one has a sand content of 27% and the lower one 38%. In the author's view these high sand contents are sufficient to prove that this deposit is not a true loess.

This analysis suggested that there is no positive evidence to indicate that the upper portion of the Scandinavian Drift has been subjected to weathering processes. The possibility does exist that two types of clay may have been present in the Scandinavian Drift suite. One a true till-like deposit and the other a marine clay with a shell fauna. The present exposure of the clay does not however allow an adequate investigation of this possibility.

Another interesting point in connection with the Scandinavian Drift, is its low carbonate content. The deposit rests directly on Magnesian Limestone, and if it represents a true sub-glacial till, must have moved a number of miles in direct contact with the Magnesian Limestone. Under similar conditions the Lower Till of the coastal area always exhibits carbonate contents of more than 20%. Coupled with this is the very strange fact that in the stone content of the Scandinavian Drift very few pebbles can be positively identified as being Magnesian Limestone, although Chalk and shell fragments are relatively common. It therefore seems highly unlikely that weathering of the clay can be suggested to have selectively removed the Magnesian Limestone. A possible explanation for the origin of this clay is considered in Chapter 13.

Pollen analysis

In an attempt to glean further information on the absolute ages of the till deposits of Eastern Durham, pollen analysis was undertaken on samples of the Scandinavian Drift; the Lower Till; and the Upper Till.

Analysis of the deposits was carried out using a technique described by (Dimbleby G.W. 1957) in which all the silicate material is dissolved using hydrofluoric acid digestion. The resulting residue is mounted on a slide, stained, and examined under a microscope.

It had been considered possible that each of the till deposits might include pollen material derived from the previous interglacial period. This unfortunately did not prove to be the case and in all the samples examined no recognisable modern pollen grains were discovered. A number of spores were however noted but on examination proved to be most likely of Palaeozoic age. Fig.78 shows the main spore types identified. This method therefore proved of little value for correlation purposes.

Conclusions

The most important point to emerge from the study of palaeosols within Eastern Durham, is that one definite palaeosol, and two probable profiles of ancient weathering horizons were discovered. These latter two strongly suggest that there is evidence for a weathering horizon between the Upper and the Lower Till sheets, and that these deposits therefore cannot be regarded as being deposited by a single composite ice sheet. No information regarding the nature of this weathering interval has been discovered.

Figure 78.

Lower Till

1	Leiotriletes tumidus
2	Densosporites (Palaeozoic)
3	Camptotriletes (Palaeozoic)
4	Densosporites (Palaeozoic)

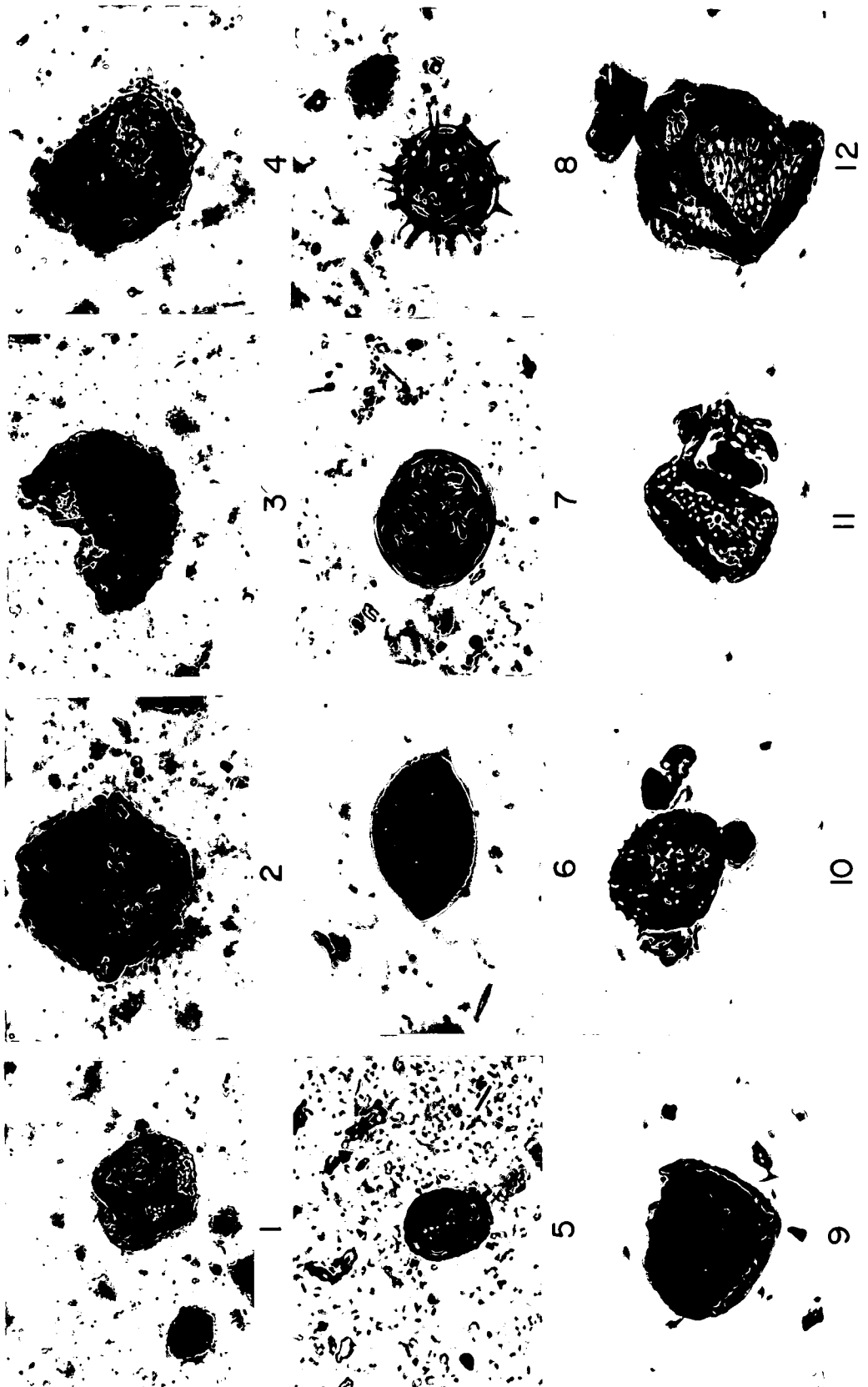
Scandinavian Drift

5	Unknown
6	Unknown
7	Punctatisporites
8	Hystriosphere

Upper Till

9	Cirratiradites (Palaeozoic)
10	Crassispora kosankii (Palaeozoic)
11	Unknown
12	Cirratiradites (Palaeozoic)

Tentative identification undertaken by Sub-Department
of Quarternary Research, Botany School, University of Cambridge,
England.



Analytical work on the upper surface of the Scandinavian Drift failed to bring to light any definite evidence of weathering activity. It must however be admitted that such evidence could have been removed by the erosive action of the Lower Till Sheet.

Chapter 11.

ARTIFICIAL DEPOSITIntroduction.

In a study where so much of the analysis has been concentrated on the stony clays of a region, it is obviously useful to attempt an evaluation of the degree to which such clays owe their present characteristics to their depositing media or to parent material sources. Many workers such as Krumbein W.C. (1933) and Shepps V.C. (1953) have shown that individual till sheets are characterized by certain, apparently diagnostic grain size distribution curves, and that the differences which exist between samples of till deposits can be utilised for the correlation of till sheets over large areas. However attempts have rarely been made to explain the reasons for such characteristics.

The present study was initiated with the idea of determining what would be the nature of a deposit formed by the mixing and grinding of local bedrock material. The idea was to see to what extent such an artificial deposit would differ from a true sub-glacially formed till, which appeared to have obtained the majority of its included material, of both large and small grain sizes from rocks of similar parent material.

Method of formation of the artificial till.

Samples of unweathered rocks of the Coal Measures of the Wear Lowlands were taken from opencast sites and quarry exposures. From the samples obtained, nine subsamples were selected - three of sandstone, three of siltstone and three of shale, which after binocular microscope examination appeared to be representative of the observed variations in grain size exhibited by the Coal Measures in the Wear Lowlands.

Rocks of these three main lithologies were then mixed in proportions of 33.3% sandstone, 33.3% siltstone, and 33.3% shale. These values approximated to the mean figure for all the Durham stony clays discovered in Chapter 8. The total amount of parent material used in this experiment was two kilograms. The mixture, which included some sandstone fragments up to 4 inches in diameter was placed in a series of polythene bags and the contents crushed in a vice between metal sheets until all the rock fragments passed through a $\frac{3}{4}$ inch British Standard Sieve. The material at this stage consisted of a mixture of shattered and angular sandstone fragments and broken pieces of shale. As expected the shale and to a lesser extent the siltstone fragments had broken down to a very fine grain size after the crushing process. The mixture from the crushing operation was then placed in an 8 inch sieve receiver and shaken for a period of 6 hours. This was undertaken in an attempt to simulate the grinding and mutual attrition of material which was thought to take place in the basal layers of a glacier during transport. Following this treatment the sample was quartered and subjected to mechanical and chemical analysis.

Results of analysis.

The first part of the analysis consisted of the separation and measurement of the medium and fine sized gravel fractions. This was carried out on a 1000 gram sample by the method of coarse analysis (Appendix 7). After this the gravel fragments were examined under a binocular microscope. The really suprising fact about them is that none of the larger fragments could be described as angular. Each fragment above c. $\frac{1}{4}$ inch in diameter shows considerable evidence of rounding (Fig 79), and is in visual form identical to the fragments of a similar grain size obtained from true glacial till. (Fig 79). This fact shows that a period of 6 hours mutual attrition on a shaking machine produced,

Figure 79.

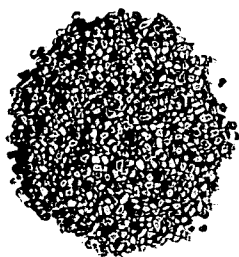
Lower Till, Finchale Priory.



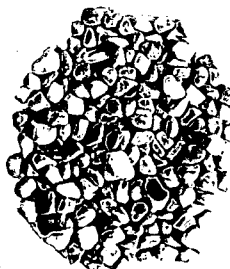
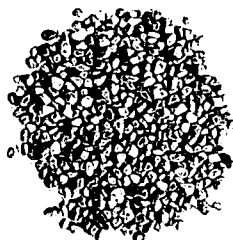
6 inches



Artificial deposit



6 inches



from similar material a particle form similar to that formed during glacial transport. Although this seems suprising at first, it might well be that these sub-rounded sandstone fragments represent some kind of semi-equilibrium form which changes little as the dimensions of the particles are reduced. A close examination of the gravel content of the tills shows that this form is indeed the most common one. The more truly rounded fragments which do occassionally occur were always of igneous or metamorphic origin. (see Chapter 6).

The total mechanical analysis of the artificial deposit revealed the following results :-

Gravel	19%
Sand	34%
Silt	36%
Clay	11%

The low clay content, even though more than 30% of shale was used in the initial mixture suggests that although breakdown and attrition of the larger sized material had taken place during the crushing and grinding processes, it had been much less effective on the finer material, and in this case only about one third of the total shale content had been reduced to its ultimate particle size. Microscopic examination showed that many small fissile shale fragments were to be found in the silt size range.

For comparison with the artificial deposit, a sample of the Lower Till of the Wear Lowlands was selected. This was a sample from near Finchale Priory with a mechanical composition closely similar to that of the artificial deposit, and formed from material similar to that composing the artificial deposit. A comparison of the mechanical analyses of the two samples is shown below.

Figures in percent

	Gravel	Sand	Silt	Clay
Artificial deposit	19	34	36	11
Lower Till Finchale Priory	18	32	34	16

In all categories differences between the two deposits are less than 6%, and a marked general similarity between the two deposits is noted.

On the basis of the particle size similarity of the two deposits, it was decided to compare other analytical results. A full and detailed mechanical analysis of the artificial deposit was made using sieve and hydrometer analysis, and from these results a cumulative frequency curve of particle size distribution constructed on semi-logarithmic graph paper. (Fig 80). The particle size distribution shows certain differences in detail from the results obtained from the stony clays of Eastern Durham. (see Chapter 8). In the size range below about 3 phi (0.15mm) the shape of the particle size distribution curve closely resembles that of the other Durham stony clays. In the coarser size ranges however the artificial deposit lacks the smoothness of curve shown by the stony clays. In quantitative terms these differences are illustrated in histogram form in Figure 81. This shows in the artificial sample a moderate to high proportion of fine and coarse sand, but very little medium sized sand. In contrast the Lower Till sample from Finchale Priory shows a gradual increase from a small proportion of coarse sand, through moderate proportions of medium sized sand, to large quantities of fine sand. In both deposits it was noted that the fine sand category is the modal value for the sand distribution.

Statistical analysis by a Spearman Rank Correlation Coefficient (r_s) (Siegal S. p202) was used to test the degree of association between the data shown in the two histograms (Fig.81).

Fig 80.

Particle size data for artificial deposit.

<u>Particle size</u> <u>diameter in mm.</u>	<u>Percentage</u> <u>finer</u>
20.0	100.00
13.0	99.70
9.7	97.50
6.0	91.20
4.7	87.70
3.2	84.80
2.0	81.60
1.2	70.80
0.6	66.00
0.4	65.10
0.3	64.40
0.2	63.90
0.15	62.60
0.10	54.60
0.075	50.10
0.062	46.10
0.046	44.44
0.038	38.31
0.034	36.74
0.027	33.60
0.021	30.30
0.016	26.27
0.013	24.68
0.0090	19.38
0.0060	16.26
0.0048	16.26
0.0033	-
0.0022	13.29
0.0014	10.17
0.0011	-

Figure 80.

ARTIFICIAL DEPOSIT

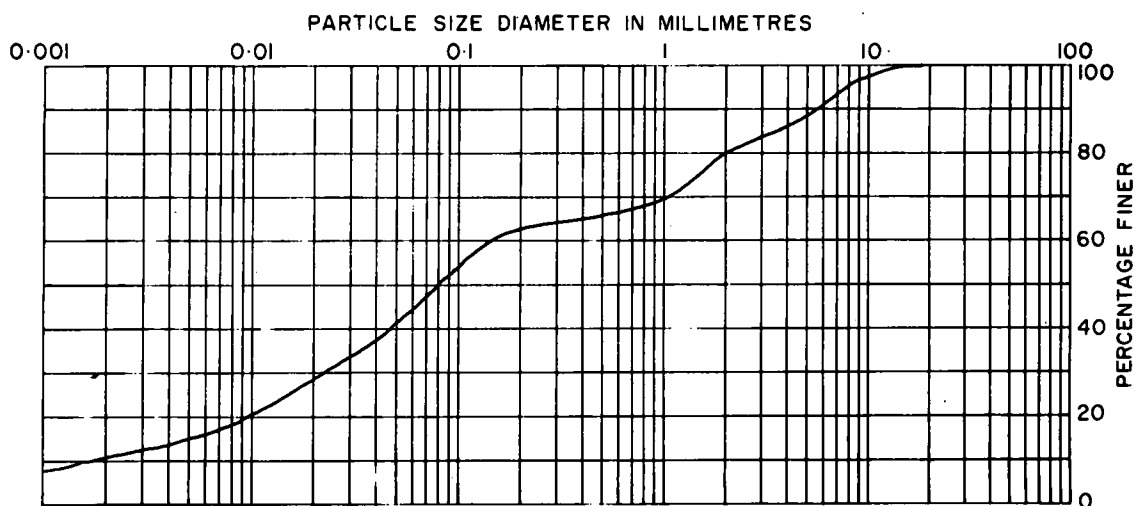
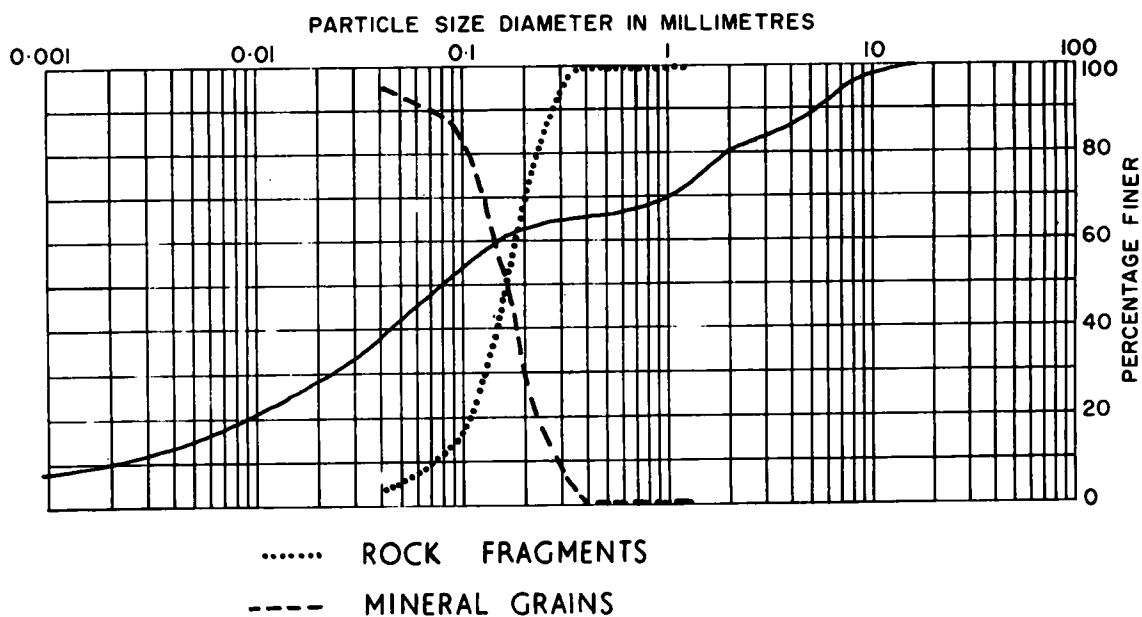
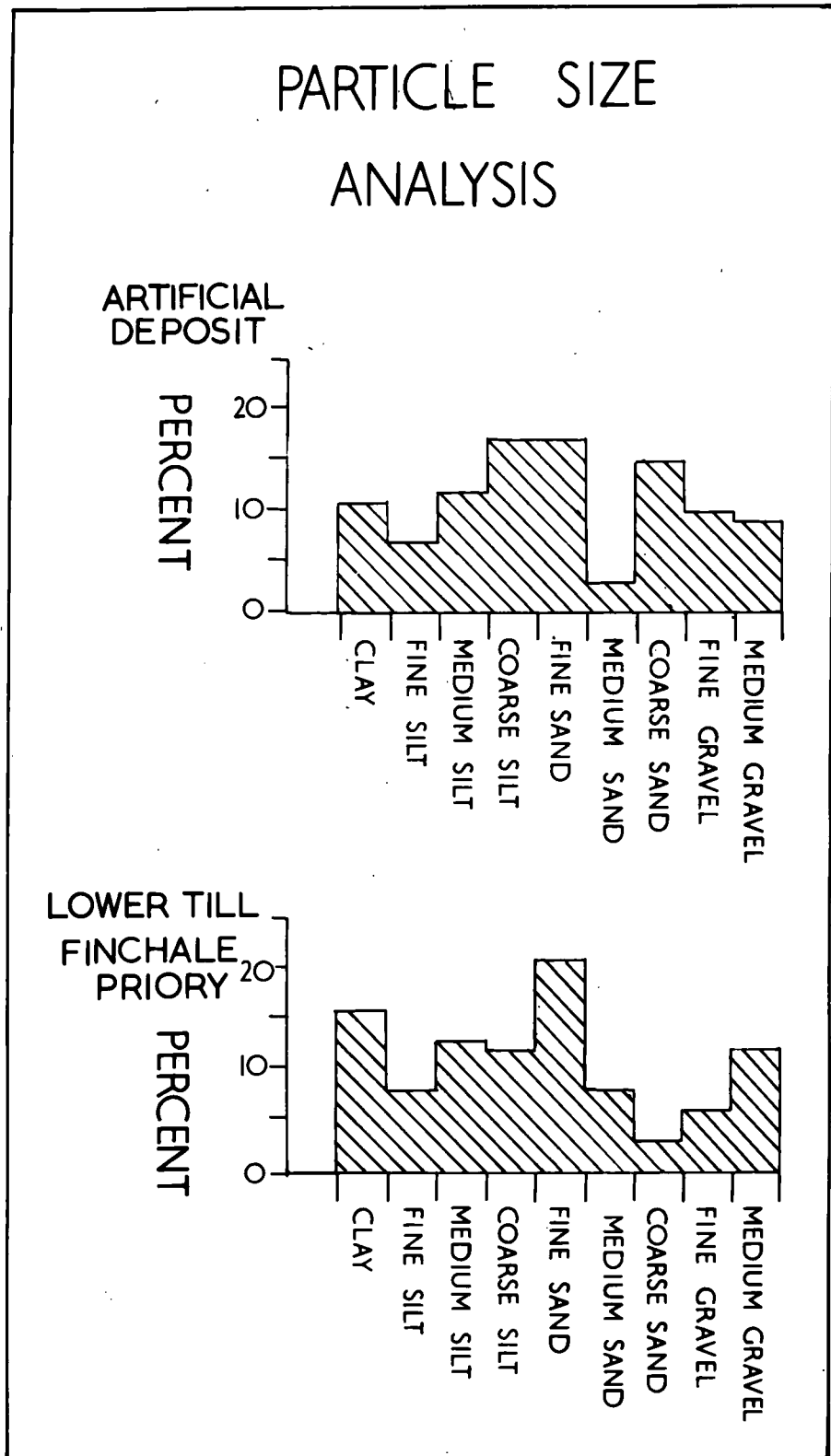


Figure 82.





$$r_s = 1 - \frac{6 \sum_{i=1}^N d_i^2}{N^3 - N}$$

N = number of observations

d_i = difference between the two ranks

A null hypothesis was postulated that the two distributions were not associated. For the samples $r_s = 0.42$. This is not significant at either the 0.01 cc or the 0.05 level. Therefore the null hypothesis is retained and the two distributions must be regarded as not being statistically associated.

The lack of association between the two deposits is largely the result of the difference between the coarse sand fractions of the two samples. The correct interpretation of this result would therefore appear to be that in the formation of the artificial deposit insufficient varieties of coarse sandstone were used for complete similarity to be produced.

A stone count of the lithological composition of the gravel fraction of the artificial deposit was also completed. For simplicity two categories were used in this count. These were :-
a. sandstone, b. siltstone and shale. The results for each of the grade sizes were as follows.

Artificial deposit

Sieve sizes	Lithologies	% of each lithology present.
$\frac{1}{2}$	Sandstone	100
	Siltstone and shale	0
$\frac{3}{8}$	Sandstone	75.0
	Siltstone and shale	25.0
$\frac{1}{4}$	Sandstone	81.7
	Siltstone and shale	18.3
3/16	Sandstone	75.9
	Siltstone and shale	24.1
$\frac{1}{8}$	Sandstone	72.7
	Siltstone and shale	27.3
8	Sandstone	68.0
	Siltstone and shale	32.0

Average proportions for total sample

Sandstone	76.4%
Siltstone and shale	23.6%

These figures show very markedly how in the gravel size range, sandstone fragments outnumber the siltstone and shale fragments by a ratio of three to one. This is of particular interest when one remembers that in the initial mixture the siltstone and shale particles outweighed the sandstone particles by a ratio of two to one. This fact undoubtedly demonstrates the greater resistance of sandstone to crushing and grinding when compared with the siltstone and shale.

A stone count of the gravel fraction of the Lower Till from Finchale Priory gives the following results:-

All figures in percentages.

Magnesian Limestone	0
Carboniferous Limestone	3.4
Sandstone	65.3
Siltstone	1.0
Coal and black shale	22.7

Ironstone	5.6
Quartz	1.0
Igneous	0.5

If one excludes the erratic material from the Finchale Priory sample (limestone, quartz, and igneous material), one finds that the ratio of sandstone to the other fine grained sedimentary rocks becomes :-

Sandstone	68.7%
Other sedimentaries	31.33%

This result is comparable with that obtained from the artificial deposit and points to the marked similarity between the two.

Statistical comparisons were also made between the particle size distributions of the two deposits.

	Artificial Deposit	Lower Till
Median	3.7 phi	4.0 phi
Mean	3.2 phi	3.8 phi
Sorting	4.7 phi	5.4 phi
Skewness	-.1075	+.0318

These values show that the artificial deposit has median and mean values of a larger grain size (in millimetres) than the Lower Till sample. The artificial deposit is also better sorted than the Lower Till sample, although comparable with the results obtained from other Lower Till samples. The majority of values for the Lower Till ranged from 3.5 to 5.0 phi, and the value for the artificial till comes almost in the centre of this range. Similarly although the skewness of the artificial deposit is considerably greater than that of the Lower Till sample, it is no more so than for other Lower Till samples.

In Chapter 8 it has already been noted that a marked break of slope is noted in the particle size distribution curve between 1 and 2 phi (0.5 to 0.25mm). This was shown to be associated with a change in the composition of the included rock material from rock

fragments to single mineral grains. In the artificial deposit two breaks of slope are noted in the particle size distribution, at -1 phi, (2mm) and a much larger one between 2 to 3 phi (0.25 to 0.125mm). Analysis was therefore undertaken to see if the breaks of slope in the artificial deposit are also related to similar lithological differences. The result of this analysis is given in Fig 82, and shows that the break of slope at -1 phi (2mm) is not associated with any lithological change. The break of slope between 2 to 3 phi (0.25 to 0.125mm) is associated with a change from rock fragments to mineral grains. The comparable change from a dominance of rock fragments to mineral grains for the Lower Till sample is also shown in Fig 83.

The fact that the artificial deposit, made entirely from the crushing of solid rock samples shows this break of slope associated with a change from rock fragments to mineral grains, proves conclusively that the break of slope is merely a reflection of the grain size of the parent material, and not some intrinsic quality associated with the actual mechanism of till deposition. In the artificial deposit the change over from rock fragments to mineral grains occurs at a finer grain size than in the Lower Till sample and suggests that the sandstone fragments used for making the artificial deposit are of a smaller modal grain size than those eroded by the Lower Till in crossing the outcrop of the Coal Measures. Another point to note is the more rapid change over from rock fragments to mineral grains in the artificial deposit, over 2.5 phi units compared with 4.5 phi units for the Lower Till sample. (Fig 83). This also is probably a reflection of the more homogeneous lithologies of the sandstone used in the formation of the artificial deposit when compared with the Lower Till.

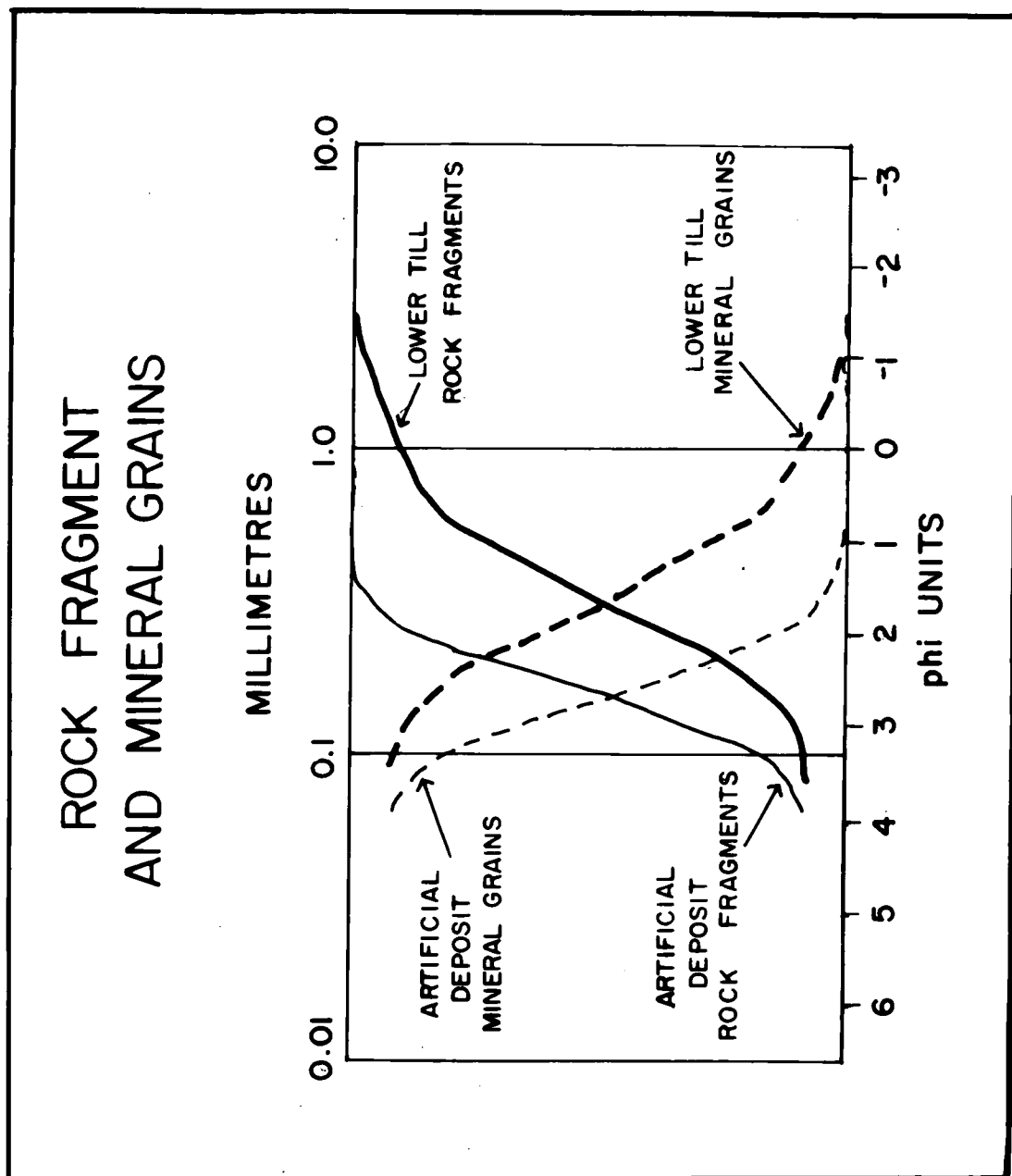
Fig 83.

Rock fragments and mineral grains

Figures in percent

<u>Sieve size</u>	<u>Types</u>	<u>Artificial deposit</u>	<u>Lower Till, Finchale Priory.</u>
1/8	Rock fragments	100	100
	Mineral grains	0	0
8	Rock fragments	100	99.0
	Mineral grains	0	1.0
14	Rock fragments	100	93.9
	Mineral grains	0	6.1
25	Rock fragments	100	83.2
	Mineral grains	0	16.8
36	Rock fragments	100	61.5
	Mineral grains	0	38.5
52	Rock fragments	92.5	45.5
	Mineral grains	7.5	54.5
72	Rock fragments	73.7	22.6
	Mineral grains	26.3	77.4
100	Rock fragments	41.1	12.4
	Mineral grains	58.9	87.6
150	Rock fragments	14.4	8.6
	Mineral grains	85.6	91.4
200	Rock fragments	8.8	-
	Mineral grains	91.2	-

Figure 83.



X ray analysis of the artificial deposit also reveals very marked similarities to that of the Lower Till. The diffractometer trace for the artificial deposit is shown in Fig 84. The similarity of this trace to one of the clay mixtures used in the quantitative clay mineral analysis is apparent (see Fig 59) and suggests that the clay mineralogy of the artificial deposit is approximately as follows:-

Illite	72.5%
Kaolin	20.0%
Quartz	5.0%
Chlorite	2.5%

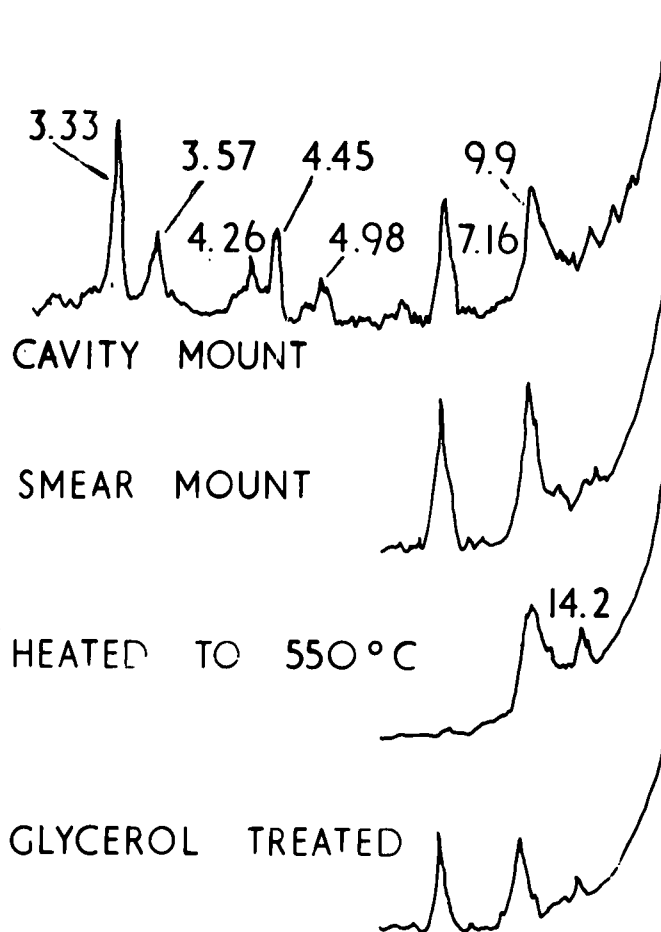
Conclusion

By far the most important conclusion to be drawn from the study of this artificial deposit is its very pronounced similarity to the true glacial tills of Eastern Durham. Allowing for the fact that the artificial deposit is composed of relatively few lithologies it is remarkable that such a close correspondence exists. In terms of mechanical analysis, stone counts, and clay mineralogy the artificial deposit is virtually indistinguishable from the stony clays of Eastern Durham.

The main implication of this is that a glacial till must be merely a random mixture of dominantly local bedrock material over which the ice has passed. The effect of the sub-glacial environment on this material appears to be relatively unimportant. This makes it extremely difficult to understand how different till sheets can possess differing textural ratios, unless they have been formed from parent material of considerable differing lithology.

X RAY DIFFRACTION CURVES OF ARTIFICIAL DEPOSIT

PEAK VALUES IN ANGSTROM UNITS



Chapter 12.

THICKNESS OF GLACIAL DRIFT AND AMOUNTS OF GLACIAL EROSIONIntroduction

The quantitative measurement of glacial erosion within an area once glaciated is an extremely difficult task. It is obviously impossible to achieve this aim by direct observations and reliance must be placed on indirect sources. One of the ways of achieving this end is by the calculation of average drift thicknesses within an area, and from this an estimate can be made of likely erosion amounts. Such attempts have been quoted by Charlesworth J.K. 1957 (pp 222-224), mainly from Western Europe and North America. Very few estimates of drift thicknesses, and associated amounts of erosion have been attempted for the British Isles.

Charlesworth (p 224) notes four major sources of error in estimating average drift thicknesses and amounts of erosion. These are:-

1. The average drift thickness is difficult to assess because the upper and lower surfaces are irregular.
2. Material has been subsequently denuded especially from the older drifts.
3. Ice sheets have carried much detritus into the sea beyond the present coast lines.
4. It is impossible to estimate how much pre-glacially weathered soil material has been incorporated within the glacial drifts.

Bearing these difficulties in mind an attempt was made to estimate the average drift thickness of Eastern Durham, and at the same time, to provide an estimate of the average amount of erosion which appears to have taken place over County Durham as a whole.

Area

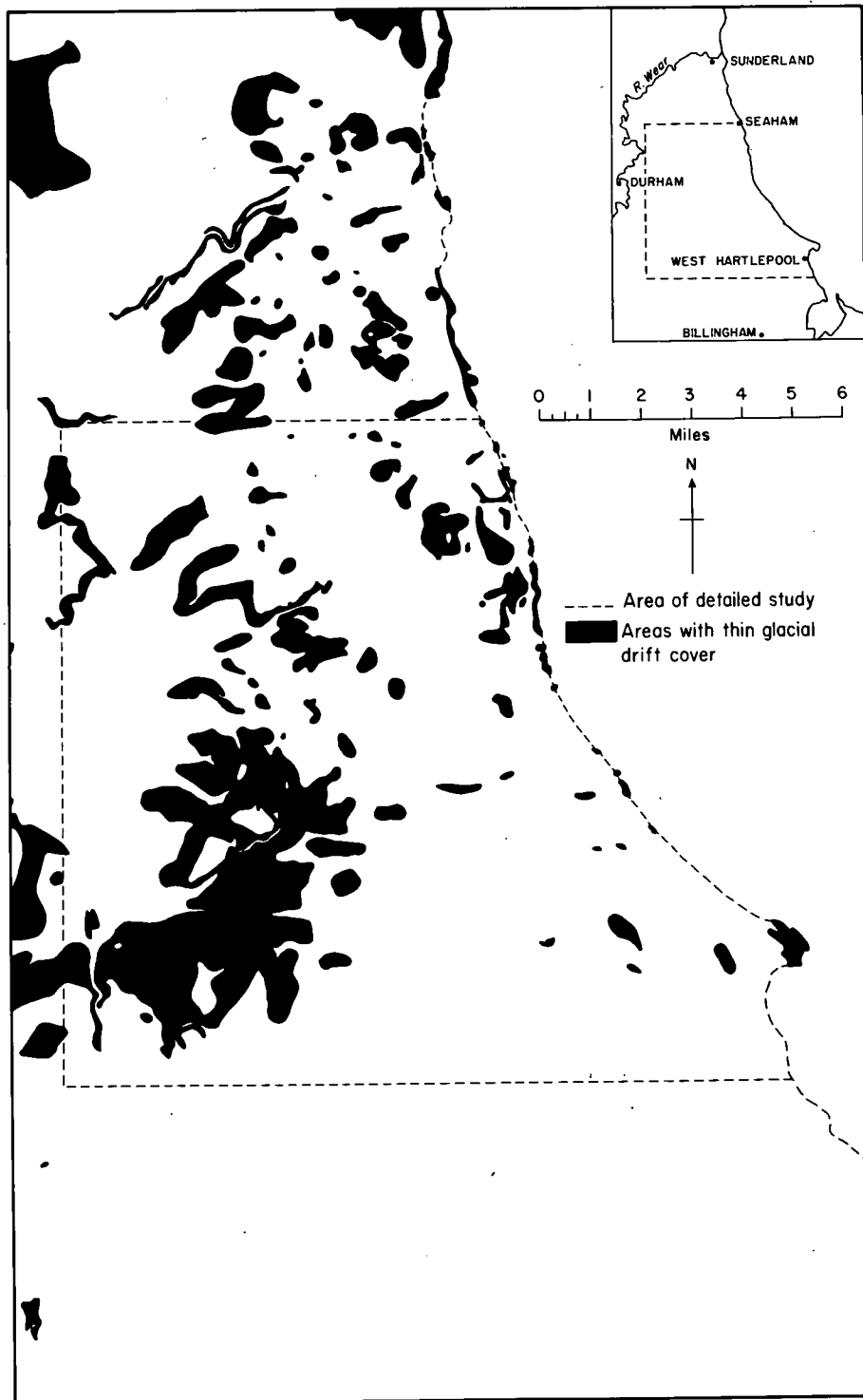
The geological maps covering the area of Eastern Durham indicate the places where glacial drift is thin. A copy of this information is shown in Fig.85. From this map a linear east to west sample area was chosen for detailed analysis. This area is about 100 square miles in extent and includes many borehole observations and quarry sections, stretching from the Wear Lowlands, across the Magnesian Limestone Plateau area to the coast. (Fig.85). The areas of very deep drift along the line of the buried valley of the R. Wear, were omitted from this study as it was considered that their inclusion might give an atypically high value for the area as a whole.

From figure 85 it can be seen that the detailed study area includes considerable proportions of land which the original Geological Survey had considered to be only thinly covered with drift, as well as areas where drift thicknesses are considerable.

Methods of analysis

The initial study attempted to estimate the thickness of drift at kilometre grid intersections, on the basis of nearby borehole and quarry information. This posed considerable difficulties as in many areas drift thicknesses were completely unknown. As a result estimates of drift thickness were made, at many points, and in all cases, underestimates were attempted. Where widely differing drift thicknesses occurred close to one another near a kilometre intersection, the lower figure was always used. This means that the final result when analysed would probably indicate a minimum average drift thickness for the area, rather than a true average figure.

A total of 373 observations were used in this method, and from these an average mean (minimum) depth for the area was calculated.



(Fig.86). The average mean thickness was 35.76 feet.

Fig.87 is an attempt to give an areal distribution of average drift depths in terms of kilometre squares. This map should be compared with the Geological Survey map showing thin drift areas (Fig.85) to see the basic similarity between the two.

As this method employed a grid and not a random sample, the data obtained in Fig.86 are not suitable for further detailed statistical analysis. The sample also suffers from the defect that it is an underestimate of actual thicknesses, but has the great advantage that it does allow a semi-quantitative drift thickness map for the area to be produced. (Fig.87).

It was therefore decided that a more objective method of assessing drift thicknesses was required based on actual borehole and quarry records. At the same time this information should be of a randomly distributed nature, so that it could be subjected to detailed statistical analysis.

With this aim in view the area of detailed study was divided into fourteen 25 square kilometre blocks and within each block 15 quarry or borehole sections were randomly chosen (Figs. 88 and 89). Altogether 210 points were plotted showing drift thicknesses. (Fig.89). These points showed a total variation in drift thickness of between 0 to 267 feet.

Mean thicknesses for each of the fourteen 25 square kilometre blocks were calculated and these varied from 30.73 to 119.80 feet. The mean value for drift thickness of the area as a whole was 62.69 feet.

The standard deviation of these data is obtained by the formula :

Fig. 86

Grid pattern sampling at kilometre square intersections.

	Cumulative drift thickness in feet (per row).	Number of observations (per row).
Row 1	186	14
2	248	14
3	215	14
4	212	14
5	389	15
6	280	15
7	313	15
8	475	15
9	332	15
10	680	16
11	562	17
12	709	18
13	587	18
14	635	19
15	799	20
16	818	21
17	634	23
18	719	22
19	1261	22
20	1600	23
21	1685	23
Total cumulative drift thickness in feet		= 13,339
Total number of observations		= 373
<u>Average drift thickness</u>		<u>35.76 feet</u>

Thicknesses in Feet

- 0-10
- 11-50
- 51-100
- 101-200
- > 201

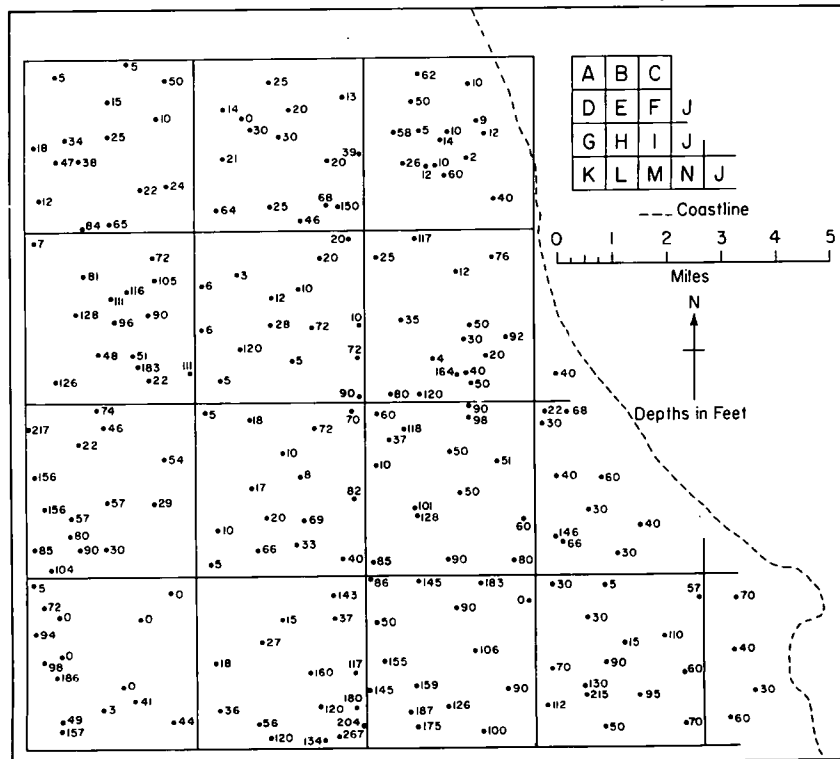
--- Coastline

0 1 2 3 4 5

Miles

N

Thickness of Glacial Drift in Borehole and Quarry Exposures



$$\begin{aligned}
 S &= \sqrt{\frac{\sum x^2}{n} - \bar{x}^2} \\
 &= \sqrt{\frac{1,403,224}{210} - 4110.09} \\
 &= \underline{\underline{50.71}}
 \end{aligned}$$

Using this figure of standard deviation one can see that about 2/3rds of the total observations of drift depth lie between 13.40 to 114.82 feet. These figures give an indication of the very great variability of drift thicknesses which occurs within the area.

In a study of this nature it is obviously important to estimate the amount by which the sample mean figure of drift thickness, is likely to differ from the true mean of the area as a whole. This is achieved by a calculation of the standard error of the mean.

$$S.E. = \frac{s}{\sqrt{n}} = 3.50$$

s = Standard deviation
n = Number of observations

The true mean of a sample is likely to fall within the range of the sample mean + or - 2 standard errors of the mean with a 95% probability.

Therefore the true mean of the area

= 64.11' (sample mean + or - (2 x 3.50) Standard error of the mean)

= 64.11 + or - 7.00

= 57.11 to 71.11 feet with a 95% probability

The author believes that the area chosen for detailed study can be used as a typical sample for the area of N.E. England below 750'. Above this height drift thicknesses are probably considerably less.

If one assumes that in County Durham above 750' no drift exists, certain interesting conclusions about drift thicknesses can be reached. The areas above 750' in County Durham make up one third of the total area. This area we have assumed has no drift cover while the area below 750' has an average thickness of c.60'. Using these figures one can calculate an average mean thickness of drift within the county of about 40'. This is if anything an underestimate as no account is taken of the drift which does exist, albeit thinly, above the 750' contour, nor of the drift filling buried valleys.

If this estimate is correct it suggests that a layer c.40' in thickness has been removed from the area of North-Eastern England during the Pleistocene glaciation. It can of course be argued that erosion and deposition within a unit area are not equal, and that some areas are dominantly erosive centres, and that others are depositional areas. This is undoubtedly true, but to claim that all the deposits of North England have been eroded from elsewhere, does not affect the volume of material which exists at the present time in County Durham. The work of the present thesis has shown that in any unit area within North-Eastern England the character of the material in the drift is of a locally derived nature.

The estimate of 40' for the average drift thickness for County Durham, and also probably for North-Eastern England as a whole is of great value as it does give an approximate quantitative assessment of the amount of erosion which occurred during the Pleistocene, and perhaps even solely in the last glaciation. At the same time it must be remembered that this figure is almost certainly an underestimate of

total erosion, as no consideration is given to the mass of Pleistocene glacial deposits lying beneath the North Sea.

In Eastern Durham further quantitative evidence of the amount of local glacial erosion is found in the area of the Magnesian Limestone Plateau. In Chapters 5 and 6 it was shown that the ice sheet depositing the Lower Till moved from west-north-west to east-south-east of Eastern Durham. This means that the ice sheet crossed the line of the Magnesian Limestone escarpment almost at right angles, and then continued eastwards over its outcrop.

In the Wear Lowlands the Lower Till contains no Magnesian Limestone within it. (Chapter 6). In the coastal sections however Magnesian Limestone makes up 50-60% of the coarse grade fraction and between 25 to 35% of the fine grade material (An average Magnesian Limestone content of the total till volume in the coastal area can be said to be about 40%). All of this Magnesian Limestone must have been incorporated by the ice sheet in crossing the 3 to 10 mile exposures of this rock type.

Throughout Eastern Durham both in cliff sections and in many borehole records the Lower Till is seen to maintain a remarkably constant thickness of between 20-30' (Smith D.B. - personal communication), except where post depositional weathering and erosion has occurred. It therefore seems reasonable to assume that at the time of its deposition the Lower Till in Eastern Durham was nearly everywhere about 25' in thickness. From these data it is possible to calculate the actual amount of Magnesian Limestone which has been eroded to account for the Magnesian Limestone material which is found today within the Lower Till sheet.

For example we know that the Lower Till contained no Magnesian Limestone when it reached the escarpment of the Magnesian Limestone, and yet had 40% average content when it reached the coastal area. If one assumes that the erosion and inclusion of the Magnesian Limestone by the till is a linear relationship, it is possible to calculate the average Magnesian Limestone content of the Lower Till of the Plateau area as being c. 20%. Fig.28 shows that fairly large quantities of Magnesian Limestone were rapidly incorporated within the Lower Till sheet when the ice first crossed the outcrop of the limestone. This would suggest that the average figure of 20%, is probably an underestimate of the actual average content.

With an average Magnesian Limestone content of about 20%, and an average Lower Till thickness of 25', this means that if all the Magnesian Limestone was recovered from the Lower Till in Eastern Durham it would make up a layer of about 5' in thickness throughout the area. From the available evidence it is therefore possible to prove that the Lower Till sheet alone eroded a layer of Magnesian Limestone of at least 5 feet in thickness in Eastern Durham.

When it is remembered that Magnesian Limestone is a constituent of many of the drifts to the south of County Durham, especially in Holderness, it is obvious that erosion of the Magnesian Limestone is probably much greater than is indicated here. In effect these data presented above indicate that a single unit movement of 10 miles of the Lower Till ice sheet across the Magnesian Limestone exposure resulted in the erosion of a layer of Magnesian Limestone of about 5 feet in thickness.

If the Drab Till of Holderness is the lateral equivalent of the Lower Till of Durham (Catt and Penny 1966), then this ice sheet must have moved at least 80 miles south of the Durham area. If each

10 miles of ice movement across the Magnesian Limestone Plateau area achieved comparable amounts of erosion, it seems reasonable to postulate that the Lower Till sheet alone would have eroded a layer of Magnesian Limestone of about 40 feet in thickness.

Conclusion

These figures of drift thickness and amounts of glacial erosion are put forward as the first detailed quantitative estimates which have been made for northern England. It is realised that at best they are only approximations, but it is considered that they are close enough to the truth to be of value in estimating of glacial erosion and deposition in the Quaternary era.

SECTION 3

Synthesis

Chapter 13.

THE NATURE AND ORIGIN OF GLACIAL STONY CLAYSIntroduction

In this chapter attention is concentrated on a description of some of the more important views which have been put forward to explain the origin of glacial deposits, and in particular glacial till. An attempt is then made to outline the criteria for recognition of the stony clays formed by differing modes of origin. Finally using data collected in Section Two, and from the observations of the author, the possible modes of origin for the different stony clays of Eastern Durham are reviewed.

Historical summary.

From the infancy of the glacial theory in the mid-nineteenth century following the work of Venetz, Charpentier, and Agassiz, glacial till has been regarded as the peculiar sub-glacial product of an ice sheet or glacier, accumulating beneath the ice and yet being fluid enough to be dragged along by it.

By the end of the nineteenth century a number of workers (Miller H. 1884, Upham W. 1891) had noted that the long axes of stones in glacial till tended to parallel the direction of ice movement. This was the first indication that glacial till was an ordered deposit and not merely as described by Geikie J.A. (1895) as a "confused and pell mell mixture of stones". This idea of a till has died slowly however, and as late as 1956 Charlesworth J.K. stated that "Since ice is unable to sort its material and deposits mainly by liquifaction unrelated to the size of the ingredients, till forms a pell mell agglomeration, unstratified and structureless and with boulders of various sizes, form and composition set at random". (p.378).

By the time of the Second World War following the work of Richter K. (1932, 1933, 1936) and Krumbein W.C. (1933, 1939) it was becoming generally accepted in geological circles that glacial till possessed an organisation, at least of its stone content. Up to this time however very little work had been done on the mechanisms by which till was deposited, and it seems to have been tacitly assumed that till mysteriously evolved beneath moving ice.

In 1941 Holmes C.D. as the result of detailed studies in New York State put forward ideas on the origin of till to explain the stone fabric patterns he had observed. He concluded that ground moraine till had accumulated by a "plastering on" process beneath a moving glacier, and that fabric patterns from successive till layers recorded the shifts in direction of glacial flow.

The main implication of Holmes' work was that the orientations observed in a till were those taken on by stones at the moment they were embedded in the stationary till below. What Holmes failed to consider however was the mode of deposition of the finer particle sized material, which in some till samples can make up to 70% of the total volume.

The actual mechanism by which stones in glacial till become orientated was discussed by Glen J.W., West R.G., and Donner J.J. (1957). They considered that stones in ice flowing by shear were rotated as they were carried forward, and that the rate of rotation was least when the long axis of the stone was most nearly parallel to the direction of flow. They therefore concluded that objects randomly placed in a flowing liquid would soon develop a parallel orientation of the long axis, although with a greater length of time a transverse orientation might develop.

Glen, West and Donner thought that the dominant process of till deposition was by "plastering on" of lodgement till similar to the process described by Holmes.

Although considerable work has been carried out on the larger particles within till deposits, very little attention has been concentrated on the nature and organisation of the matrix-sized material. A number of works do however stand out. Sittler R.F. and Chapman C.A. (1955) working on the micro-fabrics of tills discovered that a preferred orientation was to be found even amongst the silt sized particles, which seemed to be related to the shape of the larger particles and which was considered to be due to the shearing action within the ice. Their work proved beyond doubt that the finer grain sized material of a till possesses an organisation similar to that of the larger sized material.

Detailed studies by Shepps V.C. (1953) showed that in parts of North America each separate glaciation produced a till sheet with a characteristic grain size distribution, and that there was a decrease in average particle size with successively younger till sheets. Shepps stated that on the whole the coarse fractions of a glacial till appeared of local derivation, while the clay and silt sized material seemed to have been incorporated at considerable distances upstream, and ground down to a small grain size during its transport within the ice. If such an idea is correct it would obviously allow considerable time for the mixture of material, and for a uniform textural composition to be produced. This idea was to a large extent confirmed by the work of Sittler R.F. (1963) who showed that homogeneity within till sheets existed also in terms of small rock fragments and heavy minerals.

All these works therefore tended to confirm the idea that till is not a chaotic deposit, but on the contrary shows considerable evidence of organisation.

The greatest stimulus to the study of till origin and deposition was provided by the work of Carruthers R.G. in a series of papers in 1939, 1948 and 1953. Carruthers was the first person to consider in detail the actual modes of origin of the various deposits found in typical glacial sequences. As a result of these studies Carruthers put forward the "Undermelt hypothesis" in which he suggested that all the drift deposits, both stratified and unstratified were formed by the undermelt of a single stagnant ice sheet.

Carruthers main thesis was that superimposed till layers did not always signify multiple glaciation, and he suggested that in most glacial exposures a "normal" sequence of deposits consisted of, from the base upwards of till, laminated clays, silts, and sands, and gravels.

Perhaps Carruthers' most revolutionary idea concerned the mode of origin of the laminated clay deposits, which are such a common feature of the drift sequences of northern England. By orthodox interpretation these clays have always been regarded as the products of lacustrine deposition. Carruthers however regarded these deposits as englacial shear clays of tectonic origin produced by the shearing and distortion of englacial dirt or till, and finally deposited by pressed melting, with the ice melting away from between the clay bands. The sand layers which are often found associated with the upper parts of these clays layers he considered to be of secondary or water-lain origin replacing ice bands which formerly existed within the glacier.

Equally controversial however was his interpretation of the "upper tills" of glacial sequences. These deposits he claimed possessed basal contacts which were often sharp, and showed no disturbance, or incorporation of the material on which they rested. Indeed in some cases he described whisps and fragments of this "upper till" interbedded

with the sands on which the "upper till" lay. Carruthers considered these deposits must represent till, but thought of them as glacial overriders sheared up from the base of the glacier.

Although Carruthers' work became the subject of tremendous criticism by the majority of the English Pleistocene workers, who still championed a multi-glacial hypothesis, it does deserve credit for being the first comprehensive study of the nature of decay of a large ice sheet, and for the great stimulus that it provided.

One of Carruthers' critics, Hollingworth S.E. (1942) suggested that the main question at issue was whether the till is the true ground moraine formed by the sub-glacial deposition of englacial material of ice in movement, or whether it is englacial to the time of final melting of the ice sheet. Drumlins he suggested indicated moulding at or near the maximum development of an ice sheet, and this he concluded involved the building up of till material by some process of "plastering on", similar to that envisaged by Holmes.

Other workers however, such as Torrell O. (1877) have distinguished in glacial successions a tough compact lower till, of sub-glacial origin, overlain along a distinct plane often marked by stratified sands, by a separate upper clay. In this case the upper clay is regarded as superficial debris deposited by the melting of the ice.

One of the most comprehensive studies of till material and its origin was made by Harrison P.W. (1957) in which he reviewed the evidence for four main hypotheses dealing with the genesis of till.

The first theory he considered was that of Holmes which stated that till was the result of deposition of stones from a rotational environment within the ice, by the gradual accumulation of material beneath a moving glacier. Harrison questioned the sharp contact claimed to exist by Holmes between the moving ice and the till floor, and stated that this was not supported by micro-fabric analysis which showed evidence of the orientation of silt sized particles as well.

The fact that there was no disturbance of the matrix around the larger particles strongly suggested that the stones were not thrust into the matrix as Holmes envisaged, but rather that the two were part of a single system. As a result Harrison concluded that the evidence for a rotational orientation of particles within the till was not to be found, and therefore that the idea of "plastering on" of a till sheet could not be an adequate explanation of till genesis.

The second hypothesis considered by Harrison was that till fabric was the result of shearing of deposited till by the movement of overriding glacier ice. This theory required that till was melted out of the ice and deposited, and then sheared by subsequent overriding ice. Such a theory had been advocated by Sitler R.F. and Chapman C.A. (1955) to account for the veining and microfoliation of till which they observed in micro-fabric analyses. The main objection to this theory was that a shearing force which would be sufficient to orientate the particles would show itself in sediments other than till. Harrison regarded this theory as non-proven owing to the lack of sufficient evidence.

The third hypothesis was that till fabric was the result of till deposition by successive mudflows from the edge of a melting glacier. Harrison suggested that this was unlikely as Okko V. (1955) had shown that such mud flow deposition would be discernible by signs of crude sorting and the presence of air bubbles.

The final theory considered by Harrison was that till fabric was inherited from fabric developed in a transportational environment, and that ground moraine was deposited from a stagnant glacier by the slow melting of interstitial ice as was first postulated by Goodchild J.G. (1875). Harrison suggested that there existed within a glacier a series of thrust planes from the glacier base towards the

surface along which particles were orientated, and quoted Carey S.W. (1954) for the essentially fluid behaviour of crystalline glacier ice when dealing with phenomena of longer duration than a few weeks. Harrison suggested that these relict slip planes of the glacier tectonite, together with the original fabric were preserved within the till on the melting of the interstitial ice. Such an idea Harrison considered to represent the most satisfactory origin of till.

Some of the most controversial and stimulating ideas on glacial deposition were presented by Carey S.W. and Ahmad N. (1961) in a paper on glacial marine sedimentation. In this paper they stressed that greatly differing sedimentary types could be produced dependent on the physical conditions at the base of the glacier, and the environmental zones in which deposition occurred. They recognised two basic types of glacier, a wet base and a dry base depending on whether meltwater was present in the basal layers, and three main environmental zones in a transect from land to sea. The inner zone was a terrestrial zone where the base of the glacier was everywhere above sea level. Beyond this a grounded shelf zone occurred where although the glacier base went below sea level it was not floating, and finally and closely related to the grounded zone was a floating shelf where the glacier became buoyant.

Different types of sedimentation were thought to occur beneath wet and dry base ice sheets, and between the different environmental zones. In a wet base glacier bottom melting was considered to be the most important depositional process. In the terrestrial zone of a wet base glacier, a true sub-glacial till retaining the characteristic flow fabric of the glacier would be deposited by the complete melting of the basal layers. As the till would be deposited under the full load of the glacier it would be formed as a consolidated deposit. In the grounded shelf zone unstratified till

would still be formed, but the intermittent lifting of the shelf bottom during a retreat phase would cause interstratification of beds deposited beneath the floating shelf zone. Unlike terrestrial tills, the tills and meltwater sediments deposited below sea level would suffer only partial load compression, and would only be consolidated to lower void ratios during maximum glaciation when the ice sheets would be emerging to a lower sea level. Whether the ice was stationary, advancing or retreating the till deposits would be built up to the base of the ice or cut down to this level. Once this kind of stability had been reached, a submarine foreset slope would form and advance. Slumping of material would take place down this slope forming deposits almost indistinguishable from till. These deposits would occur as thick or thin beds within stratified marine glacial drift, but with increasing transport would tend to show more sorting and stratification. Finally in the floating shelf zone proper, stratification of the deposits would be well developed by meltwater, although erratics might be dropped from melting shelf ice into the bedded sands, silts and clays.

Sediments associated with a dry base glacier would be entirely different. In both the terrestrial and grounded shelf zone owing to the very low temperatures of the basal ice, deposition would be negligible, and it would be in the floating shelf zone where maximum deposition would occur. Here the main sediment source would be the melting of the ice shelf above which contains all the basal debris of the glacier. The deposit formed under such conditions would be a stony clay, with stratification very much poorer than in the case of a wet base glacier. The fabric of these stony clays would be unlikely to bear any relation to the direction of ice movement as these stones would have dropped through water.

From this summary a number of important conclusions can be drawn. The first is that till is an "organised" deposit which shows evidence of evolution. Secondly it seems obvious that different modes of origin can give rise to similar deposits. Thirdly a complex sequence of deposits can be formed at a given location by the stagnation and melting of a single ice sheet. Finally fourthly, different environmental zones in a single ice sheet can give rise to a varied suite of deposits.

The problem of glacial till.

In the discussion of glacial tills and related deposits in the past considerable confusion has arisen because many people appear unwilling to accept the fact that the nature and origin of glacial stony clays are so interrelated that they cannot be considered separately. As a result too little consideration has generally been given to the possible modes of origin capable of explaining a deposit. All too often a stony clay, merely because it is a stony clay is classified as a till, and a gravel deposit as sub-aerial outwash. When this type of reasoning is employed, other implications must automatically and logically follow. For example if each stony clay is regarded as a till, a multiple sequence of such deposits must be taken as evidence for multiple glaciation. Similarly a gravel deposit between two stony clays would generally be regarded as indicative of a period of deglaciation if not of actual interglacial conditions.

The present author believes that such views are too restrictive, for if one applies such a strict formula of interpretation, although one might be able to put forward a plausible story of glaciation with various ice advances and ice retreats, one rarely can gain any further understanding of the ways in which tills and stony clays are deposited.

Undoubtably one of the problems has been the attempt to explain Pleistocene glacial deposits in terms of results obtained from work on modern valley glaciers and small ice sheets. Such work is in its own right of very great value, but dangers exist in the attempts that some workers have made to correlate the conditions associated with valley glaciers and small ice sheets with those areas glaciated during the Pleistocene. In the Pleistocene one was dealing in terms of the expansion and contraction of huge ice sheets over many hundreds, and in some cases even thousands of miles. It is therefore not suprising that the deposits left by such enormous ice sheets appear to be so different from the present day ice masses which are experiencing drought conditions. For example in many parts of the British Isles till sheets are traceable for considerable distances showing uniform thicknesses, and apparent visual similarities. To the authors knowledge comparable widespread deposits have not been described associated with present day glaciers and ice sheets. (See also Charlesworth J.K. 1957 p.381). This suggests the possibility that Pleistocene environments and even modes of deposition may have differed markedly from those observable at the present day.

Possible modes of origin of stony clays.

As a result of the observations outlined in Section Two of this thesis one has to postulate a mode of origin for glacial till which is capable of producing a characteristic fabric pattern, and also a relatively uniform lithological and textural composition. Details of actual physical stresses and systems of deposition are beyond the knowledge of the present author. However from empirical evidence it does seem necessary to envisage for the formation of glacial till the existence in the basal layers of an ice sheet of a "plastic" medium subject to considerable shearing or flow movement which allows the

continuous mixing of the till layer and at the same time allows a fabric pattern to develop within it.

Contributory evidence for this idea can be obtained from the material within the till sheets. In Eastern Durham much of the gravel and cobble sized material shows considerable evidence of abrasion in terms of striations, polish and rounding. These facts suggest the existence of considerable pressures within the till layers, and the collision and mutual abrasion of the larger particles. The fact that the farthest travelled rocks are generally the most rounded has already been noted. A process seems to operate whereby the softer rocks are eliminated and the more resistant rocks rounded to varying degrees. Yet at the same time large pieces of extremely fragile material, for example Carboniferous coal and shale can be transported within a till sheet for distances of up to at least 15 miles, and yet show little evidence of abrasion or wear. One therefore has to postulate an environment in which considerable abrasion can occur locally but need not occur all the time. Again this would seem to point to a plastic or semi-fluid environment in which material would be relatively free from abrasion, provided that by chance it avoided contact with other larger solid particles.

In the next section an attempt is made to outline the possible environments capable of forming the stony clays observed within Eastern Durham, and at the same time to evaluate the properties of a given environment.

A. Sub-glacial origin.

(1). True sub-glacial tills would be formed in the terrestrial or grounded shelf zone of a dry base ice sheet, or in the terrestrial zone of a wet base ice sheet. Deposition would be from moving ice in the case of the wet base glacier, and after stagnation in the case of the dry base one.

The main criteria for the recognition of such a deposit would be as follows:-

- a. The deposit would have lateral continuity over long distances. The thickness of the deposit would be variable, but possibly show some relation to the relief features over which the ice had moved. The deposit would probably occur as the basal deposit in a sequence resting directly on rockhead.
- b. The deposit would possess evidence of contact with the bedrock, over which it was moving either by disturbance of the bedrock, or by the progressive inclusion of such material within the deposit. Interbedding with other deposits would be rare.
- c. The deposit would possess a fabric in which the preferred orientation of the stones and fine material would be parallel to the direction of ice movement. This direction of preferred orientation would be consistent over large areas in level terrain.
- d. The deposit would have a textural uniformity over long distances in areas of level terrain, and uniform parent material. In areas of broken relief, local erosion would be likely to effect the uniformity of the deposit but evolutionary changes in the deposit should still be discernable.

e. The deposit would contain material of all grain sizes from clay sized material to boulders many feet in diameter. The larger particles may show striations. Erratic rocks would be present.

f. The deposit may show evidence of compaction due to the weight of the overlying ice. This would not always be the case in a wet base glacier, where the ice overburden pressure may be relieved by hydrostatic pressure in the sub-glacial meltwater.

(2). In the grounded shelf zone of a wet base glacier, sub-glacially deposited till may show certain differences from the criteria described above.

The main differences would be likely to be:-

a. The deposit would show very little evidence of compaction due to basal meltwater pressure.

b. The deposit would show less evidence of disturbance of bedrock material, and of inclusion of it.

c. The deposit may show evidence of water movement along the till rock contact.

(3). Different types of stony clay would be formed in the floating shelf zone of an ice sheet, depending on whether it was wet or dry based.

In the case of a dry base glacier once the ice was buoyant, the frozen basal debris would only be able to be deposited by the melting of the ice above. The debris would therefore fall through water to be deposited on the sea bed.

The main criteria for the recognition of such a deposit would be:-

- a. The deposit would be unlikely to be associated with other deposits. It may overlie marine sorted material. Occassional evidence of water sorting may be seen.
- b. The deposit may be laterally continuous over long distances. Some evidence of an altitudinal control over deposition may be apparent.
- c. The deposit would show no signs of preferred orientation of the stones owing to the fact that the stones had fallen through water.
- d. The deposit would lack compaction.
- e. The deposit would possess a similar textural composition to that of a terrestrially deposited till, and exhibit uniformity over large distances.

(4). Beneath the floating shelf of a wet base glacier deposition would be considerably different, and would show complex inter-relationships with water sorted sands, silts, and clays.

The main criteria for recognition would be:-

- a. The deposit would show complex relationships with water sorted deposits.
- b. The deposit may be continuous over large areas. Evidence of altitudinal control over deposition may be seen, with the stony clays and other deposits being built up to the base of the floating ice shelf.

- c. The deposit would be unlikely to possess a preferred orientation of the included stones, except where it had been subjected to slumping.
- d. The deposit would lack compaction.
- e. The deposit may show evidence of water sorting locally, but otherwise would show textural heterogeneity.
- f. The deposit would be compositionally similar to the terrestrially deposited till.

B. Sub-aerial origin.

(1). In this category the most important group would be a flowage or mass movement type of deposit formed during the phase of deglaciation.

Movement of material by such means is likely to have occurred from:-

- 1. Superficial debris on the surface of the ice, or within the ice.
- 2. From ploughed up morainic debris.
- 3. From already deposited till - e.g. stagnant ice.
- 4. In lakes in outwash areas.

The criteria for the recognition of such a deposit would be as follows:-

- a. The deposit may possess a wide distribution, especially if formed from a retreating ice front. In other conditions it would more likely be of only local occurrence.
- b. The deposit may be found overlying any other type of deposit. It would be unlikely to be the basal deposit within an area, as in most cases it must have been formed from already existing

superficial deposits.

- c. The deposit may show disturbance of the material over which it moved, and also inclusion of such deposits. The basal contact may however be gradational.
- d. The deposit would have a composition similar to that of the material from which it was formed, although an increase in sorting downflow may be noted. Sorted material may be found in layers within the deposit. The deposit may be less stony than the original deposit from which it was derived.
- e. The deposit would be likely to possess a preferred orientation of the included stones parallel to the direction of movement. A general regional pattern may be seen, but a more local one would be more commonly expected.
- f. The deposit would perhaps show evidence of an altitudinal control on deposition, with movement occurring in a down slope direction. Extensive mass movement associated with periglacial conditions might give rise to a general sub-level surface.
- g. The deposit may show an increase in thickness towards the source, but may also show a thickening in the opposite direction.
- h. The deposit would lack compaction.

(2). The other sub-aerial possibility for the origin of the stony clays would be as a complex deposit formed by the mixing of other deposits under periglacial frost conditions.

The main criteria for the recognition of such a deposit would be as follows:-

- a. The deposit may be of widespread extent. It would be a surface deposit (unless subsequently buried). It would overlies other unconsolidated deposits, and would be generally only thin.
- b. The deposit would possess no preferred orientation of the included stones, except locally where slumping or flowage had

taken place.

c. The deposit would be likely to show considerable lateral diversity, and changes in grain size composition, owing to its derivation from deposits with differing textural characteristics.

d. The deposit would be unlikely to show evidence of any height control, although thickening of the deposit may occur in topographical hollows.

From the above descriptions it appears likely that the main characteristics of stony clays formed by differing modes of origin could be remarkably similar, and identification of the origin of any type of clay in the field would be likely to be possible only under favourable circumstances.

Using the above criteria, together with evidence gathered in Section Two an attempt is made to elucidate the probable modes of origin of the main Eastern Durham stony clays.

These are :-

1. the Scandinavian Drift
2. the Lower Till
3. the Upper Till
4. the Upper Wear Clay
5. the Upper Tees Clay

The Scandinavian Drift.

The Scandinavian Drift has the most limited distribution of all the Eastern Durham Clays, and is confined to a hollow in the Magnesian Limestone at Warren House Gill. Most of the deposit is

now buried beneath the pit heap of Horden Colliery, and all that exists at the present day is a very poor exposure about 3 feet high, along the northern bank of Warren House Gill.

The characteristics of this clay are very difficult to assess, and no stone orientation could be made. The material which is at present exposed consists of a greyish clay, containing many shell fragments, but with only very few and generally small stones. Of particular interest is the fact that the Scandinavian Drift contains very little material which has been derived from the floor of the North Sea, or from the Durham coastal area. In a stone count of 500 erratics Trechmann noted that more than 80% of the stones were igneous or metamorphic rocks from the Christiana district of Southern Norway, while only 6% occurred in the form of chalk and flint, and red and green Triassic material which could have been derived from the floor of the North Sea. When these figures are compared with the authors stone counts of the Lower Till of Eastern Durham one point becomes startlingly obvious. Whereas the Lower Till of the Durham coast contains very little material derived from long distances (i.e. from its source area in the Lake District and the Southern Uplands) and is dominantly composed of much more local material, the Scandinavian Drift shows an entirely different pattern with nearly all of its rock content derived from close to its source area.

The fact that the Scandinavian Drift includes material which has travelled at least 400 miles from its source proves beyond any doubt that this deposit must be associated with an ice sheet. The problem is to decide whether this clay is the sub-glacial till of a completely terrestrial ice sheet which has advanced across the floor of the North Sea, or whether the deposit was produced by the melting of frozen debris in the sole of a cold base ice shelf which had floated across the North Sea and grounded along the Durham coast.

The peculiar nature of the erratic content of the clay had been noted by Trechmann at the time of his initial description of the Scandinavian Drift, and for a time it is true that he had considered the possibility that the Scandinavian Drift at Warren House Gill was the product of the melting of an ice-berg which had floated across the North Sea. His reasoning was that "the occurrence of so many well glaciated fragments of crystalline rocks rather sparsely distributed in a shelly clay might seem to support the view that they (the rock particles) were sprinkled by ice-bergs onto the sea bed".

His main reason for dismissing this idea of ice-berg dumping was the areal distribution of erratics on the English east coast. Trechmann pointed out that in Durham only Norweigan erratics were found, while in Holderness Swedish and Baltic erratics were also present. He claimed that such an ordered distribution could not be explained by icebergs randomly floating across the North Sea, and therefore concluded that the Scandinavian ice sheet must be a terrestrial based glacier.

What Trechmann did not consider was the possibility that the Scandinavian ice formed a floating shelf zone. For by this method the major anomalies in terms of erratic distribution and erratic composition can be satisfactorily explained. The purity of the Scandinavian material in the clay would be explained by the fact that this ice sheet did not come into contact with any bedrock material until it grounded close to the Eastern Durham coast. It is interesting to note that other basal glacial deposits of the East coast succession of England have been considered at some time to have been deposited by marine sedimentation from floating ice sheets (Penny L.F. 1959 - Sub-Basement and Basement Clay of Holderness; Solomon J.D. 1932 - Cromer Till of East Anglia).

The present author is therefore of the opinion that the Scandinavian Drift may have been deposited from the basal debris of an ice sheet which had floated across the North Sea and grounded on the Durham coastal area. During this grounding stage the incorporation of the arctic marine fauna into the clay was probably accomplished, together with a rich micro-fauna noted by Catt J.A. 1963.

The fact that the Scandinavian ice sheet could have become buoyant seems a reasonable assumption to make as off southern Norway at the present day the sea is more than 600 feet in depth, and in the early Pleistocene before glacial deposition took place was possibly considerably deeper. (Unconfirmed reports of natural gas borings in the North Sea would suggest thicknesses of Pleistocene deposits of many hundreds of feet).

If a floating ice shelf origin is accepted for the origin of the Scandinavian Drift, it helps explain how Scandinavian ice could reach the coast of the British Isles before local ice from western Britain arrived. One would no longer have to postulate that the Scandinavian ice sheet expanded more rapidly than the British ice caps, (although this probably did occur), for once the ice sheet became buoyant its thickness would be greatly reduced, and its speed of advance as an ice shelf would be increased by a factor of 5 to 10 times compared with its terrestrially based speed. (Carey and Ahmed 1961). If this were the case it would appear likely that the floating ice shelf would cover the 400 miles from Norway to the Durham coast in a shorter time than would be required for a land based ice sheet to cover the 100 miles from the Southern Uplands to the Durham coast. At the present day the sea depth of 200 feet is reached about 12 miles east of the present Durham coast.

At the height of glaciation the sea level in the North Sea would have been expected to fall, and as a result the floating ice shelf would have become grounded at progressively greater distances from the Durham coast. This would mean that the invasion of Scandinavian ice onto the Durham coast as a floating ice shelf could only have occurred during the very early stages of a glacial phase. The fact that the Scandinavian Drift contains no westerly derived material proves that Scandinavian ice was the first ice to reach the Durham coastal area.

The Lower Till

The Lower Till is the most widespread deposit of all the Eastern Durham stony clays. It rests nearly everywhere directly on rockhead, and is virtually continuous throughout the whole area. It maintains an average thickness of between 20 to 30 feet, although locally from borehole records it appears to reach thicknesses of more than 100 feet. It is a highly compacted deposit, and nearly everywhere lacks any evidence of stratification.

Striated pebbles of Carboniferous Limestone are found within the deposit, together with erratic rocks from the Lake District and Southern Uplands. Some of these rocks are of very great size (more than 8 feet in length).

A marked preferred orientation of the long axes of the stones is seen in the Lower Till, and these orientation directions are consistent over large areas.

The basal contacts of the deposit in the area of the Magnesian Limestone Escarpment show disturbance of the underlying bed rock material, and in crossing the Magnesian Limestone Plateau the Lower Till can be shown to have progressively incorporated more of this

parent material. (Fig.28). The disturbance of the bed rock is well seen at Crime Rigg Quarry, near Sherburn Hill, where the beds of the Lower Magnesian Limestone have been buckled and dragged forward by ice movement. At many other places on the plateau the basal contact of the till shows clear signs of disturbance of the parent material. An examination of numerous quarry sections shows that the upper 1 to 3 feet of the Magnesian Limestone has been crushed and broken into small fragments, or even to a powder like deposit. The most probable agencies accounting for this are frost action before the advance of the ice, and the pressure of the overlying ice during maximum glaciation.

At a number of exposures the Lower Till shows evidence of considerable local incorporation of the Magnesian Limestone debris into its basal 6 inches to 2 feet. In such places the carbonate content of the Till rises to more than 60% in this zone. It is interesting to note that at these locations there appears to be a sharp transition at the top of this highly calcareous basal layer into the more uniform upper portion of the till. It seems highly possible therefore that this basal layer represents the zone of greatest shearing between the ice sheet and the solid rock, and that it is from this erosive layer that material is derived to form the bulk of the matrix of the till above. Such shearing suggested by Nye J.F. (1959) might well explain the uniform nature of the till above this layer.

In some areas of the coastal region the Lower Till shows an entirely different type of basal contact. At Salterfen Rocks the Lower Till lies on a Magnesian Limestone rubble very similar to that of the plateau area. Further south however the Lower Till can be seen to overlies the Magnesian Limestone along an extremely sharp contact zone, with the transition from uniform till to Magnesian Limestone parent material taking place over a vertical distance of less than 2 inches.

In some places also the bottom 6 inches of the till shows a marked fissility, and in a few places the lower 5 feet of the till exhibits rudimentary bedding. Analysis of such exposures (e.g. Green Steps, Crimdon) reveals that whereas the matrix of the till in the upper and more uniform portion possesses calcium carbonate figures between 25 to 35%, the lower 3 feet often show carbonate figures dropping to less than 15%. This means that the lowest calcium carbonate content within the till is found directly over the Magnesian Limestone itself. This of course contrasts markedly with the plateau area. The most reasonable explanation for these low basal carbonate figures would appear to be that considerable amounts of water must have been associated with the deposition of the till in these cases.

In the cliffs north of Castle Eden Dene the basal contact of the Lower Till with that of the powdered Magnesian Limestone takes place in a transition zone less than $\frac{1}{4}$ inch in thickness. At this site also whisps of till are seen interbedded with the powdered limestone.

These facts seem to point to the possibility of differing environments of deposition in parts of the coastal area from those inland, although the nature of these differences is uncertain. It is certainly true that in the coastal area one obtains the impression that this was essentially a depositional zone of the Lower Till, whereas on the higher ground inland erosion appears to have been dominant. Further research may well prove that erosion and deposition represent differences in the type of ice sheet, with a dry base glacier being dominantly erosive, and a wet base glacier, due to the fact that the shearing action of its forward motion would be absorbed by the till material itself, essentially protective.

The Lower Till therefore seems beyond doubt to be the sub-glacial till of a terrestrially based ice sheet. The nature of its basal contacts however suggests the possibility that different conditions at the base of the ice sheet may have prevailed in different areas.

The Upper Till

The Upper Till is well exposed in the extreme eastern part of the county below 400 feet. The clay possesses a relatively standard textural composition, and very uniform carbonate contents. Erratic blocks are present in the deposit, including material of Cheviot origin, but the stones are nearly everywhere smaller and fewer than those of the Lower Till. The deposit lacks the degree of compaction of the Lower Till, and at a number of exposures evidence of stratification within the clay is clearly seen. The majority of the stones within the till show a marked preferred orientation, and these directions are consistent over a large area.

Unfortunately the basal contact of the Upper Till is not exposed throughout much of the area. However when it is visible the Upper Till rarely shows any sign of disturbance of the underlying material. In some exposures the Upper Till is seen resting on the ripple marked surface of sands, while at other exposures it appears to grade down into gravels apparently formed by the washing of the Upper Till. Carruthers maintained that this type of junction is due to the fact that the deposit beneath an "upper till" was secondary in origin formed by the melting of clean layers of ice and the building up of the secondary deposit to the frozen roof of the glacier in which the primary "upper till" was entombed. Undermelt passing through the overlying ice then allowed the "upper till" to be deposited without disturbance on the sands.

Carruthers suggested that the positioning of the "upper till" high up on a single but composite ice sheet, was due to the presence of an overriding glacier from one of the other large ice centres of eastern England. The multiple succession of tills along the coast of Eastern England he concluded was due to a series of these overriding glaciers with sources along the valleys of the Tweed, the Tyne, the Tees and the Humber. These ice sheets he claimed would all override each other, and on melting give rise to the composite sequence of deposits observed in these areas. (Carruthers R.G. 1953).

As views very similar to those outlined by Carruthers have been accepted by Catt J.A. and Penny L.F. (1966) to explain the glacial sequence in Holderness, it is perhaps now time to consider the value of their application within the Durham area.

From the descriptions of Carruthers it appears that he envisaged a series of ice sheets shearing over one another along almost horizontal shear planes, to form a composite ice sheet. This means that a sandwich like ice sheet composed of bottom dirt, clean ice, bottom dirt of the next ice sheet, clean ice etc. was formed. No quantitative data was advanced by Carruthers but it seems reasonable to suppose that the clean ice portions of such successions must have been many hundreds of feet in thickness. For deposition to occur such a succession would have to be let down through great vertical distances without any disturbance taking place within the till. This seems extremely difficult to envisage, and to the author it would appear unlikely that bottom melting could work upwards through hundreds of feet of clean ice to produce an "upper till" deposit uniformly across the ground surface. Actual evidence in support or contradiction of this point does not however appear to exist.

The question also arises of whether one ice sheet can shear across a lower one for any great distance. Nye J.F. (1959) suggested that the greatest absolute motion of an ice sheet is confined very markedly to the basal layers, and that absolute motion in the upper part of an ice sheet is minimal. This view disagrees with Catt J.A. and Penny L.F. (1966) who quote examples of small valley glaciers shearing over other ice masses for limited distances (Sharp R.P. 1948). Nye's work however suggests that if an overriding ice sheet is thrust over a lower lying one, it would soon cease to have any motion of its own, and would move only in the direction of the lower ice. The two ice sheets would therefore have united to form a single one.

Bearing this in mind, if a composite glacial sequence had been deposited by the melting of a single ice sheet, one would have expected that once the overriding ice sheet had become part of the underlying ice sheet, its till fabric would have been fossilised in the direction of the last movement of the overriding glacier relative to the lower ice. This direction would not necessarily therefore bear any resemblance to the direction of movement of the underlying actively evolving basal dirt. Indeed because of changes in movement of the lower ice, and changes in stress fields, it would seem unlikely that a bed of till in the upper part of the ice could be preserved as a single, continuous unit. More likely it would be broken into a series of separate units with perhaps re-orientation of these units taking place relative to one another. Undermelt of such an ice sheet might therefore be expected to give rise to a series of isolated "upper till" fragments, possessing non-uniform orientation, and lying on top of a continuous sheet of lower till. (The relationship of the Purple and Drab Tills of Holderness may be of this type).

In Eastern Durham the Upper Till has been traced by Smith D.B. as a continuous deposit over many square miles, and throughout this area it has been shown by the present author that it maintains an orientation pattern consistent with an ice sheet moving southwards down the east coast area, and impinging into the Tees Lowlands. In many cases the orientation patterns of the Upper Till are almost at right angles to those of the Lower Till in the same area. To explain the relative distribution of these two deposits in the Carruther's manner one would have to envisage the Lower Till flowing west to east, with at the same time the Upper Till flowing north-east to south-west across its upper surface. Relative movement between the two ice sheets would have to be maintained at all times or else the easterly moving Lower Till would carry the overlying Upper Till out to sea.

Besides their positioning Carruthers regarded the nature and content of the rock material in the "upper tills" as further evidence for the fact that they were "overriders". He claimed that the number and size of erratics in the "upper tills" were smaller than in the lower tills, and also claimed that the percentage of far travelled rocks was greater. The present author would agree that the Upper Till of Eastern Durham does contain fewer and smaller erratics than the Lower Till, but would interpret this fact in a different way.

The "upper till" of Eastern England (the Upper Till of Eastern Durham, and the Hessle Till of Holderness) was regarded by Carruthers as the product of the Tweed glacier, which overrode Pennine ice, and then moved southwards along the coastal area. Once the Tweed ice had overridden the British ice it would no longer be in contact with bedrock material, and would therefore not incorporate any new material over which the basal layers of the ice might be travelling. Equally if it were frozen solid in the upper part of an ice sheet, the till could no longer evolve, and the size and number of particles would be fossilized at the same state as when the glacier sheared over the

lower ice. The "upper till" sheet would therefore be very characteristic of the area where it was originally formed. As the "upper till" was deposited by undermelt no material from the underlying till could be incorporated within it.

Eastern Durham is characterised by the widespread outcrop of Magnesian Limestone. North of the Tyne however this rock type is no longer found. If the hypothesis of Carruthers is correct the Upper Till of Eastern Durham would not have had the opportunity to assimilate any Magnesian Limestone into its matrix before its deposition. Yet in Eastern Durham the Upper Till contains up to 30% or more, Magnesian Limestone in its stone content. The only way in which such a clay derived from the Tweed area could have picked up Magnesian Limestone is by being able to erode Magnesian Limestone parent material, or more probably, till containing Magnesian Limestone. This latter point also possibly explains the other peculiarity of the Upper Till - the fact that it contains fewer and smaller erratics than that of the Lower Till, and also more far travelled ones. This could be because the ice sheet of the Upper Till was moving across glacial deposits of sands, silts, laminated clays and tills, and only very rarely over actual bedrock material. Glacial deposits would in effect be the parent material of the Upper Till once it had left its source area. As a result there would be the addition of very little large sized material to the Upper Till, and there would be a gradual reduction in number and a wearing down in size of the incorporated glacial pebbles. At the same time erratics as well as examples of the local country rock would be derived from the till over which the ice was moving. The result would be that the Upper Till would have its own erratic suite from its source area, together with an erratic content derived from the glacial deposits over which it was moving. Because of this the

influence of local bedrock material over which the ice was moving would be very much lower than on a lower till resting directly on rockhead. With time however and a long passage over uniform glacial deposits, an "upper till" would tend to take on the characteristics of the material over which it was moving. In Eastern Durham this is shown by the similarities in particle size distribution and clay mineralogy between the Upper and Lower Till sheets.

From the above evidence and from the nature and composition of the Upper Till of Eastern Durham, the author concludes that this deposit has originated as the sub-glacial till of an ice sheet derived from a northerly direction. However the presence of Magnesian Limestone proves that the Upper Till could not have been an "overridder" in the Eastern Durham area, in the Carruthers' sense, and must have been able to erode Magnesian Limestone directly, or glacial deposits containing Magnesian Limestone.

At the same time the nature of the basal contacts of the Upper Till, and the fact that it occasionally possesses a bedded nature with small inclusions of sand, suggests that the actual mode of deposition of the Upper Till differed greatly from that of the Lower Till. The exact nature of these differences is unknown but certain morphological points are probably important. The first is that the Upper Till in Eastern Durham was deposited at the western margin of a large ice sheet moving in a southerly direction. The second is that this ice sheet was moving in an uphill direction onto the coastal area.

The undisturbed nature of the basal contacts, the apparent gradation from gravel deposits up into the base of the Upper Till, and the fact that the Upper Till does in places appear to have been at least partially water sorted, suggests that considerable amounts of water existed in the marginal zone of the Upper Till ice sheet during deposition.

The actual mechanism of deposition is difficult to assess with any accuracy. It does seem certain however that the stratified sands and gravels below the Upper Till are essentially secondary in origin and formed from the erosion and sorting of the Upper Till, possibly at the margin of a stagnant downwasting ice sheet. Under such conditions considerable melt water movement would have occurred under the margins of the ice sheet, and a process of undermelt similar to that envisaged by Carruthers may have taken place. The general lack of compaction of the Upper Till suggests the possibility that under these ice marginal conditions with abundant meltwater, deposition of the Upper Till may have occurred as a flowage deposit derived from the basal debris at the ice front. Under such conditions a gradation into, and lack of disturbance of the underlying deposits would be expected. With this mode of origin the preferred orientation of the stones would have been caused by the actual flowage of material away from the ice front, and would not necessarily represent the direction of actual ice movement.

In the authors opinion it seems reasonable to assume that both an "undermelt", and also a flowage type of deposition may have occurred under marginal conditions at the edge of the stagnant ice sheet from which the Upper Till was deposited.

Upper Wear Clay.

An Upper Wear Clay in the Wear Valley was first recognised by Francis E.A. (1962), and described associated with the 320 feet surface in the southern part of the Wear Lowlands. As a surface deposit it is from 3 feet to possibly more than 50 feet in thickness. The idea of it being found solely on the 320 feet surface in the Wear Lowlands, seems however to be an oversimplification of the stratigraphy, as similar stony clay with very complex interrelationships with sands and laminated

clays are found in many borehole records.

Belmont

	Thickness of deposit		Total depth	
Vegetable spil	7"		7"	
Sub-soil	5"		1'	0"
Stiff light brown, mottled grey, veined, stony clay	8"		1'	8"
Brown veined clay with boulder stones and coal traces	8'	2"	9'	10"
Uniformly graded medium fine sand with coal traces	3'	2"	13'	0"
Firm grey brown silty stony clay	7'	1"	20'	1"
Uniformly graded medium fine sand with coal traces	17'	1"	37'	1"
Silty sand with silty clay layers	4'	0"	41'	1"
Firm greyish brown silty stony clay	15'	0"	56'	1"
Greyish brown silty plastic clay with sand partings	13'	11"	70'	0"

Bowburn

	Thickness of deposit		Total depth	
Vegetable soil	10"		10"	
Firm yellow bluey grey veined clay	1'	10"	2'	8"
Firm light brown mottled bluey grey veined clay	5'	4"	8'	0"
Stiff silty brown stony clay	28'	0"	36'	0"
Stiff reddish brown silty clay	11'	6"	42'	6"
Grey shale, silty sand mixture, with partings of bright coal	10'	6"	58'	0"
Hard dark grey boulder clay, with small fine coal, shale fragments of limestone	17'	0"	75'	0"

These two borehole records, both through the 320 feet surface give some indication of the complexity of the deposits in this area. Other records also suggest that the "upper stony clays" can and

do occur anywhere in the vertical sequence above the Lower Till. The question is whether these stony clays are different from each other genetically, or represent a single related sequence. The depth of the glacial deposits in the Wear Valley and their complexity makes generalisations on the basis of isolated borehole records a very chancy procedure, and it is still true to say that an adequate knowledge of the glacial deposits in this area does not exist. This fact testifies to the complex environmental conditions which must have been associated with the deposition of this sequence.

Even in its surface outcrop the Upper Wear Clay is characterised by a very close association with laminated clays and sands. Interbedding with such deposits is common, and in some sections the Upper Wear Clay can be traced laterally into a clay deposit in which stones are almost completely absent. At other exposures the stony clay passes into a clay deposit characterised by the presence of large coal fragments up to 3 inches in diameter but with no other stony material. This fact strongly suggests sorting in terms of the density of the included material. In nearly all its exposures the Upper Wear Clay shows no sign of disturbance of underlying material, and in some exposures appears to grade into the underlying deposit.

The sequence of deposits associated with the Upper Wear Clay appears to be largely relief controlled, and is rarely found above 380 feet. This suggests that the form of the Wear Lowlands may have been critical in the deposition of this sequence.

Within the Upper Wear Clay the long axis orientation of the stones is variable. Some exposures do show a preferred orientation, while others do not. No consistent orientation pattern can be detected over the area as a whole.

In terms of textural conditions the Upper Wear Clay exhibits considerable variety with rapid changes taking place over short distances. In its stonier facies however the Upper Wear Clay closely resembles the Lower Till.

The author is of the opinion that all the deposits in the Wear Lowlands are the products of deglaciation of a single ice sheet (the Lower Till), with the key to the understanding of the succession being the basin like nature of the Wear Lowlands.

During deglaciation it seems likely that the higher ground of the Magnesian Limestone escarpment and the Pennine Foothills emerged first from beneath the ice, leaving a huge mass of stagnant ice in the Wear Lowlands, which thickened northwards towards its major source in the Tyne Valley. The initial basal melting of this ice sheet would lead to the deposition of the Lower Till. Before the total release of the basal material could take place from the ice however, conditions would seem to have changed considerably. Large quantities of meltwater from the Pennines and Magnesian Limestone Plateau would probably have poured into the Wear Lowlands, and much of this would seem to have penetrated beneath the stagnant ice mass.

Under such conditions rapid melting of the basal layers of the ice would be likely to have occurred and water movement on a large scale beneath the ice to have taken place giving rise to a series of differing environmental conditions. Any deposits released from the ice would now be subjected to at least partial water sorting action. With continual thinning of the ice by surface and basal melting large masses of stagnant ice would become isolated while other masses might even begin to float. At this stage sub-aerial conditions would come into existence in places in the Wear Lowlands, and one would have complex environments of open water, stagnant ice masses, and floating ice masses.

In these types of environments the complex deposits of the Wear Lowlands are considered to have been laid down. The laminated clays as lake sediments or else deposited beneath floating ice. The sands as kames or marginal deposits. The stony clays as portions of basal till deposited from grounding ice and subjected in parts to resorting by water action, perhaps even as underwater flowage deposits.

This type of sedimentation appears to have been accomplished in the southern part of the Wear Lowlands while a large ice mass existed north of Durham, probably continuous with the main Tyne Gap glacier. With the retreat of this ice front, sedimentation in the southern part of the Wear Lowlands appears to have ceased having reached a level of 280 to 350 feet above ordnance datum. Buried stagnant ice masses probably still existed within these sediments and on later melting gave rise to the slightly rolling topography which characterises parts of the 320 feet surface. The places where larger ice masses persisted throughout this period are characterised by constructional dead ice masses composed mainly of sands. (Plawsworth, Shincliffe). At this time also periglacial conditions would have been severe, and mass movement on a large scale may have occurred.

The Upper Tees Clay

The deposits in the Tees Lowlands are in places very thick and as yet not fully mapped or understood. They consist mainly of a complex sequence of stony clays, laminated clays, sands and gravels. Throughout most of the area the surface deposit, except on the slopes and floors of the larger valleys, is a reddish brown clay with very few and only small stones. This deposit is known as the Upper Tees Clay. It varies from c. 3 feet to approximately 20 feet in thickness, and often overlies sands. Occassionally it overlies the Upper Till, or laminated clays. It was interpreted as a glacial till by the initial

survey of the Geological Survey (1882), by Radge G.W. (1939), and by Agar, R. (1954).

Typical borehole sections (near Wolviston).

Vegetable soil		11		11
Stiff reddish brown, blue veined stony clay with some sand partings	8	10	9	9
Fine sand with reddish brown clay traces	9	11	19	8
Very hard dark reddish brown stony clay	16	10	36	6

Borehole stopped

Vegetable soil		9		9
Sub soil	1	3	2	0
Stiff reddish brown, blue veined stony clay	3	8	5	8
Soft reddish brown sandy clay	2	1	7	9
Stiff dark reddish brown stony clay	16	3	24	0
Hard reddish brown sand with coal traces	16	6	40	0

Borehole stopped

The stones within the deposit tend to be rounded and possess very poor long axes. As a result fabric analyses at a number of exposures have revealed only weak or completely absent preferred orientations. At all its exposures the Upper Tees Clay possesses a marked lithological uniformity although interbedding of thin layers of sand is sometimes found. Everywhere the deposit shows average sand contents which are low, and clay contents which are high when compared with the other Eastern Durham stony clays. The shape of the particle size distribution curves suggest the possibility that this clay has

been subjected to a measure of water sorting action.

In most of its other characteristics the deposit is exceedingly similar to the Upper Till of the coastal area, and can in fact only be distinguished from it by its lower stone and sand content.

The full succession of deposits within the Tees Lowlands is still uncertain, but a basically similar sequence is thought to exist along the whole of the Tees Lowlands at least as far west as the Darlington area. For example at Rockcliffe Scar on the River Tees, the Upper Tees clay is seen overlying laminated clays and sands, a tough red till, and at the base of the succession a dark grey clay.

One is faced therefore with the explanation of a very closely related and in places interbedded sequence of stony clays, laminated clays and sands. As in the Wear Lowlands the area of the Lower Tees is a topographical hollow between the Magnesian Limestone Plateau to the north, and the Cleveland Hills to the south. Here as in the Wear Valley the ice sheet was advancing from the direction of the lowest portion of the topographical hollow. In the Tees Valley it was the Upper Till ice sheet advancing south-westwards from the North Sea area. In the early stages of the advance of the ice sheet into the Tees Lowlands ponding of the sub-aerial drainage will probably have taken place leading to an abundance of water, at or close to the ice front. Because of this it seems reasonable to suppose that some water sorting of the glacial deposits would have occurred even during the ice advance.

With deglaciation even more complex environmental conditions would probably have been initiated, giving rise to sub-glacial and marginal environments similar to those described by Carey and Ahmad, with the close association of bedded deposits and till-like clays deposited as till mud flows or turbidity currents. Flowage of till material from the ice margin into a water logged or shallow water environment would give rise to the type of partially water sorted deposit which the Upper Tees Clay appears to be.

The merit of this hypothesis is that it recognises the possibility that a total glacial sequence, made up of a series of deposits can be the product of a single ice sheet. This does away with the necessity of explaining every stony clay as an ice advance. It has the further advantage that such conditions are known to exist on the periphery of ice sheets. (Carey and Ahmad 1961).

(Price R.J. and Howarth P.J. (1966) working on a modern valley glacier in Iceland have described semi-fluid deposits of clay and stones emerging from beneath a retreating ice front to form a thick superficial layer of what appears to be till-like material. Interbedding of sand lenses in such clays was also described).

Other Stony Clays.

The only other stony clays in the area of Eastern Durham are a series of clays with few stones found in the Shotton area. These are of restricted local outcrop and the best exposure of such deposits is seen at Shotton Brick Pit where the clay attains a thickness of 20 feet and overlies laminated clays. At this exposure the clay is relatively homogeneous with small stones mostly less than 1.5 inches in diameter scattered through the deposit. At its basal contact with the laminated clays there are signs that the upper part of the laminated clays have been disturbed and bent over towards the south-east. This suggests that the upper clay was derived from the north-west, and that its deposition had an erosional and drag effect on the laminated clays.

A comparison of the particle size distribution curves for the Lower Till and upper clay at Shotton Brick Pit reveals interesting points. The main point is that in the grain size range subjected to analysis (i.e. below 20mm particle size diameter) the Lower Till has

double the amount of coarse material, above 2mm. when compared with the upper clay. (Fig 90). If sampling ability had permitted the analysis of grain sizes larger than this the difference in the coarser grades would have been even more striking. In the Lower Till stones up to 12 inches in diameter are common, while in the upper clay no stone at all above 4 inches in diameter is found. There exists therefore a vast difference in the percentages of coarse sized material present in these two samples.

If however one considers the particle size distribution in the less than 2 mm fraction, by taking the 2 mm point as the origin of the graph one can readily see that throughout most of the distribution the two curves are almost identical, except for the slightly lower percentages of very fine material in the case of the upper clay. (Fig 91).

Because of these facts the author suggests that the upper clay at Shotton Brick Pit has been derived exclusively from the Lower Till, but that during its deposition two important changes have taken place. Firstly all the larger particles have been removed from the deposit, and secondly a certain amount of the finer material below 0.01 mm has also been removed. No sign of the removed coarser material can be found within the area of the Brick Pit. Analysis of the upper part of the upper deposit reveals a marked drop in sand content and in the uppermost two feet only silt and clay sized material is present.

Upper Clay - Shotton Brick Pit.

Depth in feet below ground surface	Sand percentage
1	0.6
2	4.3
3	26.6
4	33.9
5	38.8
6	41.6

Figure 90.

SHOTTON BRICK PIT

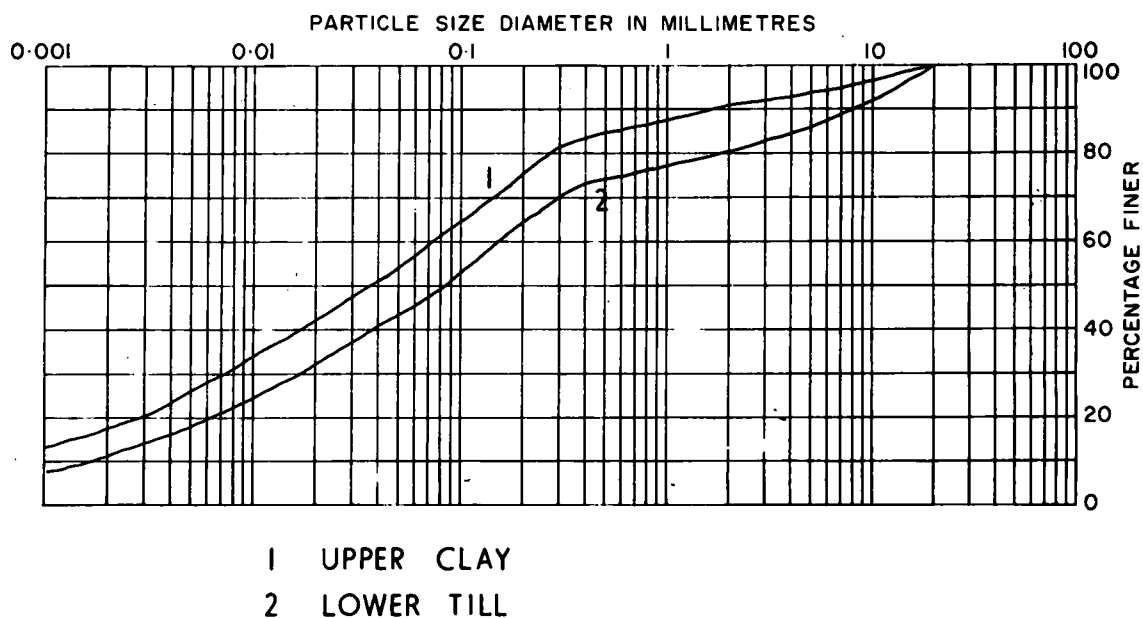
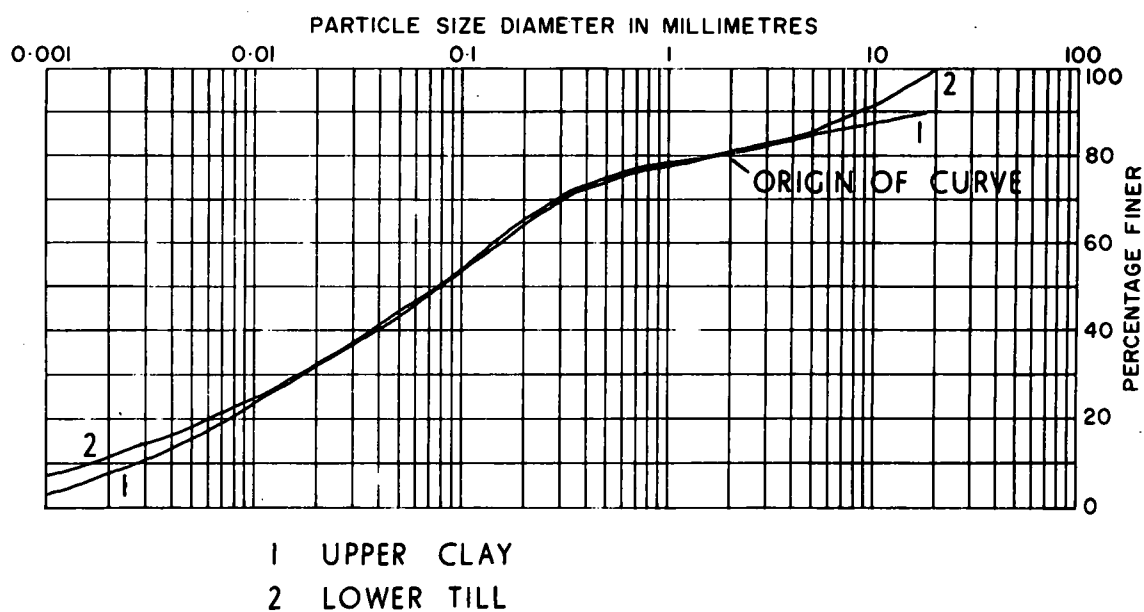


Figure 91.



This suggests the possibility that the finer material removed from the deposit as a whole has been concentrated by some process, and deposited on top of the upper clay.

One therefore has to postulate a mode of origin for this upper clay which explains the two sorting characteristics observed, namely the removal of the coarser sized particles, and a certain proportion of the finer ones, together with the erosional and drag features found at the surface of the laminated clays.

The author puts forward the hypothesis that this upper clay is a mud flow or turbidity current laid down in the lake in which the laminated clays were deposited. Knowledge on turbidity currents is still limited but a recent summary of knowledge is found in Walker R.G. (1965). According to Walker's classification the deposit at Shotton Brick Pit could be classified as an AE deposit (p.2 and 24). (The A portion being the graded division including all the material of the turbidite which is not laminated, and the E division being the uppermost silty clay portion). Walker considers that the deposits formed by an immature "traditional" turbidity current are unlikely to be graded, and will possess almost as large a range of grain size as the sediment from which they are derived. (p.9 and 13). He goes on to state (p.10) that the larger particles within such a deposit although involved in the initial sharp movement of the turbidite could be deposited during the very immature stage of turbulent flow, because they could not be transported by the turbidity current proper. Bearing this in mind it would seem likely that if the upper clay at Shotton Brick Pit was formed in this manner, a coarse gravel deposit probably in the form of a traction carpet should be found in an upstream direction at the base of the deposit. Unfortunately no exposure exists where this could be verified. The fact that some clay appears to have been removed from the

main part of the deposit also fits in well with this hypothesis. This shows that the sorting processes associated with a turbidite were just beginning when the deposit came to rest, and that this mud was disseminated in the water through which the turbidity current was moving. This mud would then settle on top of the main deposit in a way very similar to that observed at Shotton.

The possible sequence of events at Shotton Brick Pit would seem to be as follows. Initially there occurred the movement of a mass of saturated Lower Till into the lake in which the laminated clays were deposited. During this movement the material above c. 3 inches in diameter could not be transported by the speed of the current, and this material was deposited at the base. The rest of the deposit moved downslope in the lake disturbing the upper surface of the laminated clays as it passed. Sorting of the finer sized material was just beginning to occur when the deposit came to rest after probably only a very short travel, but that this had been sufficient to form muddy sediment within the lake water which later settled on top of the deposit to form the almost sandless layer.

By this mode of origin all the observed characteristics of the upper clay at Shotton Brick Pit are accounted for. The discovery of a gravel deposit in an upstream direction at the base of the upper clay would be conclusive proof for this mode of origin.

Conclusion

From this summary it can be seen that the interpretation of the origin of the stony clays of Eastern Durham is not as simple as would at first appear. At some time or other all the stony clays, with the exception of the upper clay at Shotton Brick Pit have been considered as true sub-glacial tills, and the result of a separate glacial phase within the area.

The work of the present author has shown that only the Lower Till possesses sufficient characteristics to establish beyond doubt its sub-glacial origin and deposition. All the other stony clays possess characteristics which do not entirely accord with those generally associated with sub-glacial lodgement type deposition.

Of all the other stony clays within the area only the Scandinavian Drift and the Upper Till are considered to have originated as sub-glacial dirt, and in both these examples a specialised mode of deposition seems to have occurred.

In both the Wear and the Tees Lowlands the sequences of deposits appear to be due to complex environmental conditions of a sub-glacial or marginal nature, within a single ice sheet, perhaps caused by local topographic features.

The interpretation of the upper clay at Shotton Brick Pit as a density current of the mudflow, or turbidite variety suggests a possible mode of origin for some of the stony clays of lowland glacial sequences, which has perhaps not received sufficient attention.

These ideas and hypotheses serve to indicate that glacial sequences are not simply to be interpreted in every case in terms of a series of ice advances but that a more complex environmental conditions, whose true nature we do not fully comprehend seem to have existed. As such they provide a challenging problem for further study.

Chapter 14

THE SEQUENCE OF GLACIATION IN EASTERN DURHAM AND NORTH-EASTERN ENGLAND.Introduction.

In the present work the main subject of study has been the nature of the stony clay deposits and their modes of origin, rather than a stratigraphical appraisal of the deposits and their absolute and relative ages. However the author's work has involved the collection of a considerable body of new information from a small area of north-east England, and as a result of this information certain aspects of previous interpretations of the glacial deposits of the area have been modified.

The understanding of a glacial succession in any area depends initially on the interpretation of the origin of the individual deposits making up the sequence. A glacial sequence can be described objectively in terms of sands, laminated clays, gravels, and stony clays, but once the terms such as 'glacial till' or 'end moraine' are applied to deposits the process of interpretation has begun. The concept of the 'Diluvium' illustrates this point. (Lyell C). Here is the classic example of a sequence of deposits within the British Isles being interpreted in the nineteenth century so differently from the modern view, and yet completely in agreement with the scientific thought and knowledge of the day. This example points to the fact that knowledge is not absolute, but relative to the background of scientific knowledge in which it is considered. In the study of glacial deposits where our knowledge of actual processes of deposition is still of a very elementary nature this is particularly true.

Studies of contemporary glacial areas have emphasised the complexity of glacial retreat and advance, and have pointed out that part of the evidence necessary for the full understanding of events is often removed by later processes. (Price R.J. 1964). Such conditions must have been equally true for events during the Pleistocene. The glacial deposits and landforms which exist at the present day are the sole evidence we possess for the interpretation of the pattern of former glacial events. It is important to realise however that in many cases it is not the full evidence, and it is often insufficient to interpret the sequence of events as they actually occurred.

Eastern Durham.

The distribution of the glacial deposits and the ideas of previous workers in the area of Eastern Durham have already been outlined in earlier chapters. Suffice to state here that the deposits of Eastern Durham have been regarded as the product of as many as four ice sheets (Woolacott D. 1921) or as few as one. (Carruthers R.G. 1953).

The analytical work of the present author has led him to conclude that three glacial tills, all deposited under markedly different environmental conditions exist within the area of Eastern Durham. These are the Upper Till, the Lower Till and the Scandinavian Drift. All the other stony clays are considered to have been derived from one or more of these three deposits. Of the three ice sheets, only the Lower Till ice sheet has had any influence on the area of Eastern Durham as a whole. The ice sheets which deposited the other two till sheets appears to have affected only the coastal fringe of the county.

The Upper Till

The Upper Till is the youngest till deposit in Eastern Durham, and is found only in the coastal area. In agreement with Catt

and Penny 1966 this clay is regarded by the author as the lateral equivalent of the Hessle Till of Holderness, and therefore also of the Hunstanton Till of north Norfolk. (Penny L.F. 1964).

From the nature of the stone orientations and erratic content this clay is considered to have been derived from the Cheviot area of Scotland and northern England. (Howse R. 1964, Smythe J.A. 1912, Woolacott D. 1921). In Eastern Durham the ice front of the Upper Till sheet must be regarded as the lateral margin of a glacier pursuing a general southerly course, perhaps held in this position by the presence of Scandinavian ice offshore in the basin of the North Sea. It is therefore reasonable to assume that there would be important fluctuations in this ice margin at different stages in the glaciation, and as a result of this the maximum western limit of the Upper Till in Eastern Durham would almost certainly not be contemporaneous. Possibly as a result of this the margin of the Upper Till is exceedingly difficult to plot as a line on a map. The highest exposure of the Upper Till in Eastern Durham is at about 500 feet near Easington, dropping south westwards to heights of 350 feet to the south of Sedgfield. In contrast on the northern face of the Cleveland Hills, Barrow (1886) described an upper till, thought to be the same deposit at heights of up to 1000 feet. From surveys carried out by the author the Upper Till appears to continue south into the Vale of York, although its southern limit is unknown.

At the maximum stage of the Upper Till glaciation when ice was lying along the coastal fringe of Eastern Durham, it seems highly likely that the drainage pattern of the Magnesian Limestone Plateau

would have been considerably modified. Smith D.B. (personal communication) envisaged at this stage the formation of a series of lakes held up by the ice front in which laminated clays were deposited. The laminated clays at Wingate and Shotton Colliery were considered by him to be examples of this type of deposition. The present author accepts this possibility with some reservations, as in his opinion many of these laminated clay deposits appear to be more intimately associated with the deglaciation of the Lower Till ice sheet, than with the inland advance of the Upper Till ice sheet. However the paucity of exposures in this key area does not allow adequate interpretations to be attempted.

In Carruther's interpretation of glacial sequences such laminated clays would be regarded as "shear clays" formed within the ice itself and deposited by pressed melting from stagnant ice. In the opinion of the author the laminated clays of Eastern Durham must have originated in a fluid environment as mechanical analysis of these deposits shows clear evidence of sorting, and the concentration of material within specific grade sizes. If Carruthers' hypothesis was correct such deposits should consist merely of streaked out till, and therefore in terms of particle size, be composed of till material which had merely been crushed to finer grain sizes. This is however not the case. The existence of ripple marked surfaces on some of the laminations, together with the pronounced sorting proves beyond doubt these laminated clays must be of water-lain origin. Any structures within these clays are thought to be due to load casting or slumping of material. (Potter P.E. and Pettijohn F.J. 1963).

The complex sequence of deposits, including the Upper Tees Clay in the Tees Lowlands are considered to be the product of complex environmental conditions associated with the deglaciation of the Upper Till ice sheet. It would appear that while the coastal area of

Eastern Durham was being glaciated by the Upper Till ice sheet, the rest of the county, including the Magnesian Limestone Plateau and the Wear Lowlands was at least partially ice free.

The dating of the Upper Till deposit is somewhat tenuous owing to the general lack of organic deposits within Eastern Durham. However a minimum age for the deposit can be fixed by the occurrence of peat deposits above the Upper Till at Neasham. In this peat deposit Blackburn K.B. (1952) identified Late Glacial pollen belonging to Zone 1. (A detailed division of the Late Glacial into Zones 1a, 1b, and 1c had not been attempted at the time of this work). This result suggests that the Upper Till and its associated suite of deposits must pre-date the Late Glacial and therefore belong to the Main Wurm maximum (Penny L.F. 1964) or an earlier glacial phase. The relative freshness of the topography developed on the Upper Till would possibly suggest a Main Wurm (15,000 to 25,000 years B.P.) origin for this deposit.

The Lower Till.

The Lower Till sheet of Eastern Durham marks the stage of maximum glaciation within the area. It was deposited, as shown by stone orientations and erratic content by an ice sheet moving south-eastwards across Eastern Durham from sources in the Pennines, the Lake District and the Southern Uplands. This glaciation was probably the result of ice building up in the Irish Sea basin, and then overflowing eastwards across the Pennines. Ice tongues from this large ice sheet seem to have entered the Durham area via the Tyne Gap and the Stainmore depression. In the early stages of glaciation the Tyne ice appears to have coalesced with a glacier in Weardale to form a large

piedmont glacier in Northern Durham. At this period the amplitude of relief within the area was considerably greater than at the present day, and consequently features such as the Magnesian Limestone Escarpment would have presented a greater barrier to ice movement than at the present day. As a result before the ice sheet overwhelmed all the topography, it appears likely that initial ice movement would be directly eastwards out to sea in the area of Newcastle and Sunderland. As the pressure of Tyne ice increased ice thicknesses would build up in northern Durham, and eventually the combined ice sheets from the Tyne and Wear would stream south-eastwards across the Magnesian Limestone Plateau towards the coastal region. At maximum glaciation this ice sheet probably coalesced with Scandinavian ice off shore, and with Tees ice moving over the Stainmore depression in the south. No exact boundaries can be drawn delimiting these different ice sheets owing to the fact that changes in local ice pressures probably caused considerable movement of these limits. At no time in this glaciation however does Tees/Stainmore ice appear to have penetrated into the Wear Lowlands, or into the coastal region north of Crimdon Dene.

With the decrease in snow accumulation in the source areas of western England the driving power of the Lower Till ice sheet would be removed, and the glaciers would retreat or stagnate in situ. On the whole with the exception of the valley glaciers deglaciation probably took place by the down wasting of the ice sheet rather than the actual retreat of an ice front. Therefore the first areas likely to be ice free would be the highest points of the land which would break through the ice to form nunataks. In Eastern Durham the ridges of the Pennine Foothills, and the line of the Magnesian Limestone Escarpment would possibly be the first areas to emerge, and to divide the ice sheet into separate ice masses. At this period ice would probably be thickest in the Wear Lowlands, in the Pennine Valleys, and in the coastal areas where local British ice had coalesced with the main

body of the Scandinavian Ice Sheet.

Many of the smaller relief features of the Magnesian Limestone Plateau area appear to be the result of this pattern of deglaciation. The first part of the escarpment to appear above the ice would be probably those areas above 600 feet, while to the east and west ice would have stagnated on lower ground. Meltwater from this decaying ice sheet would naturally have taken the line of least resistance downslope, probably under, or through stagnant ice masses. As a result a whole series of meltwater channels would be formed draining westwards from the Magnesian Limestone Plateau area, towards the Wear Lowlands, and marked at the present day by the series of col-like features crossing the plateau at heights of between 350 to 450 feet. (Fig.11). It has proved impossible to trace in detail the actual ice front on the Magnesian Limestone Plateau at the time of deglaciation, as during the later stages the ice seems to have broken into a series of independent masses which on further melting gave rise to very complex environmental conditions. This is particularly well illustrated in the Wheatley Hill area where sub-glacial, marginal and sub-aerially formed meltwater channels appear to be present. In the later stages of deglaciation it seemed likely that all these channels carried away water sub-aerially, until new meltwater channels were exposed from beneath the ice in the coastal area. (Smith D.B. in press, considers these channels to be of sub-aerial origin).

In the eastern part of the Magnesian Limestone Plateau area lakes would be formed in hollows on the surface of the Lower Till, or against debris laden masses of stagnant ice, and in these laminated clays would be deposited. The stagnation of this ice mass also appears to have produced a series of constructional features composed mainly of sands and gravels. An important ice contact kame complex is seen at Warden Law, while at Grindon the remains of what appear to be an ice

cored esker are found. Further south isolated gravel and sands masses of ice contact origin are found at Batter Law, Easington, Kelloe Law, Southern Law and Eppleton.

In the Wear Lowlands the pattern of deglaciation seems to have been completely different from the Magnesian Limestone Plateau area. In the initial stages ice is envisaged as withdrawing from the upland areas, and downwasting into the basin area of the Wear Lowlands. At this period environmental conditions in the area must have been extremely complex, with stagnant ice, outwash plains and lacustrine features found in close proximity. Considerable meltwater would also be arriving within the area from the Pennines the Tyne Gap and the Magnesian Limestone Plateau area. (Raistrick A. 1931).

At a later stage, ice in the Wear Lowlands appears to have retreated to the north, and an important retreat stage is marked by ice contact deposits in the area near Durham City. (Francis E.A. in press). While the ice occupied this position a series of complex outwash and kame features were built up to the south to form the 320 feet surface of Maling. These terrace like features slope down from source areas at c. 360 feet O.D. to lower levels at c. 280 feet O.D., and are largely formed by material derived from the ice front, and also outwash from the Magnesian Limestone Plateau and the Pennine Foothills. The actual surface of these terrace like features is probably of composite origin and made up of outwash sands and gravels, dead ice deposits and lacustrine clays. As a unit these features form an important landform in the southern part of the Wear Lowlands. Most of the water from these outwash areas appears to have escaped to the south via the Ferryhill meltwater channel, although it is certain that this feature was already in existence prior to this stage of the glaciation. (Maling D.H. 1955). No other well marked retreat stage of the Tyne valley ice sheet has been found within the east Durham area, suggesting

that further ice decay took place under stagnant downwasting conditions.

The dating of the Lower Till ice sheet is exceedingly difficult as no organic deposits have been found associated with it in positions where the stratigraphy is clear. From its stratigraphical position the Lower Till clearly pre-dates the Upper Till, and from this it can be concluded that the Lower Till belongs to the Main Wurm or an earlier glacial phase. The key question is to try and decide whether the Lower Till belongs to the same glaciation as the Upper Till, or to an earlier one. From the evidence of the stone content of the Upper Till outlined in Chapter 6 the author is certain that the Upper Till is not the product of an overriding glacier of the Lower Till ice sheet.

Evidence for a period of deglaciation between the Upper and the Lower Till sheets is however meagre and confined to the two possible weathering profiles developed on the surface of the Lower Till (Chapter 10). These two profiles suggest a period of weathering between the Upper and the Lower Till ice sheets, but of course give no indication as to whether they were formed under interstadial or interglacial conditions.

The key deposit in the stratigraphy of the till sheets of eastern Durham is the raised beach deposit at Easington. (Woolacott D. 1920). In this deposit the fauna present indicates warm temperate, rather than interstadial conditions. (Identification and examination of the fauna by Baden-Powell led him to believe that this deposit was of Eemian or Last Interglacial age). A carbon-14 dating of these shells gave an age of more than 38,000 years B.P. Provided that the shells have not assimilated ancient elemental carbon during their growth, the deposit must therefore be of last interglacial age or earlier.

The exact stratigraphical position of this crucial deposit is however uncertain. The gravel in which the temperate fauna was

found rests directly on the Magnesian Limestone. Overlying this highly fossiliferous gravel is a gravel deposit with very few shells, and above this the Upper Till. It is therefore certain that the Upper Till is younger than the beach deposit, and therefore younger than the Fennian Interglacial. It is however in the relationship between the Lower Till and the beach deposit that most confusion arises. On either side of the beach the Lower Till rests directly on rockhead, but slumping of the cliffs has completely obscured the nature of the junction between the two deposits, so that it is impossible to detect whether the formation of the beach has eroded the till, or whether the Lower Till is merely absent from this point. The fact that the Lower Till appears to thin uniformly from either side towards the beach strongly suggests that the Lower Till was deposited first, and subsequently truncated by the high interglacial sea level which deposited the beach. One interesting point is that westerly derived erratics are abundantly found in the beach gravel. This means that if the beach pre-dated the Lower Till, it must of necessity post-date at least one glaciation with a westerly origin from which its erratics could be derived. No such till deposit has ever been described in the Eastern Durham area, and nearly everywhere the Lower Till is the basal glacial deposit. Gravel deposits with westerly erratics do however occasionally occur beneath the Lower Till. Most of these deposits are probably of sub-glacial origin, but others do appear to represent true beach deposits, and so suggest the possibility than an earlier western glaciation, of which virtually no trace remains at the present day could have taken place. At Limekiln Gill a gravel deposit beneath the Lower Till contains a marine fauna, and shell fragments from these gravels collected by the author were examined by Baden-Powell D.F. The remains proved too fragmentary to identify successfully, but hinges of *Tellina* sp. and an *Astarte* hinge were

identified. The Astarte hinge appeared to be that of *Astarte borealis*, but exact identification could not be made. If the identification is correct it would point to a cold climate at the time of the beaches formation. Baden-Powell concluded that the shell fragments from Limekiln Gill bore no resemblance whatsoever to the shell fragments he had examined from the Easington Raised Beach.

If the Easington Raised Beach post-dates the Lower Till it is almost certain that the two till sheets of Eastern Durham, the Upper and the Lower Till are separated by interglacial conditions, and that the Upper Till is therefore the only representative of Wurm glacial conditions in Eastern Durham. If the beach pre-dates the Lower Till it means that the Upper and Lower Tills are the products of the same glaciation.

Both interpretations therefore present considerable problems. One interpretation calling for the almost complete removal of the deposits of a whole glacial phase, and the other interpretation suggesting that only a very minor part of Northern England was glaciated during the last glaciation.

Morphological evidence exists which appears to show that the landscape developed on the Upper Till is younger than that on the Lower Till. On the Magnesian Limestone Plateau the eastward draining streams flow in shallow wide valleys in their upper parts, but on entering the area of the Upper Till sheet immediately become incised to form the coastal denes. In the south of the plateau area the River Skerne has been diverted to the south at a point which approximately marks the inland limit of the exposure of the Upper Till (Fig.4). Finally in the coastal fringe the topography developed on the Upper Till has a much fresher appearance, with rounded hillocks and ill-drained basins, than the more mature and dissected topography developed on the Lower Till to the west.

Evidence against such an interpretation is the fact that the amount of erosion and valley cutting which has taken place on the surface of the Lower Middle Sands and the Lower Till does not appear consistent with a long period of sub-aerial conditions between the deposition of the Upper and Lower Till sheets. No definite conclusion can be reached at the present time on the validity of either hypothesis.

In summary the author concludes that an interval of deglaciation exists between the Upper and Lower Till sheets (Chapter 10) but that the evidence at present available is insufficient to decide whether this interval is of an interglacial or interstadial nature.

The Scandinavian Drift.

The Scandinavian Drift is found underlying the Lower Till, and rests directly upon Magnesian Limestone. Its erratic content suggests that it was the product of the earliest glaciation to reach the east coast of the British Isles, and that it included within it the remains of an Early Pleistocene fauna and flora, together with a cold marine fauna of unknown age. (Trechmann C.T. 1919).

Evidence for interglacial conditions following the deposition of the Scandinavian Drift is based on the presence of the so called "loess" deposit described by Trechmann (1915). In this respect it is interesting to note that even Trechmann admitted that the loess was interbedded with the Scandinavian Drift, and that it did appear to be more of a deglaciation deposit when the ice was close at hand, rather than a true interglacial deposit. The fact however that no westerly derived British material exists within the Scandinavian Drift almost certainly suggests a pre-Last Glaciation origin for this deposit, and therefore the fact that interglacial conditions must have followed its deposition.

At the present day the Scandinavian Drift is found only at a single locality. Yet the evidence concerning the fissures in the Magnesian Limestone presented by Trechmann, suggests that at the time of its deposition the Scandinavian ice sheet influenced at least a 6 mile stretch of the Durham coast. If the initial deposition of the Scandinavian Drift was relatively uniform throughout the area it means that very large proportions of the deposit must have been eroded before the deposition of the overlying Lower Till. This erosion could probably have been accomplished solely by the Lower Till ice sheet, which moving in a general easterly direction would have removed all traces of the Scandinavian Ice sheet in a seaward direction. However the presence of what appears to be isolated fragments of beach deposits beneath the Lower Till (at Limekiln Gill) suggests the possibility of complex environmental conditions between the deglaciation of the Scandinavian ice sheet, and the advent of the Lower Till.

A morphological feature of interest in the coastal area is a bench-like platform cut in the Magnesian Limestone at heights of between 30 to 100 feet above sea level. This feature can be seen in the coastal sections, and also recognised from borehole data. Occassionally as at Chourdon Point it is overlain directly by calcreted gravels, but elsewhere the Lower Till forms the basal deposit. To some extent at least this bench is a depositional feature of the Magnesian Limestone against the coral reef knolls of the Zechstein Sea, but in detail it can be seen that this platform planates individual beds of the limestone and is therefore undoubtedly an erosional feature, possibly of marine origin. The age of the platform is unknown. It is certainly pre-Lower Till in age, but its relationship to the Scandinavian Drift is not clear. The possibility does exist that this feature was formed in a period following the deposition of the Scandinavian Till, and might have

accounted for the almost complete removal of this deposit.

All one can definitely say concerning the dating of the Scandinavian Drift is that it is probably pre-Last Glaciation, and post Lower Pleistocene. This means that it is likely to belong to either the Saale or Elster glacial periods.

Summary of the possible interpretations of the Eastern Durham sequence.

Three interpretations of the above evidence are possible.

1. The first possibility is that the Scandinavian Drift is the product of the Elster Glaciation, and that the Upper and Lower Tills are the product of the Last or Wurm or Weichsel Glaciation. This means that little direct evidence of a Saale Glaciation exists in County Durham, and is confined to possible beach deposits with westerly derived erratics beneath the Lower Till. This fact implies that any Saale Till sheet which had existed has been completely removed by erosion before, or by the arrival of the Lower Till ice sheet.
2. The second possibility is that the Lower Till is the product of the Saale Glaciation, and that the westerly derived erratics in the Easington Raised Beach have been derived from this clay. The Scandinavian Drift would still then be regarded as the product of the Elster Glaciation. This interpretation necessarily means that the Upper Till is the only product of the Last or Wurm or Weichsel Glaciation, and that possibly only the coastal fringe of County Durham was glaciated at this period.
3. The final possibility is that the Scandinavian Drift is the product of the Saale Glaciation, and that the Upper and Lower Till sheets belonged to the last or Wurm Glaciation. From this interpretation one concludes that northern England does not appear

to have been glaciated during the Elster Glaciation, but at the same time it does suggest the possibility of a westerly derived ice sheet reaching the coastal area of Eastern Durham, during the same glacial phase as the Scandinavian Drift.

All three hypotheses are equally tenable in the present state of knowledge of the Eastern Durham area, and the present author feels that until more adequate dating evidence can be obtained further speculation on the relative validity of the various theories is of little value.

Possible interpretations.

	1	2	3
Wurm Glacial	Upper Till Lower Till	Upper Till	Upper Till Lower Till
Eemian Interglacial			
	Easington raised beach	Easington raised beach	Easington raised beach
Saale Glacial	? Till sheet completely removed	Lower Till	? Till sheet completely removed
			Scandinavian Drift
Holstein Interglacial			
	No remains	No remains	No remains
Elster Glacial	Scandinavian Drift	Scandinavian Drift	No glaciation

Comparison of the Durham sequence with other areas.

The comparison of glacial deposits between different areas is generally attempted in terms of similarities of stratigraphical

sequence. In the present work no attempt is made to correlate the deposits of the east coast of England with those of the west coast in such areas as the Vale of Eden, as it was felt that the basic lack of knowledge of the glacial deposits in the intermediate areas of the Tyne Gap and Stainmore Depression makes suggested correlations little more than inspired guesses.

Along the East Coast itself however from Northumberland to Holderness cliff sections provide excellent exposures of the glacial deposits, and allow correlations to be made with greater certainty.

In Northumberland no recent published work of a stratigraphical nature on the glacial deposits themselves has appeared. However from the detailed records of Howse R., Smythe J.A., and Carruthers R.G. it seems certain that the basic glacial succession consists of a lower dark grey till with westerly derived erratics, overlain in places by an upper reddish till with Cheviot erratics. Between the two tills waterlain deposits are often found. This succession is almost identical to that of Eastern Durham, and the author considers these two Northumberland deposits the lateral equivalents of the Lower and Upper Till sheets respectively of Eastern Durham.

In Holderness a more complex succession of 4 till sheets is described by Catt and Penny (1966). These are the Basement, Drab, Purple and Hessle Tills. The Hessle, Drab and Basement Tills are correlated respectively with the Upper, Lower and Scandinavian Tills of Eastern Durham by Catt and Penny. Analytical work undertaken as part of this thesis confirms this interpretation. However the interpretations of the Holderness sequence is considerably different than that suggested for the Eastern Durham area. Catt and Penny put forward the hypothesis that the three upper tills of Holderness, the Hessle, Purple and Drab are deposited from a composite ice sheet of superimposed glaciers from the Tees, Tyne and Cheviot areas. This ice sheet is regarded as Main Wurm in age (Penny L.F. 1964). The Basement

Series is regarded as the product of an earlier and separate Saale Glaciation.

For reasons already outlined in Chapter 13 the present author can not agree that the Hessle/Upper Till has been deposited by an overrider of the same ice sheet as the Drab/Lower Till, although he is willing to accept the possibility that these two deposits belong to the same glaciation.

Therefore although in Holderness a similar succession exists to that in Eastern Durham differences in supposed modes of origin for the deposits has led to differing interpretations being put forward to explain them. Such differences clearly show the necessity for obtaining a greater knowledge of the modes of origin of glacial deposits.

The correlation of the Eastern Durham deposits with those in the Vale of York is exceedingly difficult because of the lack of modern studies in the latter area. This is particularly unfortunate as the York and Escrick moraines, at the southern margin of the Vale of York are generally accepted as delimiting the margin of the Last Glaciation in northern England. (Penny L.F. 1964; Suggate R.P. and West R.G. 1959; West R.G. 1963;) The only modern article dealing with chronology in the Vale of York is by Palmer J. (1966). In this he claims that the maximum extension of ice in the Vale of York during the Last Glaciation was beyond the York and Escrick moraines to the Doncaster area. (Balby Stage). The retreat of the ice to the York moraine from this maximum stage is considered to have occurred during Zone 1a of the Late Glacial, and the retreat northwards from the York moraine during Zone 1b. If this interpretation is correct it means that ice must have still been in existence in County Durham during at least Zone 1a of the Late Glacial.

Conclusions.

In Eastern Durham three till sheets are recognised, the Upper Till, the Lower Till and the Scandinavian Drift. The Upper Till and the Lower Till appear to be part of a sequence which stretches in coastal exposures from north Northumberland to at least as far south as the estuary of the Humber. The Scandinavian Drift would appear to be the lateral equivalent of the Basement Till of Holderness.

The dating of the deposits is extremely difficult on the evidence available in Eastern Durham. If one accepts the views outlined by Catt and Penny (1966) for Holderness one must conclude that the Upper and Lower Till sheets of Eastern Durham are the products of the Main Wurm glaciation. The evidence of the present author however strongly suggests that a period of deglaciation separates the deposition of the Lower Till from the Upper Till. The nature of this interval is still unknown, although it is suggested by Smith D.B. (personal communication) to be possibly of interglacial type.

Chapter 15

CONCLUSIONS.Introduction

The work described in this thesis has consisted mainly of an analytical study of the glacial stony clays of Eastern Durham. It has been an attempt to obtain detailed knowledge of deposits within a small area, and therefore by its very nature has been limited intentionally in both content and scope. It is freely admitted that the maximum utility of the results obtained in this work can only be achieved by a comparison with similar results in other areas of the British Isles. Unfortunately such results do not as yet exist within the published literature, although it is likely that in the near future this position will be changed as other research work becomes published.

One of the main criticisms that can be levelled against quantitative analysis of the type used in this thesis is that the tremendous investment of time does not justify the results obtained. Because of this time factor it means that in a given period only a limited number of samples can be fully analysed. As a consequence it can always be claimed that these results are never sufficient to allow any detailed conclusions to be reached, because of the fact that geological populations from which the samples have been obtained are almost infinite. Such criticisms can be countered by ensuring that samples are randomly selected in the field, but as Krumbein W.C. and Graybill F.A. (1965) point out, this is often out of the question because sampling techniques do not allow sampling from depth if a particular deposit is deeply buried beneath other deposits. Under such circumstances it is only possible to sample the deposit being studied from chance exposures where it outcrops, or where it can be reached by shallow boring. It is therefore often extremely difficult to decide

whether the sample population and the target population (the population of the deposit as a whole) is similar. This means that if generalisations are drawn about the target population they are based more on geological considerations than statistical ones. However at any outcrop detailed sampling can be done on a random basis and this gives rise to what have been called 'semiprobability samples' (Cochran, Mosteller and Tukey 1954). In this case there is no choice at the upper level of sampling (i.e. at the outcrop level) but complete freedom of choice at the hand specimen level. The result is that while the small scale characteristics of the sampled population may agree well with the target population, the large scale characteristics may differ, depending on the non-random nature of the selection of sampling sites.

In this work the very large number of man made, and natural exposures along stream sections and in the coastal area, have allowed a random choice to be made between a series of exposures in a given locality. Where such exposures were not present randomly selected pits were dug where the deposit being studied had a surface exposure. In some places however such as the Tees Lowlands it was impossible to obtain any samples of the Lower Till, whether of a random or other nature.

One of the great advantages of quantitative analysis, if its procedures are standardised is the fact that if the same analysis were carried out on a number of occasions by different workers the results would be similar (allowing for operator and sampling error). This means that a body of objective factual information can be built up for glacial deposits as a whole, throughout the country which will in time allow comprehensive studies of variations within them to be made. The author is strongly of the opinion that efforts should be made in the future to collect factual information even at the expense of the more traditional type of study. With an increasing number of people studying glacial deposits and successions, there is a tendency to be

almost as many interpretations of the evolution of the deposits as there are workers. What is needed is an overall concept of what is trying to be achieved in terms of the understanding of glacial deposits. Some techniques such as pollen analysis are clearly suited to the historical approach. However most other techniques taken from the fields of geomorphology, geology and soil mechanics tell us something about the deposit themselves, but generally very little about the history of the deposit. In many cases also the general lack of knowledge of this type of work means that it is extremely difficult to assess the validity of the results obtained.

Main conclusions.

1. In Chapter 4 the similarity of orientation patterns over short distances at individual exposures when the mid-point of the 60 degree modal sector is used as a means of analysis is demonstrated. For rapid investigations of directions of ice movement a 25 stone orientation pattern is found to give satisfactory results, but for detailed statistical analysis 100 stones are essential.

It is seen that both the Upper and Lower Till sheets possess a preferred orientation of the long axes of their included stones, and that these preferred orientation directions are consistent over large areas. The Lower Till is found to have originated from a westerly direction and the Upper Till from a northerly direction. In the coastal area the directions of ice movement of these two till sheets is similar in places. Other stony clays which appear very similar to either the Upper or the Lower Till are often found without a preferred orientation of their included stones, even though they appear to have been undisturbed since deposition.

Statistical analysis of the orientation patterns indicate that angular differences between two adjacent orientation patterns can in some cases be more than 30 degrees, and yet still be considered

to have been drawn from the same total population. This emphasises the danger of placing too much importance on different orientation directions as evidence of changes in the direction of ice movement.

2. In Chapter 5 the importance of studying the total lithologies present within a stony clay rather than indicator erratics is demonstrated. By the use of this method it is shown that local parent materials have contributed more than 75% of the stones present within a deposit in almost all cases. The only marked exception to this is the Scandinavian Drift which possesses a lithological content which is entirely different from the other Eastern Durham stony clays.

The mapping of percentages of Magnesian Limestone within the Lower Till sheet allow the evolutionary nature of the formation of the till sheet to be clearly seen. Plotting of these data graphically shows how the dominant lithology of a till sheet can change in a distance of 10 miles after the ice sheet has crossed a lithologically different parent material.

When the lithologies results are grouped into the six main clay types similarities are seen between the Upper Till and the Upper Tees Clay and between the Upper Wear Clay and the Lower Till of the Wear Lowlands. Statistical analysis of these groups shows that significant differences occur even between those which appear similar. Such differences are thought to be accounted for by evolutionary changes within the deposits.

In general it is found that igneous rock types are present in greater proportions in the coarser grade sizes of the deposits, than in the finer grades.

A marked correlation is noted between roundness and the distance of glacial transport and/or the lithological hardness. Igneous, metamorphic, and greywackes are the most rounded types, and sandstones and Magnesian Limestone the most angular.

3. In Chapter 6 a study of the environments of the unweathered stony clays shows marked similarities in terms of pH between the coastal area, the Magnesian Limestone Plateau area and the Tees Lowlands. In the Wear Lowlands much lower pH values are usually found, although even here some high pH values are sometimes found. The modal pH of Eastern Durham for unweathered stony clays is pH 8.5.

Calcium carbonate analysis shows marked variations between the deposits. In the Lower Till calcium carbonate figures show an evolutionary increase in an easterly direction across the Magnesian Limestone outcrop. All the other clay types tend to exhibit relatively constant carbonate values throughout their exposures. No stony clay in the Wear Lowlands possesses a carbonate content of more than 5%, while throughout the rest of Eastern Durham carbonate figures are almost everywhere more than 5%.

Statistical analysis of the calcium carbonate data show similarities between the Upper Till and the Upper Tees Clay, and between the Upper Wear Clay and the Lower Till of the Wear Lowlands. Significant differences are noted between the Upper Till and the Lower Till of the Coastal Region, and between the three divisions of the Lower Till.

The coal contents of the deposits indicate marked similarities between nearly all the deposits. Statistical analysis of these data indicate no significant difference between the Upper and the Lower Till sheets of the Coastal Region, but a significant difference between the three divisions of the Lower Till.

The ~~absence~~ absence of coal material in the Scandinavian Drift suggests that this clay had been deposited prior to the arrival of western ice in the coastal area.

4. In Chapter 7 marked similarities between the sand, silt and clay contents of all the stony clays of Eastern Durham are noted. Other glacial stony clays from northern England also appear to have

similar sand, silt and clay contents. A linear relationship exists between sand and clay contents which allows the prediction of the clay values from the sand contents.

The sand, silt and clay contents of the different stony clay types when plotted on triangular graph paper are of little value for correlation purposes. This contrasts markedly with American experience.

The sand and clay contents of the Lower Till sheet are found to remain relatively constant in a down ice direction across Eastern Durham. No significant changes are seen associated with the crossing of the Magnesian Limestone escarpment.

Detailed particle size analysis shows that the mean values of the clay deposits can be used for interpretative purposes. Statistical analysis shows similarities between the mean values of the Upper Till and the Lower Till of the Coastal Region, and also between the three divisions of the Lower Till. Significant differences are however noted between the Upper Till and the Upper Tees Clay. These may be due to differing modes of deposition. In all cases the sorting values between the different stony clay deposits are similar.

Significant correlations for all the stony clays are shown to exist between mean size and sorting values, and for the Lower Till of the Magnesian Limestone Plateau area, and the Coastal Region between mean size and skewness values. These correlations indicate the ordered nature of the clay deposits over moderate distances.

No changes in mean size or sorting values are seen associated with the Lower Till ice sheet crossing parent material of differing lithologies.

Examination of the cumulative frequency curves showing particle size distribution reveals that the marked break of slope seen at about 0.2 to 0.5 mm. is associated with a change in the composition of the deposit from a dominance of rock fragments in the coarser grade

sizes to one of mineral grains in the finer grades. This feature appears to be a reflection of the size ranges of the local parent material.

Statistical analysis of the gravel contents of the clays indicated similarities between all the deposits except between the Upper Till and the Lower Till of the Coastal Region. As a generalisation it was found that the Upper Tees Clay, the Upper Wear Clay and the Upper Till contain fewer and smaller stones than the Lower Till. A slight drop in the gravel content of the Lower Till sheet is seen after this ice sheet has crossed the line of the Magnesian Limestone Escarpment.

5. In Chapter 8 X-ray diffraction of the clay samples reveals some of the difficulties of using this technique for the analysis of clay mineral mixtures.

Qualitative analysis shows the pronounced similarities in clay mineralogy between the different clay types of Eastern Durham, with the single exception of the Scandinavian Drift. Illite (and mixed-layer minerals), kaolin and quartz are present in all samples. Chlorite appears to be present in some samples but not in others, although this may be due to the fact that below a certain percentage occurrence this mineral is not being identified with the equipment used. The presence or absence of any clay mineral cannot be used as a diagnostic property of identification for any of the stony clay deposits.

Quantitative analysis reveals the dominance of illite in the clay mineralogy of all samples, making up in many cases more than 50 percent of the less than 1.4 micron fraction. Kaolin is the second most frequently occurring mineral, and appears to vary in quantity between 15 to 25%. Quartz percentages vary from 5-15%. In all cases it appears that chlorite is present in quantities of less than 10%.

Studies of the clay mineralogy of local rock materials suggest that the clay minerals found in the Eastern Durham stony clays have been almost solely derived from shale and siltstone of Carboniferous age.

Differential Thermal Analysis confirms the findings of X-ray analysis, but owing to the very pronounced overlap between peak values of the main clay minerals and quartz, this technique is not recommended for studies of this kind.

Studies of the silt sized particles of the stony clays reveal similarities between the Upper and Lower Till sheets of the Coastal Region, and differences between these two deposits and the underlying Scandinavian Drift.

The clay mineralogy of the Holderness tills is shown to be almost identical with the clay mineralogy of the tills of Eastern Durham.

6. In Chapter 9 an analysis of present day weathering environments reveals differences in what might be called 'weathering intensity' between the major topographical regions of Eastern Durham. The most acidic environments are found in the Wear Lowlands. Average depths of leaching, organic matter concentration, gleying and root penetration are estimated for the region of Eastern Durham as a whole. These all emphasise the relatively shallow imprint that Post Glacial weathering has had on the glacial stony clays.

Buried palaeosols are described from the Tees Lowlands and the coastal area, and these show characteristics which are very similar to those observed in present day weathering profiles. Two palaeosols on the upper surface of the Lower Till sheet would seem to indicate a period of deglaciations and weathering between the deposition of the Lower Till and the deposition of the Upper Till. No evidence of palaeosol development was found on the upper surface of the Scandinavian Drift, nor on the upper surface of the Magnesian Limestone beneath the Lower Till sheet.

Pollen analysis of samples from the Upper Till, the Lower Till and the Scandinavian Drift failed to reveal any modern pollen grains.

7. In Chapter 10 a comparison is made between an artificial deposit formed of Coal Measures parent material, and a sub-glacial till formed by the erosion of similar parent material. The analysis shows that the characteristics of a till are largely explained by the properties of the original parent material. The sub-glacial environment is therefore shown to be a zone in which a relatively uniform type of deposit is formed from dissimilar types of parent material by a very thorough mixing process.

8. In Chapter 11 a semi-quantitative drift thickness map is produced using information collected on a grid network pattern.

Detailed statistical analysis from borehole and quarry records is used to compute an average drift thickness of 63 feet for Eastern Durham as a whole. From this an estimate is made of average thickness within County Durham.

Using information obtained from stone counts and calcium carbonate contents, together with the results of drift thickness analysis, an estimate of the amount of erosion achieved by the Lower Till ice sheet in crossing the Magnesian Limestone Plateau of Eastern Durham is made. The amount of erosion of the Magnesian Limestone is thought to have been between 5 to 40 feet.

9. In Chapter 12 it is suggested that the mode of origin of stony clay deposits may be deduced under favourable circumstances from the content and organisation of the included material, and from relationships with other deposits and landforms.

Using such observations possible modes of origin of the stony clay deposits of Eastern Durham are suggested. Both the Lower and the Upper Tills are regarded as the sub-glacial dirt of separate ice sheets.

The actual mode of deposition of the two clays is considered to be different, with more meltwater and mass movement being associated with the deposition of the Upper Till. It is considered that the Upper Till ice sheet could not have been an overrider of the Lower Till ice sheet in the manner postulated by Carruthers. The two tills may however belong to the same glaciation.

Both the Upper Wear Clay and the Upper Tees Clay are considered to have been the result of complex local environmental conditions during stages of deglaciation. The Upper Wear Clay is considered to be the same age as the Lower Till, and the Upper Tees Clay the same age as the Upper Till.

The Scandinavian Drift is regarded as the product of deposition of an ice-shelf which had floated across the North Sea.

The upper clay deposit at Shotton Colliery is tentatively considered to represent a turbidity current or mud flow deposit into a lake.

10. In Chapter 13 the stratigraphy of the Eastern Durham area is outlined. A tentative dating scheme is considered for the ages of the three till deposits, but it is concluded that the present evidence which exists is insufficient to allow a definite conclusion on absolute ages to be reached.

The Upper Till of Eastern Durham is considered to be the lateral equivalent of the upper red clay of coastal Northumberland, and the Hessle Till of Holderness. The Lower Till of Eastern Durham is considered to be the lateral equivalent of the basal dark grey till with western erratics of coastal Northumberland, and the Drab Till of Holderness. The Scandinavian Drift is considered to be the lateral equivalent of the Basement Till of Holderness.

Significance of results.

These results indicate beyond doubt that glacial till is not a "chaotic and pell mell" deposit, but does show considerable evidence of organisation and orderly evolution.

It is clearly demonstrated in this thesis that both coarse and fine grained fractions of a glacial till are almost completely of local origin, and have only rarely been transported more than 20 miles. In almost every case with the notable exception of the Scandinavian Drift far travelled material makes up less than 10% of the total sample. No definite evidence exists in Eastern Durham to suggest that even the finest sized material (clay minerals) have been derived from any but local sources.

The fact that glacial till is composed dominantly of local material carries with it the implication that a till sheet must form rapidly beneath a glacier, and evolve quickly in response to changes in the bedrock material over which it is passing. This of course means that the same till sheet separated by considerable distances and lying on different parent material would not necessarily be expected to be similar. This points to the difficulty of long distance correlations.

One of the most striking features of this work has been the fact that different types of analysis give rise to different correlations.

For example stone counts show general similarities between the Upper Till and the Upper Tees Clay, and between the Upper Wear Clay and the Lower Till of the Wear Lowlands. However when the results for the six main clay types are considered statistically it is found that there are significant differences between the three divisions of the Lower Till, between the Upper Till and the Upper Tees Clay, between the Upper Wear Clay and the Lower Till of the Wear Lowlands, and between

the Upper Till and the Lower Till of the Coastal Region. Statistical analysis of carbonate contents show similarities between the Upper Tees Clay and the Upper Till and between the Upper Wear Clay and the Lower Till of the Wear Lowlands. However significant differences are seen between the three divisions of the Lower Till, and between the Upper Till and the Lower Till of the coastal region. On the other hand statistical analysis of the mean values for the particle size distributions indicate similarities between the three divisions of the Lower Till, and between the Upper Till and the Lower Till of the coastal region, but differences between the Upper Till and the Upper Tees Clay. X-ray analysis does not allow the definite distinction between any of the deposits with complete certainty. Bearing some of these examples in mind it would be possible to prove a series of different conclusions depending on which techniques of analysis one selected.

For example if it were not known on the basis of stratigraphical mapping that the Lower Till in its three divisions in Eastern Durham was a laterally continuous deposit, it could be shown in terms of stone counts and carbonate contents that three different clay deposits were present within the area. This emphasises some of the difficulties involved in studying deposits by purely quantitative techniques. In the authors opinion quantitative analysis of glacial deposits must always be regarded as complementary to the more traditional methods of stratigraphical methods rather than as in competition with them.

At the present time analytical studies such as attempted by the author in this thesis have tended to be based on a single region, and to have considered a series of deposits in a vertical sequence. In the author's opinion, the next stage and probably the more useful one must be to study single deposits in terms of their lateral evolution and development over large areas. Owing to the tremendous amount of time involved in the analysis of samples, it would seem that such a

study would have to be planned as a team venture with the combined efforts of a number of laboratories being used. Even so difficulties would no doubt arise as to the sampling of deposits, which are often deeply buried by younger drifts. These difficulties could only be overcome by an extensive drilling programme but this would be both expensive and time consuming. A possible solution to this problem would be to study a deposit which has dominantly a surface outcrop. In eastern England as a whole one deposit in particular would fulfill this condition. This is a till sheet of the Last Glaciation represented by the Upper Till of Eastern Durham, the Hessle Till of Holderness, and the Hunstanton Till of north Norfolk. Throughout a distance of more than 150 miles this deposit maintains a visual uniformity which is quite remarkable. The study of samples obtained from this deposit might well help to explain some of the anomalies of glacial clay formation and deposition which have been noted during regional studies.

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APPENDICES

Appendix 1Place Names

Map references on Ordnance Survey Sheets 78 and 85 (One inch map of Great Britain.)

Aycliffe	285225	Croxdale	268370
Batt ^e ar Law	406460	Dalton-le-Dale	410480
Belmont	295438	Dalton Piercy	468313
Billingham	468235	Darlington	295145
Birtley	270564	Deaf Hill	380365
Bishop Middleham	330315	Durham City	273425
Bishopton	364212	Eaglescliffe	418135
Balckhall Colliery	457395	Easington	417435
Blackhall Rocks	472388	Easington Colliery	439440
Boldon	355610	Easington Lane	365460
Bowburn	306382	East Herrington	360530
Bradbury	316283	Elwick	455323
Braffeton	297211	Embleton	420298
Brancepeth	221280	Eppleton	369482
Brierton	478300	Ferryhill	290325
Carlton	396220	Finchale Priory	296472
Cassop Colliery	346385	Foxholes	447438
Castle Eden	426381	Fulwell	395595
Chester-le-Street	273510	Fulwell Hills	384596
Chourdon Point	442465	Gateshead	256615
Cleadon Hills	395640	Greatham	493278
Cold Hesleden	414467	Grindon	358550
Cornforth	314344	Hart	470350
Coxhoe	320360	Hartlepool	525338
Crimdon	482370	Haswell	376435

Hawthorn	420456	Ryhope	414528
Hazel Dene	436485	Salterfen Rock	416542
Heighington	250222	Seaham Harbour	430495
Hesleden	440381	Seaton Carew	525300
Hetton-le-Hole	352473	Sedgefield	355290
High Bittenby	290398	Shadforth	342410
High Moorsley	337459	Sheraton	440350
Holy Cross	388437	Sherburn	320425
Horden Colliery	442415	Shincliffe	290408
Houghton-le-Spring	340500	Shotton	412398
Kelloe	345362	Silksworth	367530
Kelloe Law	365375	Southern Law	365364
Kimbleworth	260473	South Hetton	380452
Limekiln Gill	479378	South Hylton	355568
Low Newton	286457	South Shields	375663
Low Stotfield	457290	Spennymoor	255335
Ludworth Colliery	362413	Stockton	445195
Lumley	305504	Sunderland	400575
Marsden	406644	Sunderland Bridge	267372
Middlesbrough	490185	Ten O'Clock Barn	395303
Middridge	252260	Town Kelloe	350368
Morden	330266	Trimdon	365340
Penshaw	330535	Trimdon Colliery	380360
Peterlee	425415	Trimdon Grange	370360
Pittington	325448	Tunstall	390534
Pity Me	266457	Tunstall Hills	392544
Plawsworth	263479	Tuthill	393423
Portrack	459200	Warden Law	373506
Quarrington Hill	336373	Warren House Gill	450420
Redmershall	388212	Washington	310565
Rockcliffe Scar	313085	Westmoor Farm	398421
Roker	409589	West Rainton	320466

Wheatley Hill	375392
Whelly Hill	450341
Whinney Hill	280420
Whitburn	408620
Windy Nook	274608
Wingate	400382
Wolviston	452257
Wynyard	420256

Appendix 2.

Detailed results of orientation patterns at 14 sites.

Results of 14 exposures which were subjected to detailed stone orientation analysis.

At each exposure between 4 to 6 orientation patterns were recorded at 6 to 10 feet intervals along a till face. Each of these orientation patterns was made up of the measurement of the long axes of 25 stones.

These data were subjected to numerical analysis in terms of a modal 10° sector, a modal 30° sector and a modal 60° sector. The centre point of these sectors was recorded in tabular form.

Exposures

1. Biddick Burn
2. West Cornforth Quarry
3. Sherburn Sand Pit
4. Middridge Quarry
5. South Hylton Quarry
6. High Moorsley Quarry
7. Houghton-le-Spring Quarry
8. Eighton Banks Quarry
9. Warden Law
10. Westmoor Farm Quarry
11. Wingate Quarry (D)
12. Quarry one mile east of Wingate Quarry A.
13. Bishop Middleham Quarry
14. Coxhoe Quarry

All figures in degrees.

Biddick Burn

25 stone orientation counts.	Mid-point of modal 10°sector	Mid-point of modal 30°sector	Mid-point of modal 60°sector
a.	45, 275,	35	70
b.	55	65	60
c.	65, 5, 285	45	90
d.	75	75	90
50 stone orientation counts.			
a + b	55	45	60
b + c	75	75	90

West Cornforth Quarry

25 stone orientation counts.	Mid-point of modal 10°sector	Mid-point of modal 30°sector	Mid-point of modal 60°sector
a.	295	295	290
b.	285	275, 295	290
c.	75, 85	85	280
d.	285	275	90
50 stone orientation counts			
a + b	295	295	290
c + d	85	295	280

3. Sherburn Sand Pit

25 stone orientation counts.	Mid-point of modal 10°sector	Mid-point of modal 30°sector	Mid-point of modal 60°sector
a.	85	75	90
b.	275, 305, 55	85, 295	280
c.	295	295	280
d.	85, 295	285, 275	90
50 stone orientation counts.			
a + b	85	85	280
c + d	295	295	280

Middridge Quarry

25 stone orientation counts.	Mid-point of 10°modal sector	Mid-point of 30°modal sector	Mid-point of 60°modal sector
a.	285, 295, 65, 75	75, 285	90
b.	285, 55, 75	65	80
c.	85	275	90
d.	285, 295	285	280
50 stone orientation counts.			
a + b	285, 75	75	90
c + d	85	275	90

South Hylton Quarry

(Upper Till)

25 stone orientation counts.	Mid-point of 10°modal sector	Mid-point of 30°modal sector	Mid-point of 60°modal sector
a.	25, 35	35	40
b.	75	65	60
c.	24, 45, 65	35	50
d.	25	35	50
50 stone orientation counts.			
a + b	35, 65, 75	65	50
b + c	25	35	50

High Moorsley Quarry

25 stone orientation counts.	Mid-point of 10°modal sector	Mid-point of 30°modal sector	Mid-point of 60°modal sector
a.	25	15	360
b.	295, 5	5	10
c.	335	345	360
d.	335, 15	335	10
50 stone orientation counts.			
a + b	325, 15, 25	15	0
c + d	335	45	350

Houghton-le-Spring Quarry

25 stone orientation counts.	Mid-point of modal 10° sector	Mid-point of modal 30° sector	Mid-point of modal 60° sector
a.	25,35,45	35	30
b.	35	45	40
c.	45	45	40
d.	25,45	35	40
50 stone orientation counts.			
a + b	35	35	30
c + d	45	35	40

Eighton Banks Quarry

25 stone orientation counts.	Mid-point of modal 10° sector	Mid-point of modal 30° sector	Mid-point of modal 60° sector
a.	275,285	285	300
b.	85	85	290
c.	275,295	285	290
d.	285	275	280
50 stone orientation counts			
a + b	275	85	290
c + d	85,275,285	275	290

Warden Law

25 stone orientation counts.	Mid-point of modal 10° sector	Mid-point of modal 30° sector	Mid-point of modal 60° sector
a.	275	285	290
b.	285	285	290
c.	315	305	310
d.	295	295	290
50 stone orientation counts.			
a + b	285	285	290
c + d	295	305	310

West Moor Farm Quarry

25 stone orientation counts.	Mid-point of 10° modal sector	Mid-point of 30° modal sector	Mid-point of 60° modal sector
a.	295,305,5,35	295	300
b.	305	295	290
c.	295,315	315	310
d.	305	295	290
e.	285	295	300
f.	305	305	320
50 stone orientation counts.			
a + b	315	295	280
c + d	315	305	300
c + f	285,305	295	300

Wingate Quarry D

25 stone orientation counts.	Mid-point of 10° modal sector	Mid-point of 30° modal sector	Mid-point of 60° modal sector
a.	305	315	310
b.	285,295	295	310
c.	295	305	310
d.	285	295	300
50 stone orientation counts.			
a + b	285,305	295	310
c + d	295	295	310

Quarry 1 mile east of Wingate Quarry A.

25 stone orientation counts.	Mid-point of 10° modal sector	Mid-point of 30° modal sector	Mid-point of 60° modal sector
a.	285	305	280
b.	315	305	290
c.	285	305	290
d.	295	295	280
50 stone orientation counts.			
a + b	285	295	290
c + d	295	295	280

Bishop Middleham

25 stone orientation counts.	Mid-point of modal 10° sector	Mid-point of modal 30° sector	Mid-point of modal 60° sector
a.	305	315	300
b.	285,305	315,295	310
c.	305	295	310
d.	315	315	320
50 stone orientation counts.			
a + b	305	315	300
c + d	305	305	310

Coxhoe Quarry

25 stone orientation counts.	Mid-point of modal 10° sector	Mid-point of modal 30° sector	Mid-point of modal 60° sector
a.	285,305	295	300
b.	325	315	320
c.	315	315	310
d.	305	295	310
50 stone orientation counts.			
a + b	305	295	300
c + d	305	305	310

Appendix 3Lower Till

<u>No.</u>	<u>Place Name</u>	<u>Map reference</u>
		O.S. Sheets 1" to 1 mile No.78 and 85.
1.	Windy Nook Quarry	276,606
2.	Eighton Banks Quarry	276,587
3.	Chester-le-Street	266,517
4.	Biddick Burn	304,551
5.	Crime Rigg Quarry	325,541
6.	South Hylton Quarry	362,572
7.	Fulwell Quarry	384,596
8.	Salterfen Rocks	415,540
9.	Cliffs north of Seaham	420,518
10.	Warden Law	363,508
11.	Houghton-le-Spring Quarry	340,505
12.	Lumley Brick Pit	306,504
13.	Finchale Coal Staithes	283,467
14.	Finchale Priory	308,460
15.	High Moorsley Quarry	334,456
16.	Eppleton Colliery	361,480
17.	Dalton-le-Dale	412,484
18.	Chourdon Point	443,467
19.	South Hetton	372,456
20.	Sherburn Sand Pit	343,418
21.	Westmoor Farm Quarry	400,420
22.	Warren House Gill	448,424
23.	Low Grange, Bowburn	306,399
24.	Brancepeth Beck	232,368
25.	Wingate Quarry A.	379,382
26.	Wingate Quarry D.	372,379

<u>No.</u>	<u>Place Name</u>	<u>Map reference</u>
		O.S. Sheets 1" to 1 mile No.78 and 85.
27.	Quarry 1 mile east of Wingate Quarry A.	395,379
28.	Peterlee Shotton Hall School	421,398
29.	Castle Eden Dene mouth	455,410
30.	Blackhall Colliery Aerial Flight	465,400
31.	Quarry west of Blackhall Colliery	458,388
32.	Crimdon Dene mouth	478,382
33.	Castle Eden Village	433,368
34.	Trimdon Grange Quarry	368,362
35.	Coxhoe Quarry	334,364
36.	West Cornforth Quarry	319,345
37.	Thrislington Quarry	307,333
38.	Trimdon, East House Quarry	382,334
39.	Bishop Middleham Quarry	333,319
40.	Bradbury	313,294
41.	Bedlam Gill	420,303
42.	South of Dalton Piercy	464,301
43.	Middridge Quarry	257,245
44.	Aycliffe Quarry	282,220

Fig.19

Upper Till

<u>No</u>	<u>Place Name</u>	<u>Map reference</u>
1.	South Hylton Quarry	361572
2.	Seaham Harbour Brick Pit	412496
3.	Hazel Dene	434482
4.	Hawthorn Quarry	436463
5.	Foxholes	446437
6.	Main drain, Peterlee	423398
7.	Castle Eden Dene mouth	457409
8.	Peterlee near A.19	410391
9.	Blackhall Colliery	465398
10.	Blackhall Rocks	473388
11.	Crimdon Dene	482375
12.	Hesleden Dene	460371
13.	Sheraton Hill Farm	440362
14.	Hart Road	458347
15.	Whelly Hill Quarry	449340
16.	Naisberry Quarry	477333
17.	Low Stotfield Farm	451291
18.	Seaton Carew	524304
19.	Embleton	421301
20.	A.19 road improvements	453281
21.	Greatham Beck	496263
22.	Portrack Brick Pit	454204

Upper Wear Clay Fig.20

1.	Usworth Hall	306582
2.	Railway cutting, north of Durham	283450
3.	High Butterby	288387

4.	Bowburn	304387
5.	Ferryhill	285346

Upper Tees Clay

<u>No.</u>	<u>Place Name</u>	<u>Map reference</u>
1.	Brierton Sand Pit	478298
2.	Stob Cross	442268
3.	Shillington Gravel Pit	371228
4.	Wynyard Hall Gravel Pit	414247
5.	Gilly Flat	365198
6.	Portrack Brick Pit	454204

LOWER TILL

Number of stones in each orientation sector indicated.

Orientation Sector in degrees	1	2	3	4	5	6	7	8	9	10	11	12
270 - 280	5	16	2	8	7	16	10	4	6	15	0	4
280 - 290	3	13	6	10	7	15	7	14	14	20	2	12
290 - 300	2	11	6	9	7	15	1	11	20	23	1	22
300 - 310	2	7	13	4	4	12	3	3	6	12	1	16
310 - 320	4	5	17	6	4	4	2	12	8	15	1	16
320 - 330	3	1	14	4	3	4	2	9	6	3	1	8
330 - 340	2	1	5	4	4	1	0	11	6	4	0	3
340 - 350	3	0	8	3	1	1	1	5	4	3	1	8
350 - 360	2	2	4	4	4	2	3	3	3	2	1	6
0 - 10	6	2	6	2	0	3	1	3	7	2	7	4
10 - 20	10	1	3	5	1	2	2	2	8	0	6	2
20 - 30	8	1	3	6	2	3	3	1	3	2	19	4
30 - 40	10	2	3	5	4	1	8	3	3	1	26	1
40 - 50	24	4	2	7	6	4	4	3	5	1	29	3
50 - 60	10	3	3	9	14	6	7	2	2	2	16	1
60 - 70	3	4	1	11	17	4	2	1	2	5	9	3
70 - 80	5	11	4	15	23	24	4	5	3	5	3	2
80 - 90	5	16	1	12	18	5	4	9	1	7	6	1
Total	107	100	101	124	126	100	64	107	107	122	129	116

LOWER TILL (Continued):

Orientation in degrees	25	26	27	28	29	30	31	32	33	34	35	36
270 - 280	7	7	11	19	0	1	1	4	1	5	4	7
280 - 290	17	13	16	27	7	7	9	3	5	8	16	16
290 - 300	22	7	18	25	6	3	9	3	6	6	18	13
300 - 310	17	7	19	19	6	4	17	11	4	5	24	6
310 - 320	10	2	8	9	4	7	13	9	11	5	18	6
320 - 330	12	6	4	7	8	7	11	11	17	7	13	5
330 - 340	4	8	2	7	1	12	8	19	14	3	5	4
340 - 350	5	6	4	8	7	14	7	14	11	2	8	5
350 - 360	4	2	1	4	3	5	6	5	6	3*	4	3
0 - 10	0	5	3	0	4	7	3	6	6	3	4	0
10 - 20	3	4	4	0	8	6	4	2	6	4	4	4
20 - 30	5	2	3	0	5	6	1	5	2	4	5	4
30 - 40	10	2	4	9	6	7	1	4	1	1	2	2
40 - 50	8	0	2	8	12	6	4	5	0	4	1	1
50 - 60	8	5	3	9	9	1	1	1	1	5	1	1
60 - 70	5	4	6	7	6	2	2	1	1	2	2	4
70 - 80	6	7	4	5	3	3	2	2	1	3	2	8
80 - 90	6	2	6	23	2	2	2	1	1	3	2	17
	149	89	118	186	97	100	101	106	94	75	133	106

LOWER TILL (Continued):

Orientation in degrees.	37	38	39	40	41	42	43	44
270 - 280	2	12	5	13	13	8	12	6
280 - 290	2	16	8	12	6	12	14	5
290 - 300	5	16	6	6	13	8	13	12
300 - 310	7	15	5	5	3	3	2	14
310 - 320	10	13	5	3	2	6	9	15
320 - 330	17	12	7	2	2	0	6	18
330 - 340	10	5	3	4	2	1	4	9
340 - 350	7	1	2	6	0	1	1	8
350 - 360	7	12	3	0	4	0	2	4
0 - 10	5	1	3	2	6	2	0	1
10 - 20	10	1	4	4	4	1	2	2
20 - 30	2	1	4	2	2	2	3	5
30 - 40	6	3	1	3	2	0	4	3
40 - 50	3	3	6	7	2	0	4	4
50 - 60	3	4	5	4	0	5	8	1
60 - 70	8	4	2	4	0	5	8	2
70 - 80	3	5	3	11	6	7	11	2
80 - 90	3	6	3	17	7	11	18	1
	110	120	75	105	74	72	121	112

UPPER TILL

Number of stones in each orientation sector indicated.

Orientation in
degrees.

	1	2	3	4	5	6	7	8	9	10	11
270 - 280	8	7	6	1	1	11	5	4	3	4	2
280 - 290	1	2	6	1	5	5	6	2	1	4	0
290 - 300	3	3	4	3	6	13	11	6	9	4	7
300 - 310	1	3	5	6	3	11	6	8	2	2	8
310 - 320	2	3	4	1	1	13	6	7	4	2	3
320 - 330	1	6	2	2	2	14	7	4	4	1	2
330 - 340	3	3	5	2	8	14	3	4	1	2	2
340 - 350	2	6	5	6	8	20	12	3	3	0	4
350 - 360	2	10	7	3	10	18	12	4	4	4	6
0 - 10	2	8	20	14	7	20	12	4	6	1	13
10 - 20	3	10	15	22	5	14	16	9	5	5	13
20 - 30	14	1	7	15	9	20	8	18	22	5	12
30 - 40	10	4	3	14	5	11	6	16	18	8	21
40 - 50	13	7	9	7	7	5	3	6	7	11	17
50 - 60	11	5	8	3	7	15	9	1	7	15	7
60 - 70	16	2	2	5	9	19	2	4	5	13	4
70 - 80	13	3	6	5	7	4	6	4	6	17	1
80 - 90	9	3	6	3	3	9	1	8	2	8	2
	114	86	120	113	103	236	131	111	109	106	124

UPPER TILL (Continued) :

Orientation in degrees.	12	13	14	15	16	17	18	19	20	21	22
270 - 280	4	4	1	5	2	2	10	4	2	3	4
280 - 290	4	2	1	4	2	5	1	4	3	2	0
290 - 300	3	0	0	7	5	3	8	3	4	4	2
300 - 310	7	2	1	7	7	0	1	2	8	2	2
310 - 320	8	2	0	5	10	1	5	4	5	0	1
320 - 330	11	5	3	6	17	1	1	6	2	0	1
330 - 340	7	0	2	4	10	0	4	1	4	0	1
340 - 350	6	3	6	3	7	0	2	4	4	2	0
350 - 360	6	3	5	5	7	0	2	2	5	3	5
0 - 10	13	4	4	7	5	1	4	4	2	3	8
10 - 20	8	7	8	6	10	2	1	2	3	3	5
20 - 30	6	6	9	7	2	2	6	9	11	5	11
30 - 40	5	6	8	7	6	4	8	12	26	3	10
40 - 50	4	30	4	6	3	3	9	12	18	4	5
50 - 60	5	24	3	7	3	25	10	18	5	5	8
60 - 70	4	6	9	8	8	15	8	5	6	3	2
70 - 80	5	6	1	3	3	9	7	7	4	12	3
80 - 90	5	1	1	5	3	4	14	2	4	7	3
	111	111	66	199	110	101	101	101	118	61	71

UPPER WEAR CLAY

Number of stones in each orientation sector indicated.

Orientation ^o	1	2	3	4	5
270 - 280	2	4	3	8	6
280 - 290	1	2	2	8	2
290 - 300	1	0	6	11	8
300 - 310	0	3	2	2	8
310 - 320	3	2	3	3	6
320 - 330	0	2	5	10	6
330 - 340	4	7	4	7	10
340 - 350	2	4	8	9	4
350 - 360	2	8	11	6	3
0 - 10	2	5	8	10	5
10 - 20	2	6	15	9	4
20 - 30	5	6	4	6	8
30 - 40	5	7	1	8	6
40 - 50	2	4	8	4	6
50 - 60	2	2	3	9	5
60 - 70	4	2	1	8	7
70 - 80	2	1	2	10	6
80 - 90	2	4	2	4	7
	41	69	88	132	107

UPPER TEES CLAY

Number of stones in each orientation sector indicated.

Orientation°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
270 - 280	10	5	3	0	5	4	7	6	2	3	8	4	11	2	6	3	4	9	1	4	4	6	1	2	4	3	8	2	10	4	6	1	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11	2	3	8	10	9	10	3	11

Appendix 4

Chi square values for orientation patterns.

$$X^2 = \frac{(O - E)^2}{E}$$

For the purposes of calculation the orientation data was divided into 3 sectors of 60 degrees each. One of these sectors was the modal 60 degrees sector. Three categories were selected to minimise the possibility of random concentrations of stones affecting the final X^2 result.

X^2 values with 2 degrees of freedom.

Significance levels

0.05	5.991
0.02	7.824
0.01	9.210
0.001	13.815

Therefore all X^2 values of more than 6.0 could have been obtained from randomly distributed data in only 5 cases out of 100.

X^2 values of more than 14.0 could have been obtained from randomly distributed data in only 1 case out of 1000.

Appendix 5

Calcium carbonate contentEquipment

1. Balance readable and accurate to 0.01 grams.
2. 12 x 100 mls. tall beakers.
3. 1 x 25 mls. burette.
4. 1 x 100 mls. burette.
5. 1 x 20 mls. pipette.
6. 1 x 1 ml. pipette.
7. 6 Erlemayer flasks.

Solutions.

1. N HCl .

1. N NaOH

Bromo-thymol blue indicator solution.

Procedure

5 grams of air dried soil (material passing the No.8 mesh sieve) shall be weighed into a tall 100 mls. beaker.

100 mls of 1 N HCl shall be run from a burette into the beaker and the mixture stirred. The beaker shall be left to stand for a period of 8 hours until the liquid becomes clear.

20 mls. of the supernatant liquid shall be pipetted into an Erlemayer flask, and 10 drops of Bromo-thymol blue indicator solution shall be added.

The solution shall be titrated against the 1 N NaOH until the liquid changes to a bluish colour.

For standardisation purposes 2 to 4 blank determinations shall be carried out to determine the titre of the hydrochloric acid.

The percentage of calcium carbonate is given by the equation

$$\% \text{CaCO}_3 = (\text{Blank titration} - \text{actual titration}) \times 5.$$

To ensure accuracy 2 sub-samples of each sample shall be analysed for CaCO_3 content and the result expressed as an average of the two values.

Appendix 6

Determination of coal content.Equipment

1. A three inch sieve. Mesh No.300
2. A balance readable and accurate to 0.001 grams.
3. 6 x six inch diameter evaporating dishes.
4. A centrifuge capable of holding 4 x fifty mls
centrifuge.
tubes.
5. 4 x fifty mls centrifuge tubes.
6. 1 x 250 mls. measuring cylinder.
7. Heating unit.
8. Drying oven.
9. Buckner funnel, vacuum flask and vacuum pump.
10. Whatmans No.50 filter paper.

Solutions.

1. Dispersing agent. Sodium hexametaphosphate.
(25 grams dissolved in distilled water to make up a solution of
1 litre).
2. Carbon tetrachloride.

Procedure.

50 grams of the till sample (passing the No.8 sieve) shall be weighed into a 6 inch evaporating dish, and 200 mls. of the dispersing agent solution shall be added. The evaporating dish and contents shall be warmed and stirred for thirty minutes.

The suspension in the evaporating dish shall be wet sieved through the No.300 sieve.

The sand and coarse silt fraction retained upon the sieve shall be placed in a drying oven, and the water evaporated.

When dry the sand and silt fraction shall be removed from the evaporating dish and weighed to the nearest 0.001 gram.

The sample of sand and silt shall be quartered and added to 4 x fifty mls. centrifuge tubes each containing 30 mls. of carbon tetrachloride, and stirred.

The tubes shall be centrifuged at 4000 rpm for 5 minutes, to ensure that silt particles are removed from suspension.

The tubes shall be removed from the centrifuge, and the floating coal fragments and carbon tetrachloride poured into a Buckner funnel containing a No.50 filter paper.

The centrifuge tubes shall be topped up with carbon tetrachloride, stirred and re-run to ensure that all the coal fragments are segregated from the sand and silt fraction.

The filter paper containing the coal fragments shall be removed from the Buckner funnel and weighed to the nearest 0.001 gram.

The weight of coal shall be expressed as a percentage of the original 50 gram sample.

Appendix 7

Coarse analysis by wet sievingScope

This method covers the quantitative determination of the particle size distribution on a soil down to the fine sand size. The combined clay and silt fraction can be obtained by difference with this method.

Equipment.

1. British standard sieves as follows:- $\frac{3}{4}$ in, $\frac{1}{2}$ in, $\frac{3}{8}$ in, $\frac{1}{4}$ in, $\frac{3}{16}$ in, $\frac{1}{8}$ in, Nos. 8, 14, 25, 36, 52, 72, 100, 150, 200, 240, and a receiver.
2. A balance readable and accurate to 0.01 gram.
3. A thermostatically controlled oven capable of maintaining a temperature of 105 to 110 degrees C.
4. At least 6 evaporating dishes of about 6 inches in diameter.
5. At least 6 metal trays of about 12 inches square.
6. Sieve brushes.
7. Sodium hexametaphosphate.
8. Mechanical sieve shaker.
9. Large wide necked bottles with capacities of c. 2 litres.

Procedure

The sample for testing shall be dried at 105 to 110, degrees C. for 24 hours. From this sample a sub-sample of 2000 grams which passes the $\frac{3}{4}$ in, sieve, shall be obtained by quartering.

This sub-sample shall be divided into 4 of the large necked bottles and a solution of sodium hexametaphosphate added. (c 10 grams per litre).

The soil and water mixture shall be stirred and allowed to stand overnight to aid dispersion.

The suspension shall be washed through a No.8 and 240 sieve, and the finer material allowed to run to waste. Great care shall be taken to ensure that the No.240 sieve is not overloaded with sediment.

The washing process shall be continued until the water passing the No.240 sieve is substantially clear.

The material retained on the sieves shall be tipped into evaporating dishes and dried.

When dry this material shall be dry sieved, using the full range of sieve sizes.

Calculations

The percentage by weight of material retained on each sieve shall be calculated. The percentage of material passing the No.240 sieve shall be obtained by difference.

The cumulative percentages (by weight of the total sample) passing each of the sieves shall be calculated.

Method of fine-analysis - Hydrometer method.

Scope

This method covers the quantitative determination of the particle size distribution in a soil from the coarse sand size downwards.

Equipment

1. A hydrometer fulfilling the requirements of B.S. 718
2. Two 1000 ml graduated glass measuring cylinders with parallel sides or two parallel sided glass cylinders with ground glass stoppers about $2\frac{3}{4}$ in (7 cm) diameter and 13 in (33 cm) high marked at 1000 ml volume.

3. A thermometer to cover the range $0-50^{\circ}\text{C}$ ($32-122^{\circ}\text{F}$), readable and accurate to 0.5°C (1°F).
4. A mechanical stirrer.
5. British Standard sieve No.240 and receiver.
6. A balance readable and accurate to 0.01 g .
7. A thermostatically controlled drying oven, capable of maintaining a temperature of $105-110^{\circ}\text{C}$ ($221-230^{\circ}\text{F}$).
8. A stop clock or stop watch.
9. Four evaporating dishes. (A convenient size is about 15 cm (6 in) in diameter).
10. A wide-mouth conical flask or conical beaker of 1000 ml capacity.
11. A Buchner funnel about 10 cm (4 in) in diameter.
12. A filter flask to take the funnel (about 500 ml).
13. A 100 ml measuring cylinder.
14. A wash bottle preferably plastics containing distilled water.
15. Filter papers to fit Buchner funnel No.50
16. Litmus paper (blue).
17. A length of glass rod about $6-8\text{ in}$ ($15-20\text{ cm}$) long and $3/16\text{ in}$ ($4-5\text{ mm}$) in diameter.
18. Source of vacuum, e.g. a good filter pump.
19. A length of rubber tubing to fit vacuum pump and filter flask.
20. A constant temperature bath or cabinet large enough to take the apparatus used in this test. The bath shall not vibrate the sample.

REAGENTS.

The reagents used shall be of recognized analytical reagent quality :

- a. Hydrogen peroxide. A 20 volume solution.
- b. Hydrochloric acid N solution. Dilute 89 ml of concentrated hydrochloric acid (specific gravity 1.18) with distilled water to make 1 litre of solution.
- c. Sodium hexametaphosphate solution. Dissolve 33 g of sodium hexametaphosphate and 7 g of sodium carbonate in distilled water to make 1 litre of solution. (Note: this solution is unstable and shall be freshly prepared approximately once a month. The date of preparation shall be recorded on the bottle).

CALIBRATION OF HYDROMETER

Volume.

The volume of the hydrometer bulb (V_h) shall be determined in one of the following ways:

- (i) From the volume of water displaced.

Approximately 800 ml of water shall be poured into the 1000 ml measuring cylinder. The reading of the water level shall be observed and recorded.

The hydrometer shall be immersed in the water and the level shall again be observed, and recorded.

The difference between the two readings shall be recorded as the volume of the hydrometer bulb in ml plus the volume of that part of the stem that is submerged. For practical purposes the error due to the inclusion of this stem volume may be neglected.

- (ii) From the weight of the hydrometer.

A. The hydrometer shall be weighed to the nearest 0.1 g.

B. The weight in grammes shall be recorded as the volume of the hydrometer in ml. This includes the volume of the bulb plus the volume of the stem below the 1.000 graduation mark. For practical purposes the error due to the inclusion of this stem volume may be neglected.

Calibration

(i) The sectional area of a 100 ml measuring cylinder in which the hydrometer is to be used shall be determined by measuring the distance between two graduations (e.g. 100-900). The sectional area (A) is equal to the volume included between the two graduations divided by the measured distance in cm between them. The sectional area shall be constant throughout the length of the cylinder.

(ii) The distances from the lowest calibration mark on the stem of the hydrometer to each of the other major calibration marks (R_h) shall be measured and recorded.

(iii) The distance from the neck of the bulb to the nearest calibration mark shall be measured and recorded.

(iv) The distance H_h corresponding to a reading R_h is equal to the sum of the distances measured in Clauses b and c.

(v) The distance (h) from the neck to the bottom of the bulb shall be measured and recorded as the height of the bulb.

(vi) The effective depth (H_R) corresponding to each of the major calibration marks (R_h) shall be calculated from the formula :

$$H_R = H_1 + \frac{1}{2} \left(h - \frac{V_h}{A} \right)$$

where H_1 = length from neck of bulb to graduation R_h (cm).

h = twice the length from neck of bulb to its centre of volume (cm)

V_h = volume of hydrometer bulb (ml).

A = area of measuring cylinder (sq cm).

(vii) The relationship between H_R and R_h shall be plotted as a smooth curve; using the smooth curve so obtained; a scale of R_h values shall be constructed to the right of the H_R scale on the nomographic chart for the solution of Stokes' Law.

Meniscus correction.

- (i) The hydrometer shall be inserted in a 1000 ml measuring cylinder containing about 700 ml water.
- (ii) By placing the eye slightly below the plane of the surface of the liquid, and then raising it slowly until the surface seen as an ellipse becomes a straight line, the point where the plane intersects the hydrometer scale shall be determined.
- (iii) By placing the eye slightly above the plane of the surface of the liquid, the point where the upper limit of the meniscus intersects the hydrometer scale shall be determined.
- (iv) The difference between the two readings taken in Clauses b and c above shall be recorded as the meniscus correction (C_m).

ProcedurePretreatment of soil.

(1) A 50 gm sample of soil shall be weighed, and placed in the wide-mouth conical flask. 150 ml of hydrogen peroxide shall then be added and the mixture stirred gently with a glass rod for a few minutes after which it shall be covered with a cover glass and left to stand overnight. The mixture in the conical flask shall be gently heated. Care must be taken to avoid frothing over and the contents of the dish shall be periodically stirred. As soon as vigorous frothing has subsided the volume shall be reduced to about 50 ml by boiling.

(2) In the case of soils containing calcium compounds the mixture shall be allowed to cool and 100 ml of hydrochloric acid added. The solution shall be stirred with a glass rod for a few minutes and allowed to stand for 1 hour. When the treatment is complete the solution shall have an acid reaction to litmus. The mixture shall be filtered and washed with warm water until the filtrate shows no acid reaction to litmus.

(3) The damp soil on the filter paper and funnel shall be transferred without any loss whatsoever to the evaporating dish (weighed to 0.01 g) using a jet of distilled water. Only the minimum quantity of distilled water shall be used. The dish and contents shall be placed in an oven and dried at 105-110°C (221-230°F). They shall then be weighed to 0.01 g, and the weight of soil remaining after pretreatment shall be recorded (W_p).

Dispersion of soil.

- (i) To the soil in the evaporating dish 100 ml of the sodium hexametaphosphate solution shall be added from a pipette and the mixture shall then be warmed gently for about 10 minutes.
- (ii) The dispersion shall be carried out using a mechanical mixer. The mixture shall be transferred to the dispersing cup containing the wire baffle, by means of a jet of distilled water from a wash-bottle. The amount of water used shall not exceed 150 ml. The soil suspension shall then be stirred for 15 minutes by means of the mechanical stirring device.

The suspension shall be transferred to the 1000 ml measuring cylinder and made up to exactly 1000 ml with distilled water. This suspension shall then be used for the sedimentation analysis as described below.

Sedimentation.

- (i) A rubber bung shall be inserted in the mouth of the measuring cylinder which shall then be shaken vigorously and finally be inverted end over end. Immediately the shaking has ceased, the measuring cylinder shall be allowed to stand and the stop watch started. The hydrometer shall be immersed to a depth slightly below its floating position and then allowed to float freely. Hydrometer readings shall be taken after periods of $\frac{1}{2}$, $1\frac{1}{2}$, 2 and 3 minutes. The

hydrometer shall then be removed slowly, rinsed in distilled water and kept in a cylinder of distilled water at the same temperature as the soil suspension.

(ii) The hydrometer shall be re-inserted in the suspension and readings taken after periods of 5,10,15 and 30 minutes, 1,2,4, 8,24, and 48 hours, after the shaking. The hydrometer shall be removed, rinsed and placed in the distilled water after each reading. In taking all readings, insertion and withdrawal of the hydrometer before and after taking a reading must be done carefully to avoid disturbing the suspension unnecessarily. Ten seconds shall be allowed for each operation. Vibration of the sample shall be avoided.

(iii) The temperature of the suspension shall be observed and recorded once during the first 15 minutes and then after every subsequent reading. The temperature shall be read with an accuracy of at least ± 0.5 degC (± 1 degF).

(iv) The correction (x) to be applied for the dispersing agent shall be ascertained by placing exactly 50 ml of the sodium hexametaphosphate solution in a weighed glass weighing bottle and after evaporating the water by drying at $105-110^{\circ}\text{C}$ in the oven the weight of dispersing agent (W_d) shall be calculated.

The dispersing agent correction (x) shall then be calculated from the formula:

$$x = 2W_d$$

This correction is independent of the temperature.

Calculations.

Loss of weight in pretreatment.

The percentage loss in weight in pretreatment (P) shall be calculated from the weight of air-dried soil used (W_a), and the weight of soil after pretreatment (W_b) from the formula:

$$P = 100 - \frac{W_b (100)}{W_a} \text{ per cent}$$

The weight of pretreated soil (W_b) shall be used to calculate the percentages below.

Sedimentation.

(i) The observed data and the computed quantities shall be recorded in a table containing the following columns:

1	2	3	4	5	6	7	8	9
Date	Time	Temperature	Elapsed time	R_h^1	$R_h = R_h^1 + C_m$	D	$R_h + M_t - x$	K per cent

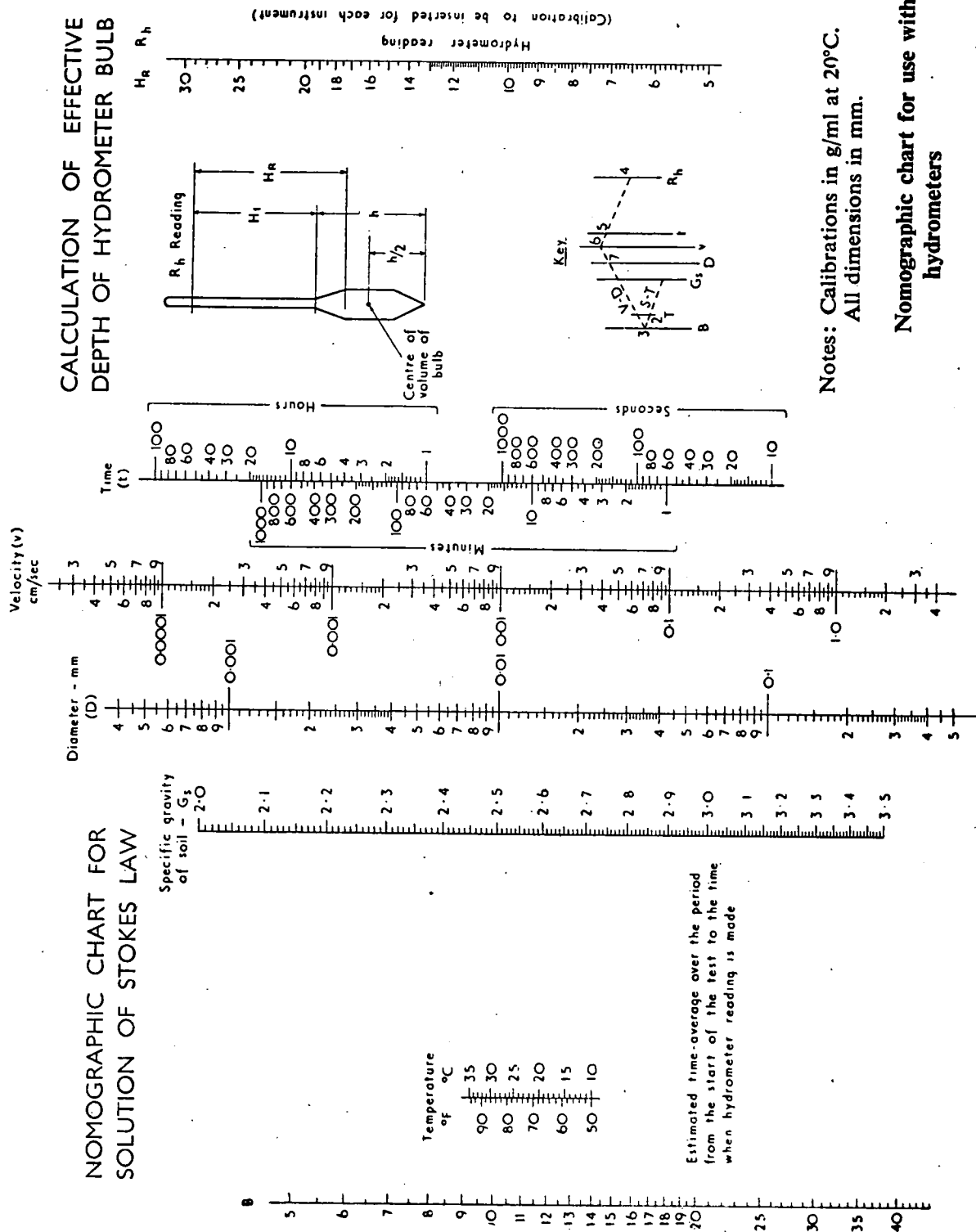
where R_h^1 = the hydrometer reading at the upper rim of the meniscus. This shall be made by reading the decimals only and placing a decimal point between the third and fourth decimal places. For example, the density 1.0325 would read $R_h^1 = 32.5$

C_m = meniscus correction.

M_t = temperature correction, which shows the appropriate correction for hydrometers calibrated at 20°C (68°F).

x = dispersing agent correction.

NOMOGRAPHIC CHART FOR SOLUTION OF STOKES LAW



Nomographic chart for use with
hydrometers

- (ii) The equivalent particle diameter (D) is determined by means of the nomographic chart for the solution of Stokes' Law. To do this a value of the constant B shall be obtained by placing a straightedge across the specific gravity (G_s) and temperature (T) scales at the appropriate values. The value of B so obtained shall be noted.
- (iii) A value of velocity (v) shall be obtained by placing a straightedge across the hydrometer reading (R_h) and time (t) scales at the appropriate values.
- (iv) A value for the equivalent particle diameter (D) shall be obtained by placing a straightedge across the velocity and B scales at points corresponding to the values of v and B found in Sub-clauses b and c. The value of the equivalent particle diameter so obtained shall be entered in Column 7 of the table.
- (v) The temperature correction (M_t) shall be obtained from the temperature correction chart and shall be added to the quantity $R_h - x$ and recorded in Column 8 of the table.
- (vi) The percentage by weight (K) of particles smaller than the corresponding equivalent particle diameters shall be calculated from the formula:

$$K = \frac{100 G_s}{W_b (G_s - 1)} (R_h + M_t - x)$$

where W_b = total dry weight of soil after pre-treatment.

G_s = specific gravity of soil particles = 2.70.

- (vii) The values of K shall be calculated for all the values of D obtained and shall be expressed as percentages of particles finer than the corresponding values, of D . These percentages shall then be expressed as cumulative percentages of the total sample.

Appendix 8

Separation of clay sized material for analysis.Equipment

1. 12 large wide necked 2 litre bottles with water tight lids.
2. A mechanical soil mixer.
3. A glass tube of $\frac{1}{4}$ inch diameter with the end of the tube bent to form a U.
4. Suction pump.
5. Vacuum flask.
6. Steam water bath.
7. Centrifuge and 50 mls. centrifuge tubes.
8. 12 x five hundred mls. beakers.
9. Glass stirring rods.
10. Agate mortar and pestle.
11. 6 evaporating dishes.

Solutions

9N acetic acid.
Magnesian chloride.
Conc. ammonium hydroxide.
80% Ethyl alcohol.
96% Ethyl alcohol.
Hydrogen peroxide 20 vol.

Procedure

50 grams of soil shall be placed in an evaporating dish. To this shall be added 200 mls. of distilled water and 40 drops of conc. ammonium hydroxide. The solution shall be transferred to the mechanical soil mixer using a jet of distilled water, and stirred for 15 minutes. The suspension shall be transferred to a 2 litre

bottle and topped up with 1500 mls. of distilled water. The bottle and contents shall be shaken end over end for 4 to 5 minutes.

After 16 hours the top 10 centimetres of the suspension shall be siphoned off into the large vacuum flask using the U shaped glass tube.

The 2 litre bottle shall be topped up with distilled water and a further 20 to 30 drops of conc. ammonium hydroxide added. The bottle shall be shaken again and after a further 16 hours the top 10 centimetres siphoned off.

For X ray analysis.

600 mls. of the siphoned off suspension shall be dried in a beaker on the steam bath. The dried mixture shall be ground down in an agate mortar and pestle, and passed through a No.72 sieve. This material shall then be bottled and labelled.

For D.T.A. analysis.

600 mls of the siphoned off suspension shall be neutralised with 9N acetic acid. To this 20 mls. of neutral normal magnesian chloride shall be added to coagulate the clay. The supernatant liquid shall be siphoned off, and the concentrated suspension shall be centrifuged in 50 mls. centrifuge tubes. The clay in the tubes shall be washed once with neutral 80% ethyl alcohol, and twice with neutral 96% ethyl alcohol. The clay shall then be transferred with a jet of distilled water to a 600 mls. beaker and evaporated almost to dryness on the steam bath. The suspension shall be treated with hydrogen peroxide until free from organic matter. It shall then be dried completely on the steam bath, and ground down in an agate mortar and pestle until it passes the No.72 sieve. This material shall be labelled and bottled.

All samples for D.T.A. analysis shall be equilibrated at 56% relative humidity by allowing them to stand in a vacuum dessicator over a saturated solution of $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ for at least 4 days.

Appendix 9

Organic matter determinationEquipment

1. Balance readable and accurate to 0.001 grams.
2. 100 ml. burette.
3. Pipettes, 1 ml., 10 ml., and automatic 20 ml.,
4. 500 ml. conical flasks.

Reagents

Potassium dichromate.

Concentrated sulphuric acid.

Phosphoric acid.

Diphenylamine reagent.

0.5N ferrous sulphate solution.

Procedure

1 gram of soil shall be weighed out and placed in a 500 ml. conical flask. To this shall be added 10 mls. potassium dichromate, and 20 mls. concentrated sulphuric acid.

The mixture shall be swirled gently and left to stand for thirty minutes.

After this period 200 mls. distilled water, 10 mls. phosphoric acid, and 20 drops 0.5% diphenylamine indicator shall be added.

The mixture shall then be titrated against 0.5N ferrous sulphate solution until the colour changes from blue to green.

For standardisation purposes a blank titration shall be run without any soil being present.

Calculations

Organic matter = Number of mls. of potassium dichromate reduced x

$$\frac{0.0039 \times 100}{\text{Weight of soil}}$$

Number of mls. of potassium dichromate reduced = R

Blank titration = S

Sample titration = T

$$R = \frac{10}{S} (S-T)$$

$$R = 10 \left(1 - \frac{T}{S}\right)$$

The correction factor 0.0039 is derived as follows:-

The m.e.q. weight of carbon is 0.003 and the recovery factor (Walkley) is 77 per cent or $\frac{100}{77}$

$$\text{The factor is therefore } 0.003 \times \frac{100}{77} = 0.0039$$

$$\text{Therefore \% organic matter} = \frac{10 \left(1 - \frac{T}{S}\right) \times 0.0039 \times 100}{\text{Weight of soil.}}$$

